Spring Final Review

INFERNO

INtegrated Flight-Enabled Rover For Natural disaster Observation

Customer: Barbara Streiffert, Jet Propulsion Laboratory
Faculty Advisor: Jelliffe Jackson

Adam Archuleta, Devon Campbell, Tess Geiger,
Thomas Jeffries, Kevin Mulcair, Nick Peper,
Kaley Pinover, Esteben Rodriguez, Johnathan Thompson

UNIVERSITY OF COLORADO AT BOULDER · INFERNO · JET PROPULSION LABORATORY

Jet Propulsion Laboratory

Aerospace Engineering

PRESENTATION OUTLINE

- Project Purpose and Objectives
- Design Description
- Test Overview
- Test Results
- Systems Engineering
- Project Management

PROJECT PURPOSE AND OVERVIEW

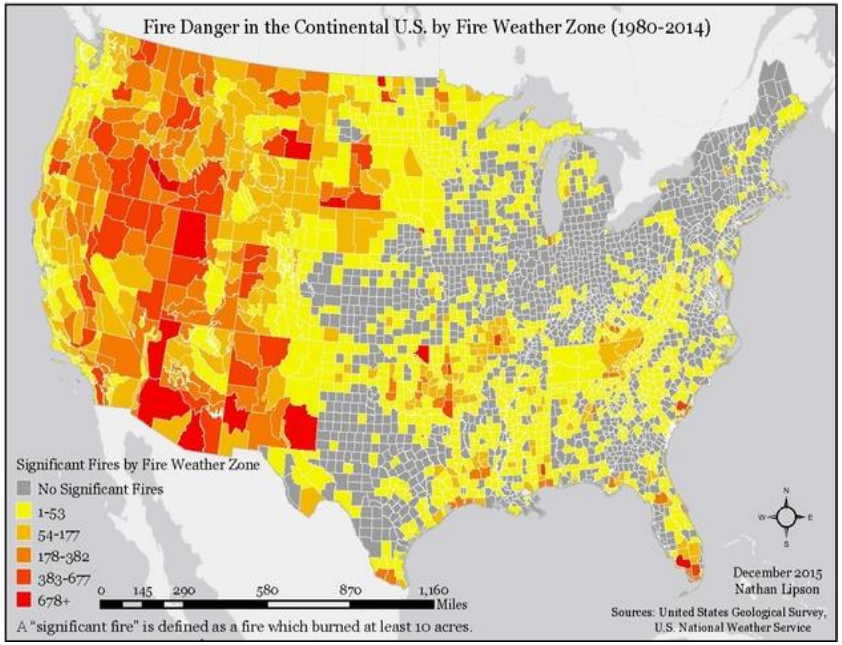
PROJECT MOTIVATION

Wildfires in 2015 [1]

- 68,151 fires
- 10,125,149 acres burned
- Over $2 billion spent

Human Danger

- 2013 Yarnell Hill Fire
  - 19 firefighters killed



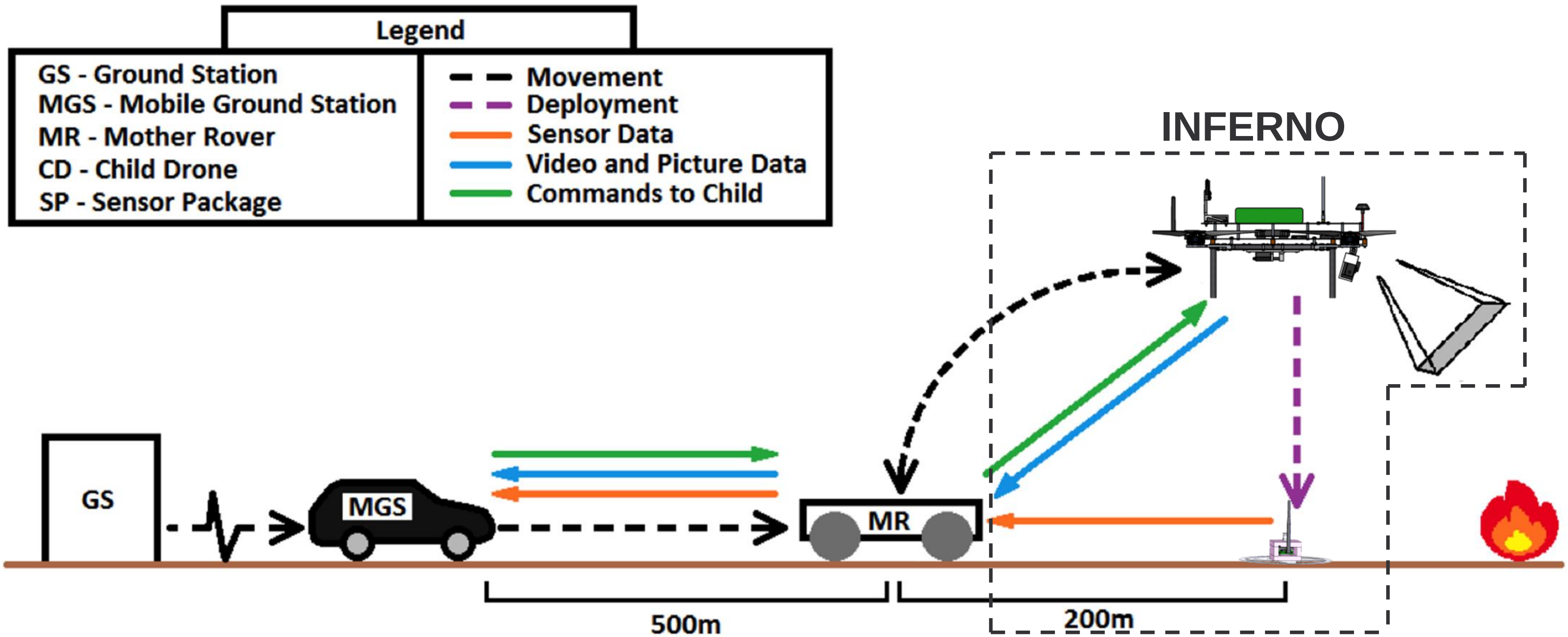
[1] National Interagency Fire Center

Project Context | Design Solution | V&V | Systems and Management

INFERNO MISSION STATEMENT

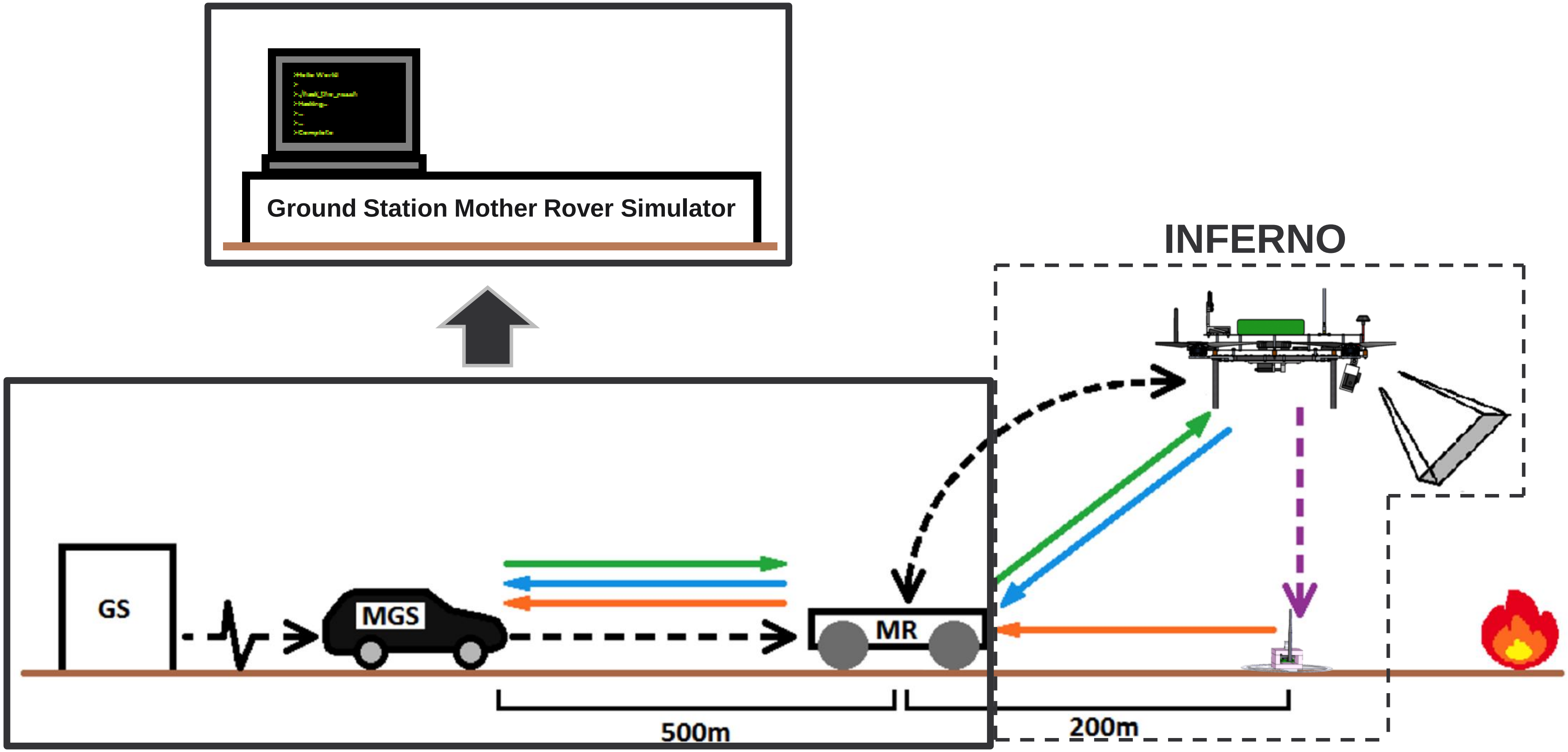
Design and create an ***aerial, sensor package delivery system*** *for future integration with a natural disaster observation system*

FIRE TRACKER SYSTEM



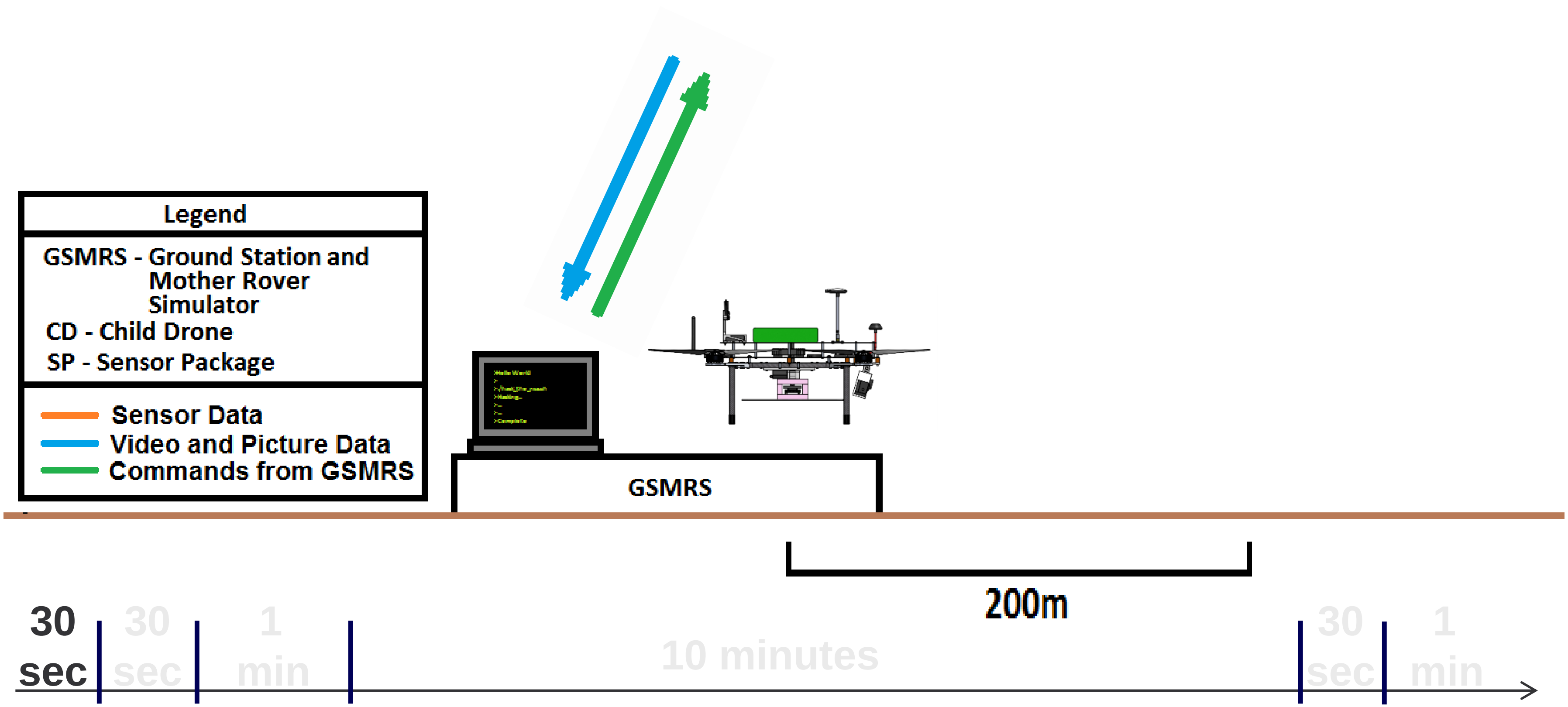
Project Context | Design Solution | V&V | Systems and Management

INFERNO SYSTEM



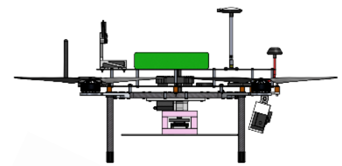
INFERNO SCOPE: CONCEPT OF OPERATIONS

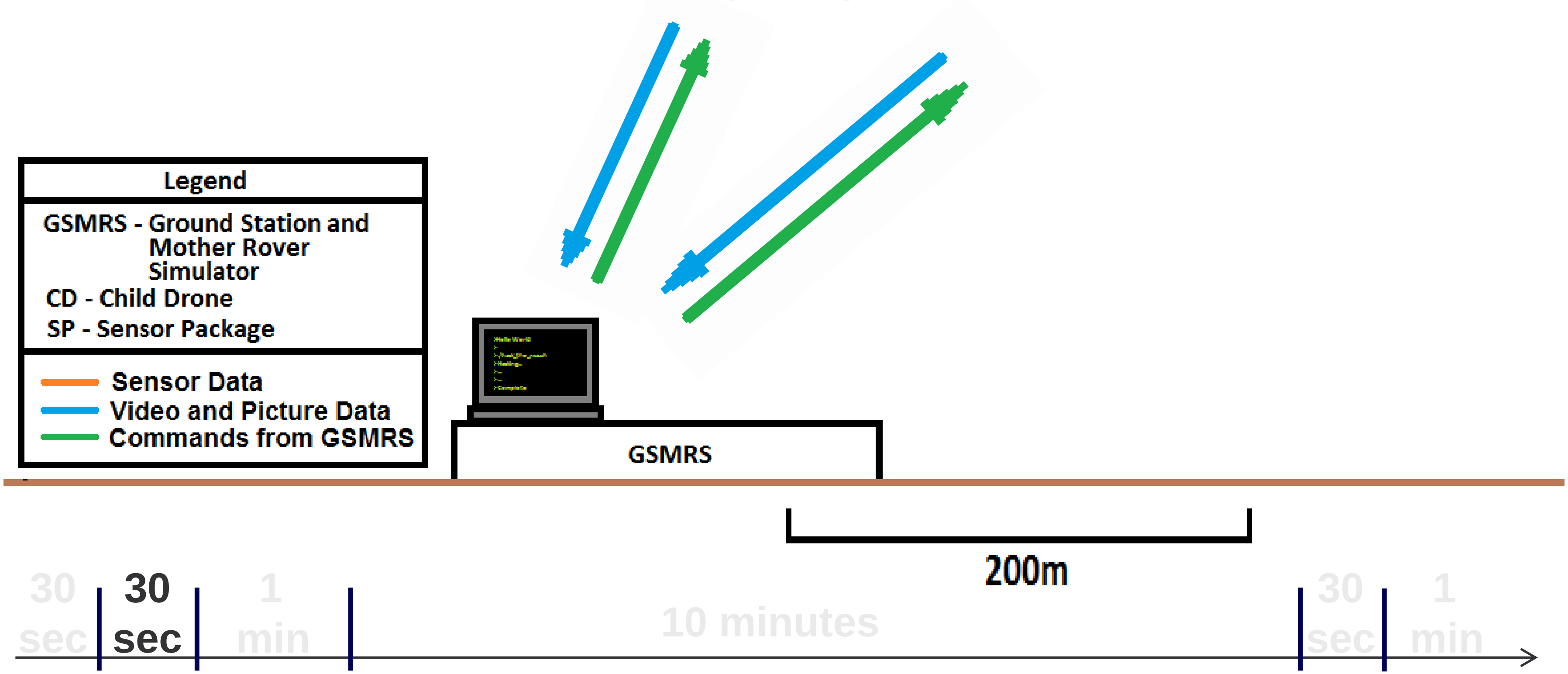
The CD takes off from the GSMRS using autopilot.



INFERNO SCOPE: CONCEPT OF OPERATIONS

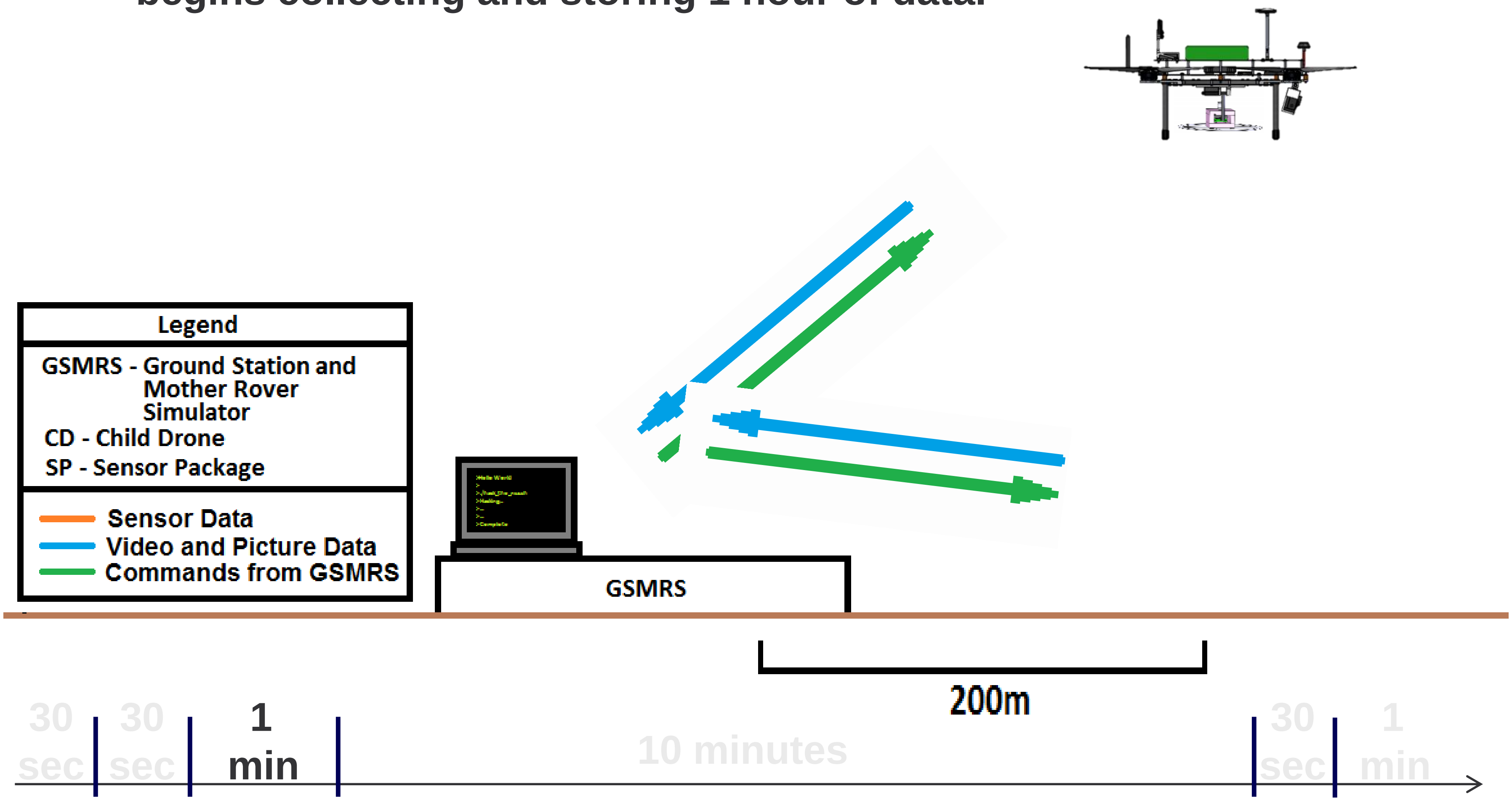
The CD flies to a GPS waypoint up to 200 meters away using autopilot. The CD then maintains its commanded position to 5 meter accuracy.





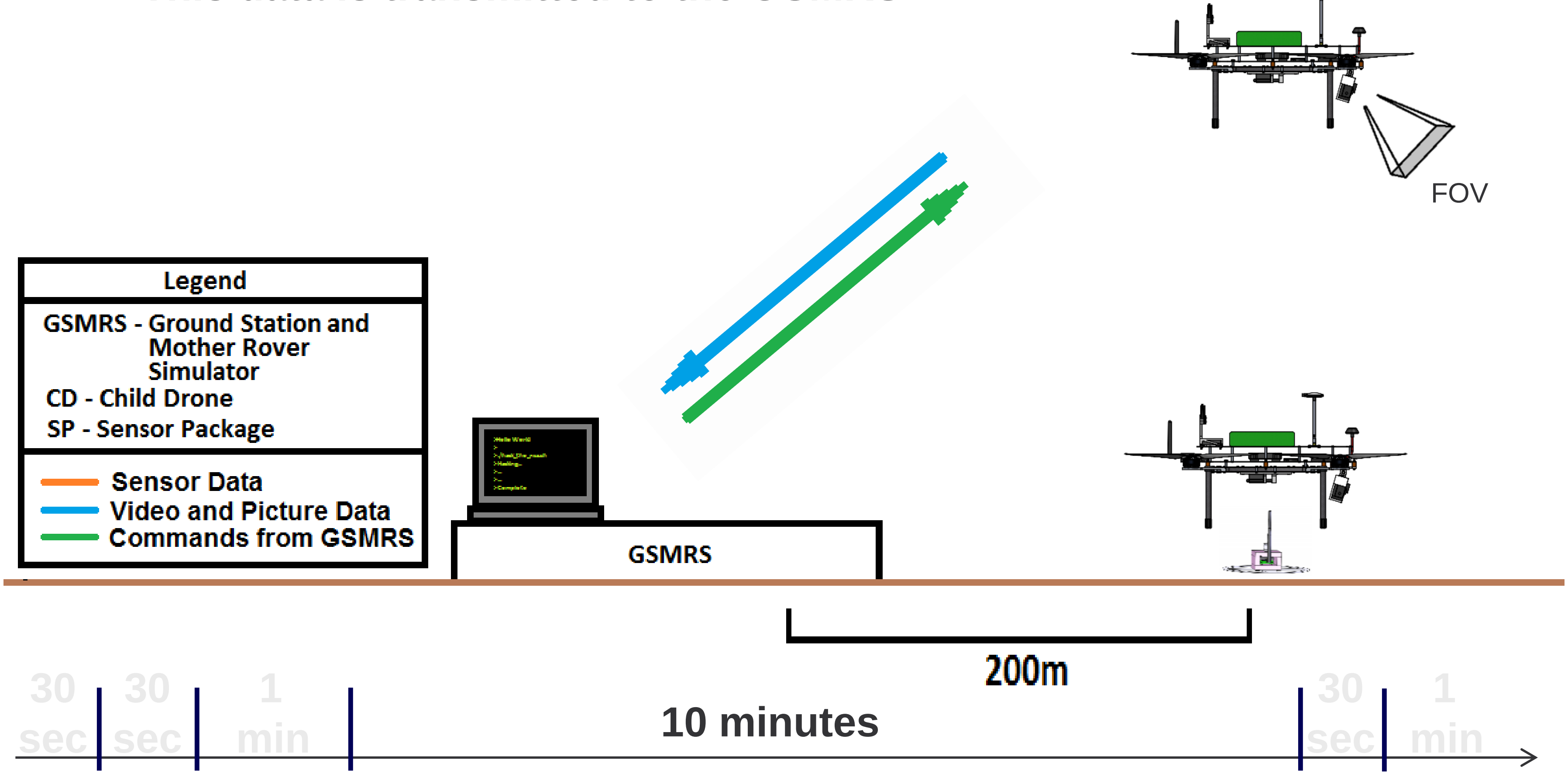
INFERNO SCOPE: CONCEPT OF OPERATIONS

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



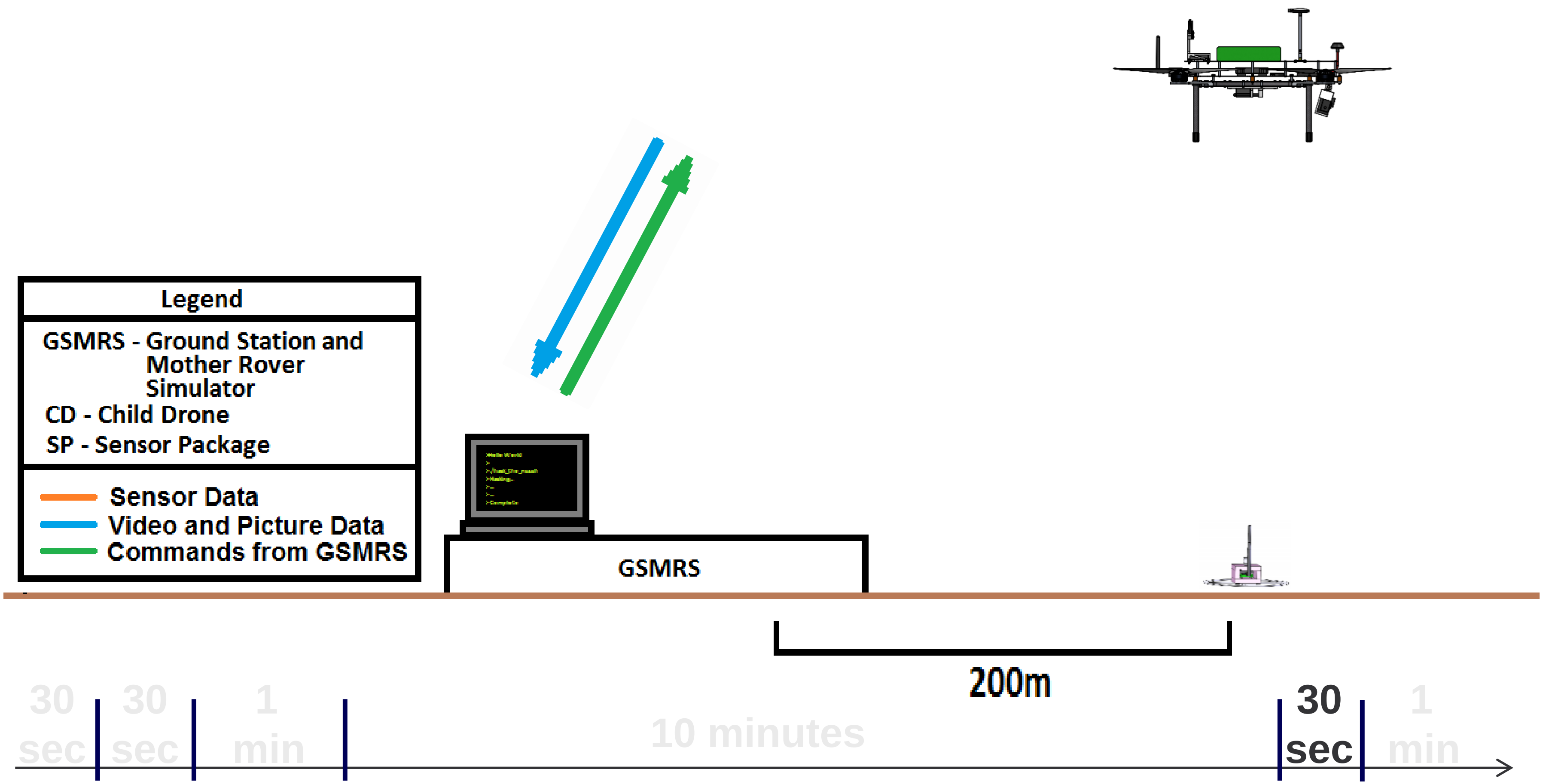
INFERNO SCOPE: CONCEPT OF OPERATIONS

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.



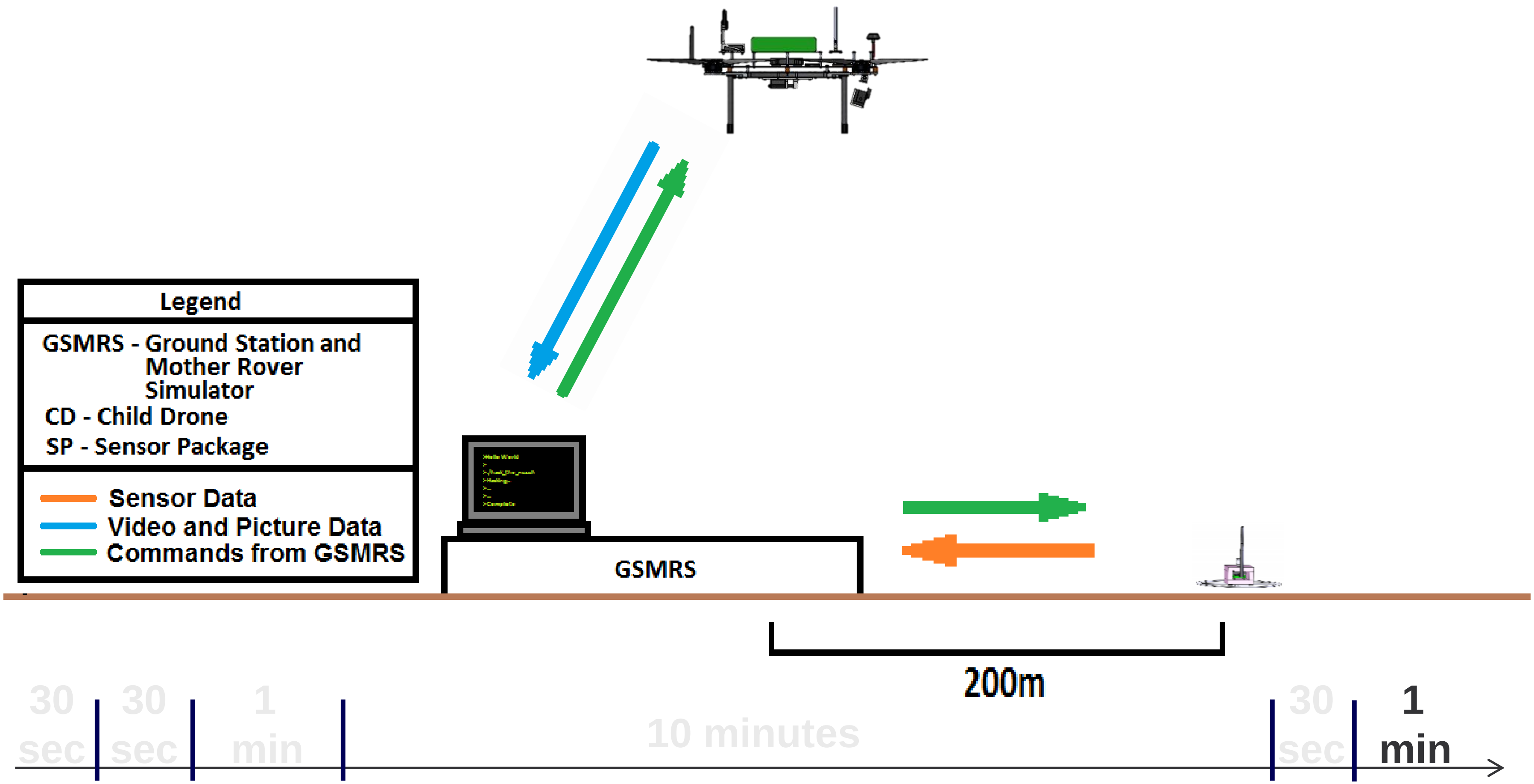
INFERNO SCOPE: CONCEPT OF OPERATIONS

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.



LEVELS OF SUCCESS

Level	Child Drone	Imaging	Sensor	GSMRS
1	Flies at Loaded Weight Lands Safely Simulated Deployment Manually Piloted	Time stamped video 420p at 30fps Wired communication 8MP pictures taken	Wired Communication Time Stamped 1 Hz 8 bit Temperature Collection	Stationary Workbench Wired transmission and reception
2	10 minute flight time Translational Flight	Wireless communication Time stamped video 720p at 30fps	Establish wireless communication Store 1 hour of data Temperature Accuracy	Wireless transmission and reception
3	15 minutes flight time 5 m/s Translational Flight Deploys SP within 10 m Manual takeoff/landing	Time stamped video recorded 1080p at 30fps	>50% Data Transmission	Portable simulator
4	10 m/s Translational Flight Deploys SP within 5 m Fully autonomous takeoff	Time stamped video transmitted 720p at 30fps	>90% Data Transmission Retransmission	Data transmission and reception GUI

Achieved | Partial | Not Achieved

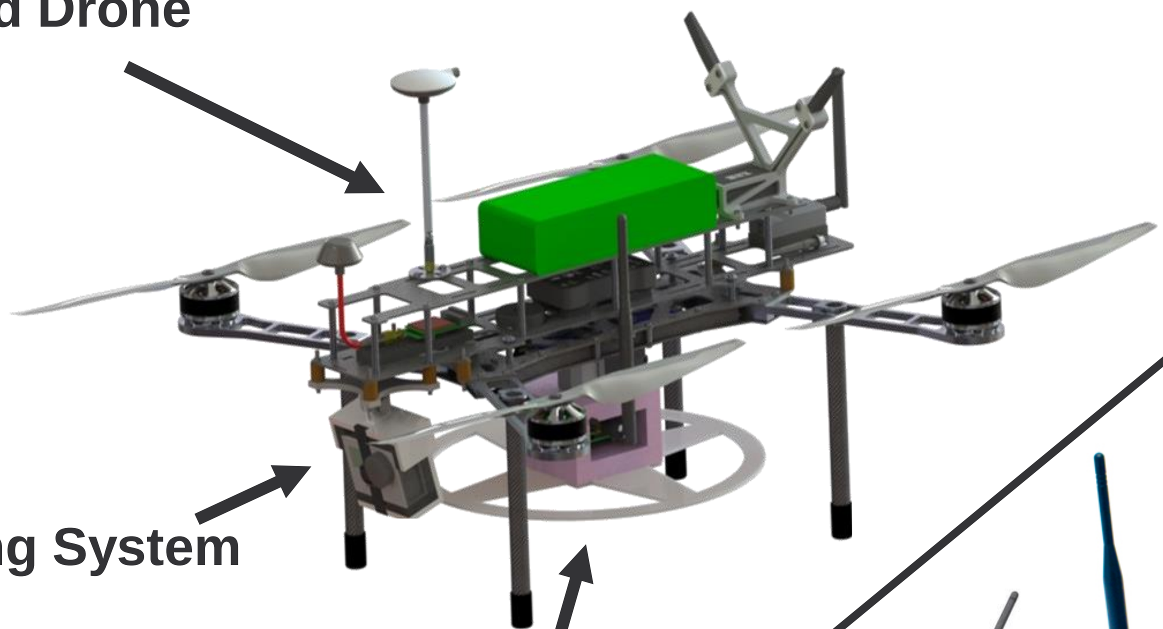
CRITICAL ELEMENTS

Critical Element	Mission Influence	Solution
Subsystem Integration	Mission failure without successful operation of each subsystem	• Maintained ICDs • Integrated components early
Power Limitations	Mission profile can't be executed without required endurance	• Modeled power draw • Budgeted mass
Software	All systems require SW: mission failure if any system's SW fails	• Team strength & knowledge with SW
Communications	All systems must communicate: mission failure if any system fails to communicate	• Performed link budget analysis • Performed communication tests
Scheduling	Necessary for verification and validation of requirements and mission profile	• Maintained testing schedule • Designated scheduler

DESIGN DESCRIPTION

Integrated INFERNO System

Child Drone

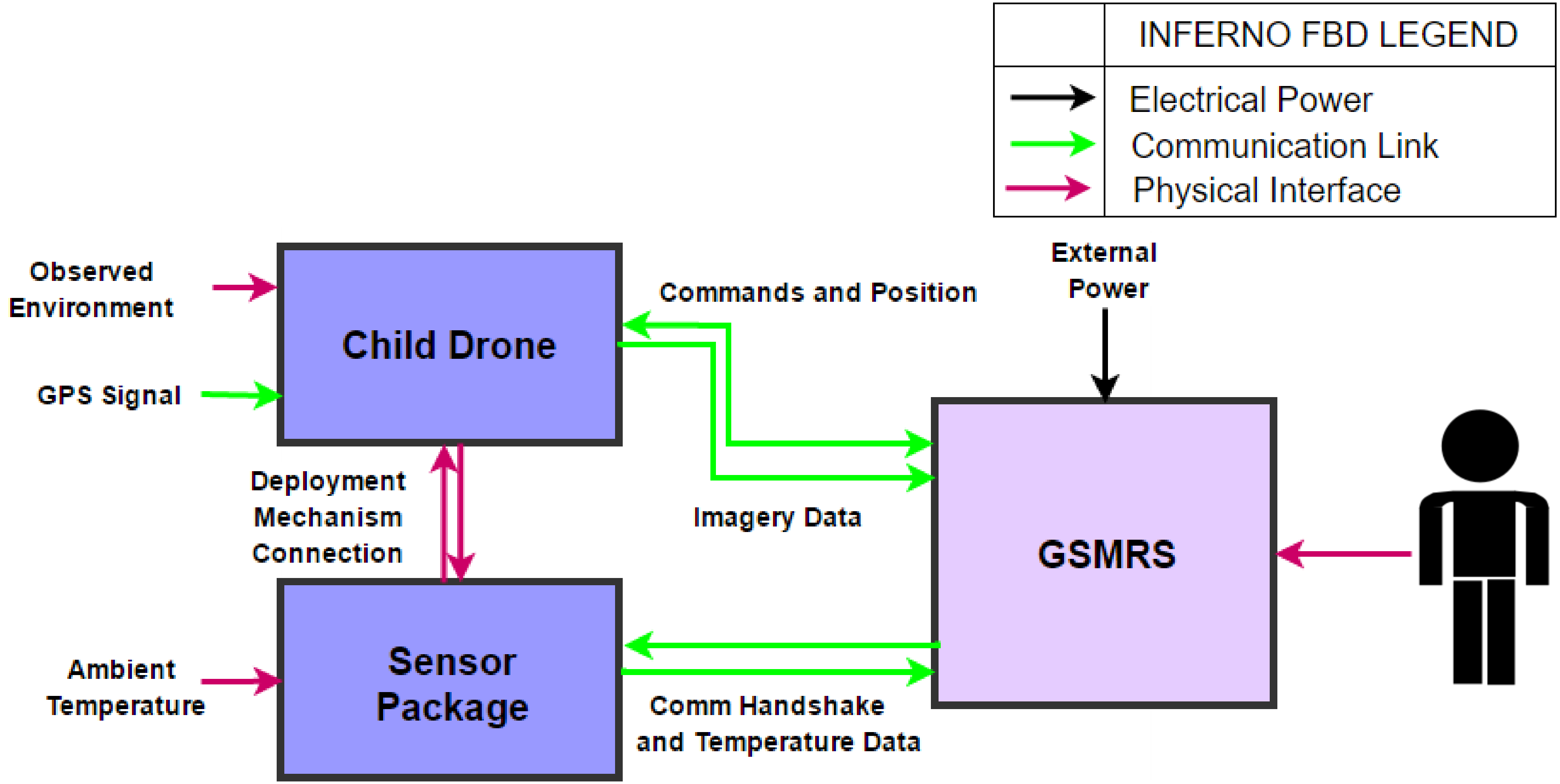


Imaging System

Sensor Package

GSMRS (Simulator)

FUNCTIONAL BLOCK DIAGRAM: SYSTEM



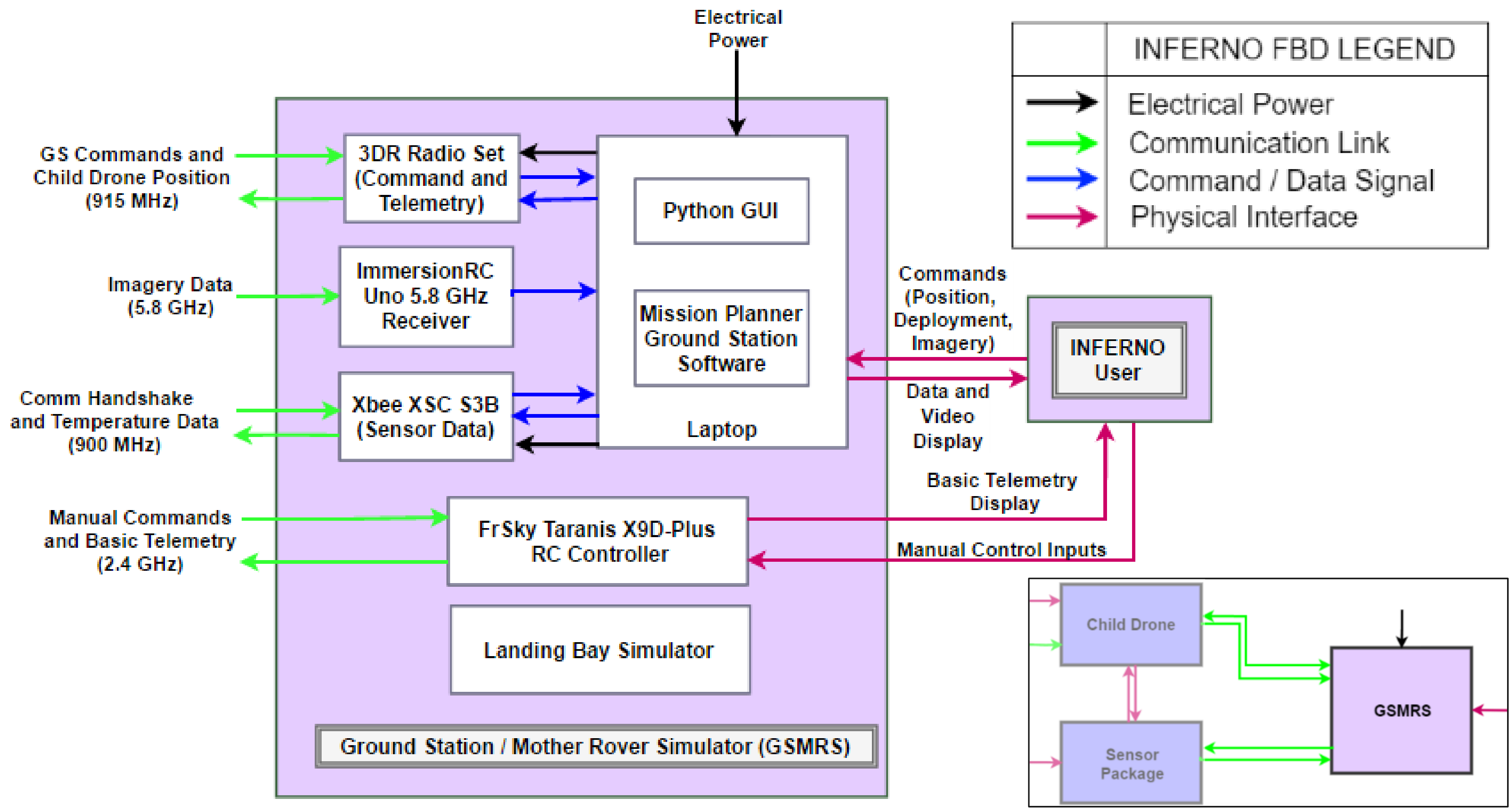
GSMRS

GROUND STATION MOTHER ROVER SIMULATOR OVERVIEW

GSMRS Specifications	
RC Controller	FrSky Taranis XRD+
CD Telemetry Transceiver	3DR Radio V2: 900 MHz
SP Telemetry Transceiver	XBee-Pro XSC S3B: 900 MHz
Video Receiver	ImmersionRC Uno: 5.8 GHz
Cost	$403

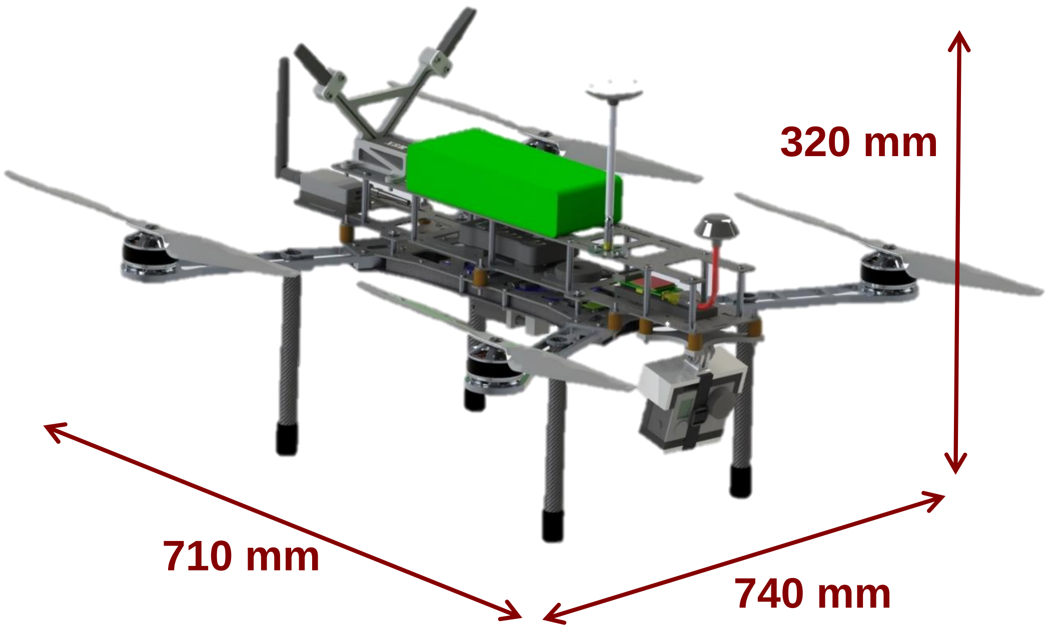
New antenna bought for 3DR radio to increase gain for ground communications

FUNCTIONAL BLOCK DIAGRAM: GSMRS



CHILD DRONE

CHILD DRONE OVERVIEW

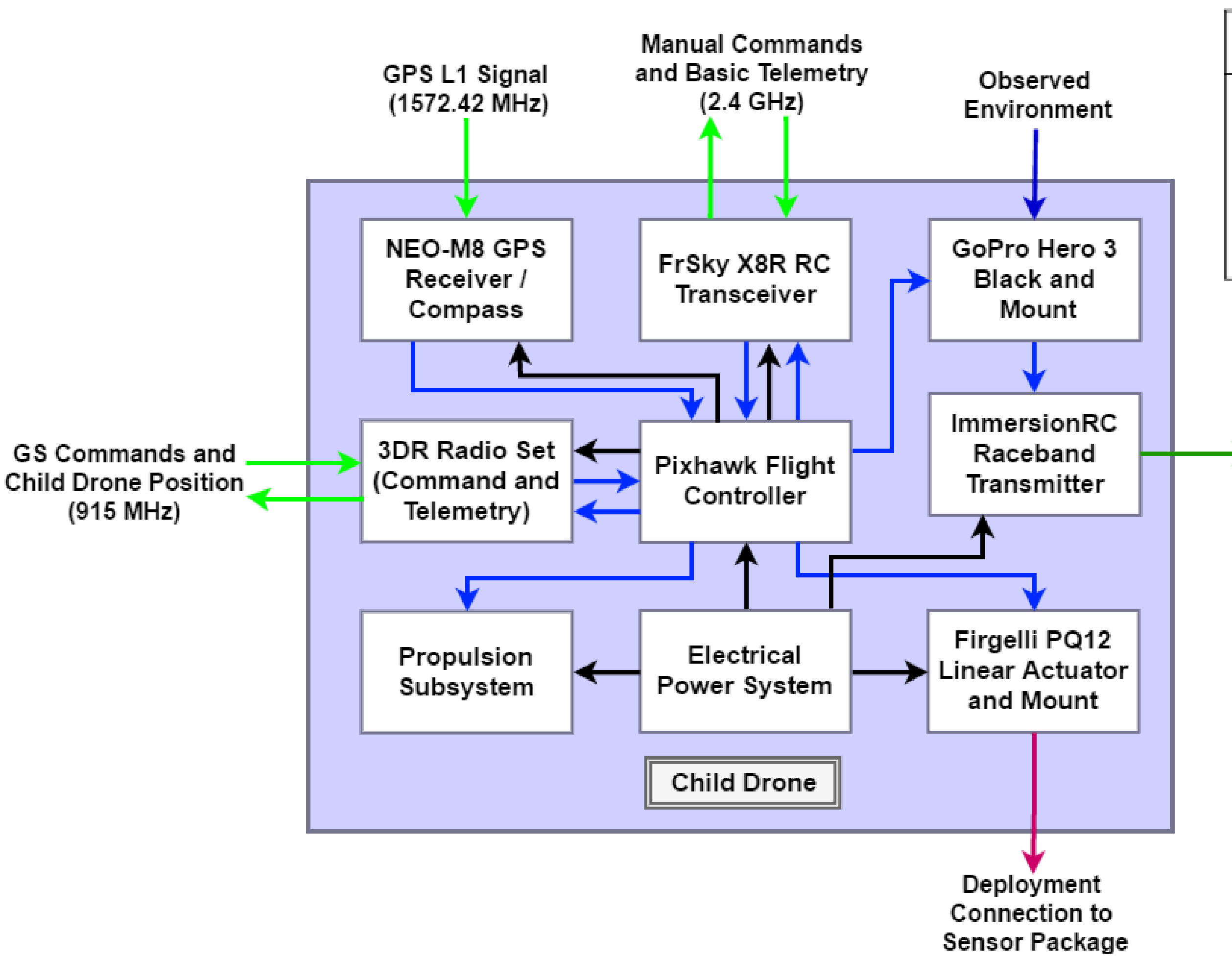


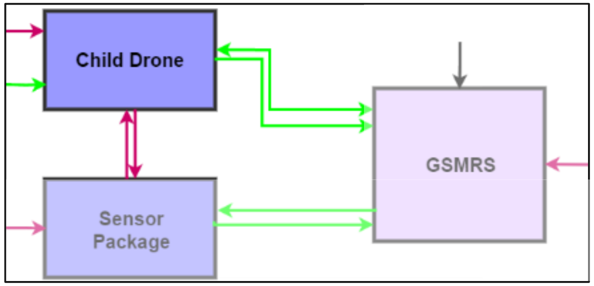
Child Drone Specifications	
Airframe	Lumenier QAV500 V2
Flight Controller	3DR Pixhawk
Telemetry Transceiver	3DR Radio V2: 900 MHz
RC Transceiver	Taranis X8R: 2.4 GHz
Video Transmitter	ImmersionRC: 5.8 GHz
Drone Mass	2520 g
Cost	$1847

- Purchased COTS LC Filter for video transmitter to replace in-house design
- New antenna bought for 3DR radio to increase gain for ground communications

Camera Specifications	
Model	GoPro Hero 3 Black
Image Quality	8.5 MPixels
Photo Rate	0.2 Hz
Video Quality	1080p @ 30 fps
FOV	118.2° H x 69.5° V
Mass	78 g
Cost	$370

FUNCTIONAL BLOCK DIAGRAM: CHILD DRONE

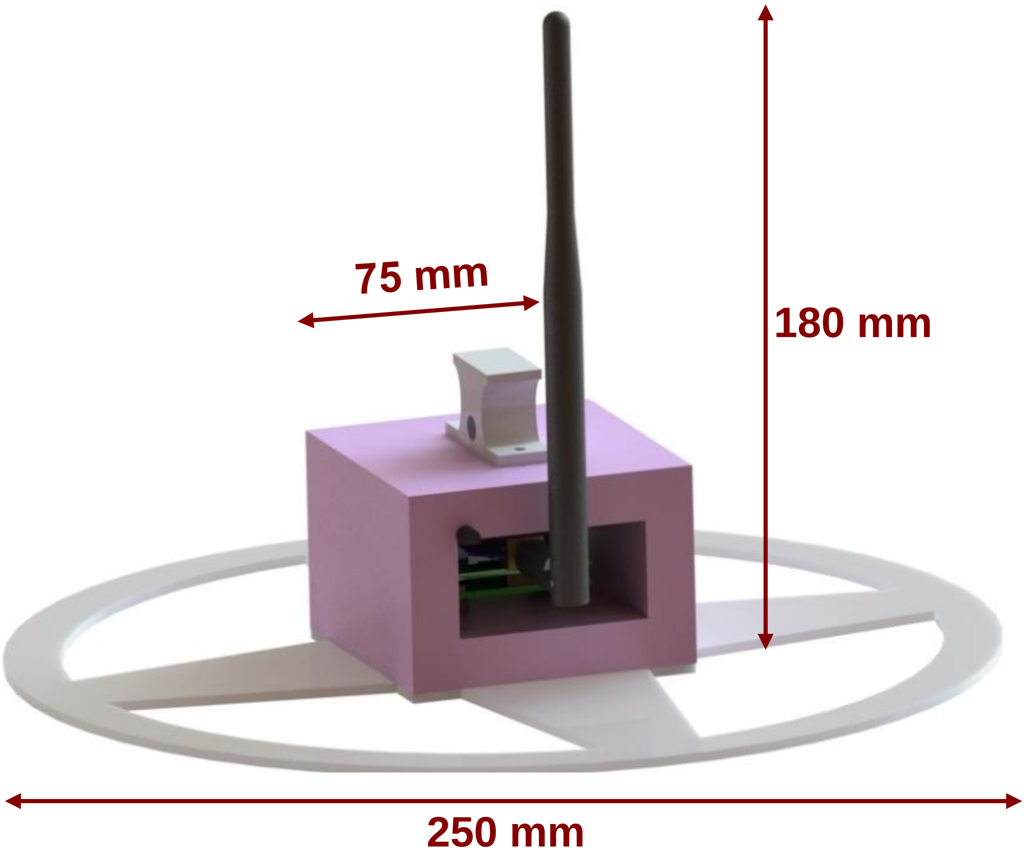




Project Context | Design Solution | V&V | Systems and Management

SENSOR PACKAGE

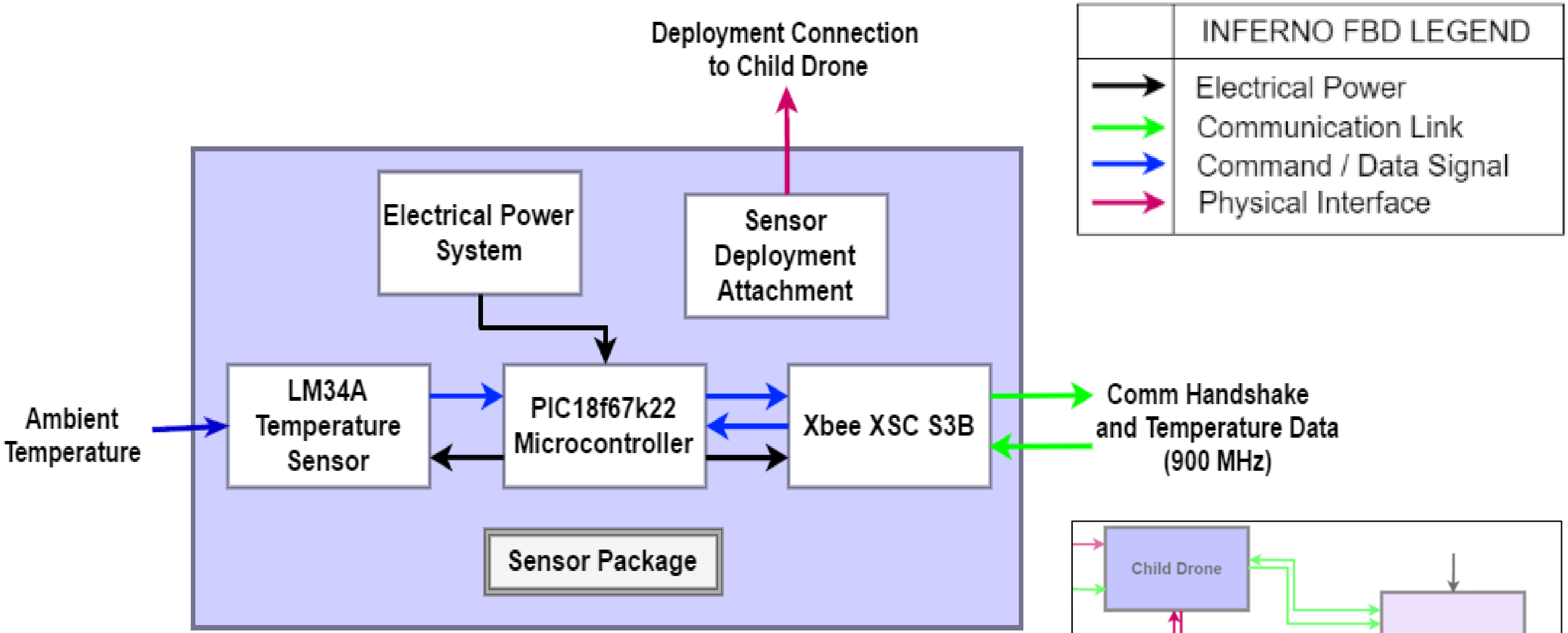
SENSOR PACKAGE DESIGN

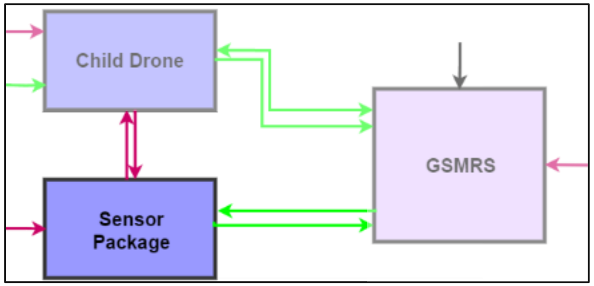


Structural Specifications	
Overall Mass	180 g
Baseplate Material	Polycarbonate
Housing Material	Extruded Polystyrene Foam
Attachment Piece	3D printed ABS plastic
Cost	$146

Electrical Specifications	
Transmitter	XBee-Pro XSC S3B: 900 MHz
Antenna	900 MHz dipole
Microcontroller	PIC18F67K22
Battery	450 mAh LiPo
Temperature Sensor	LM34CA
Cost	$221

FUNCTION BLOCK DIAGRAM: SENSOR PACKAGE





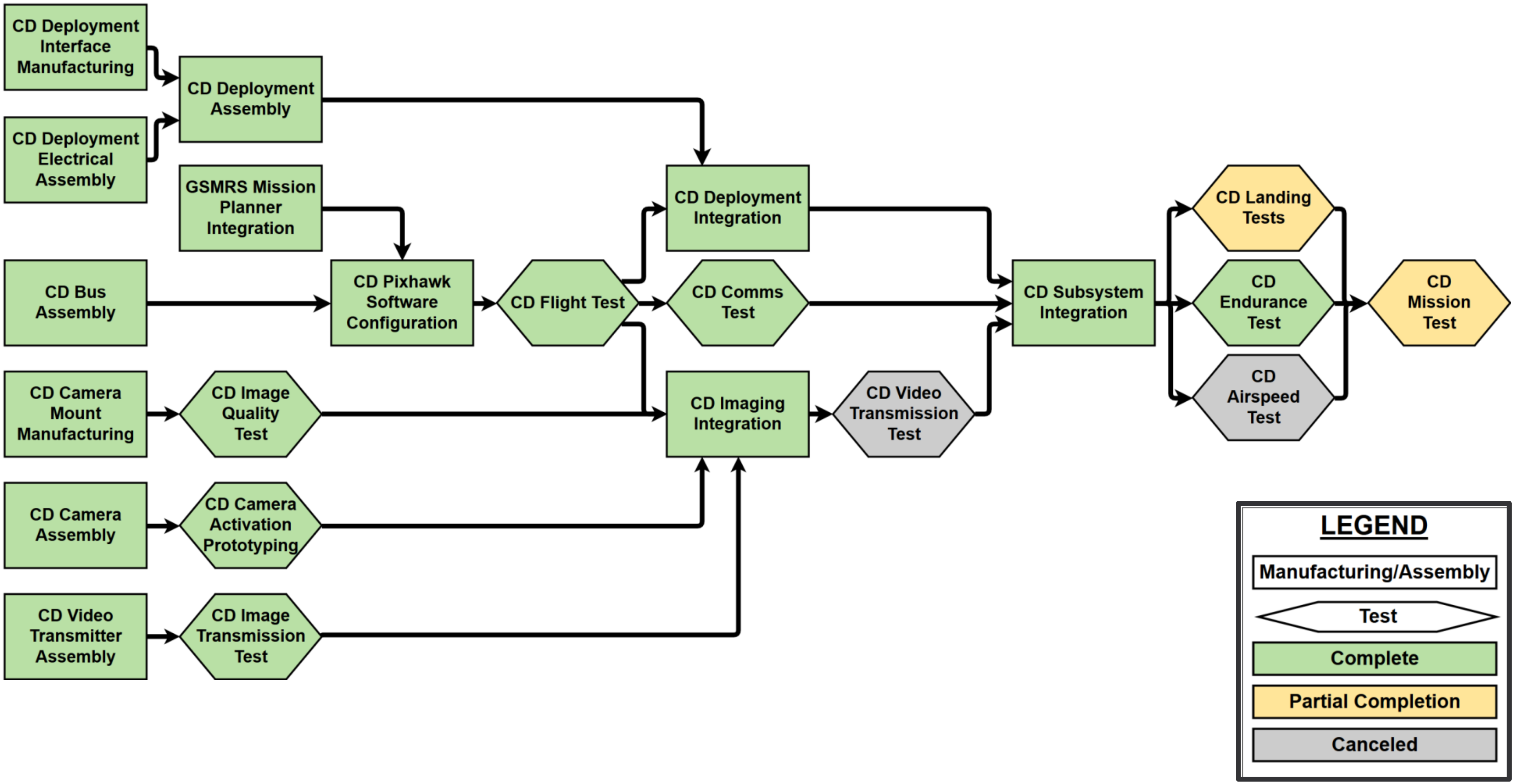
TEST RESULTS

TEST OUTLINE

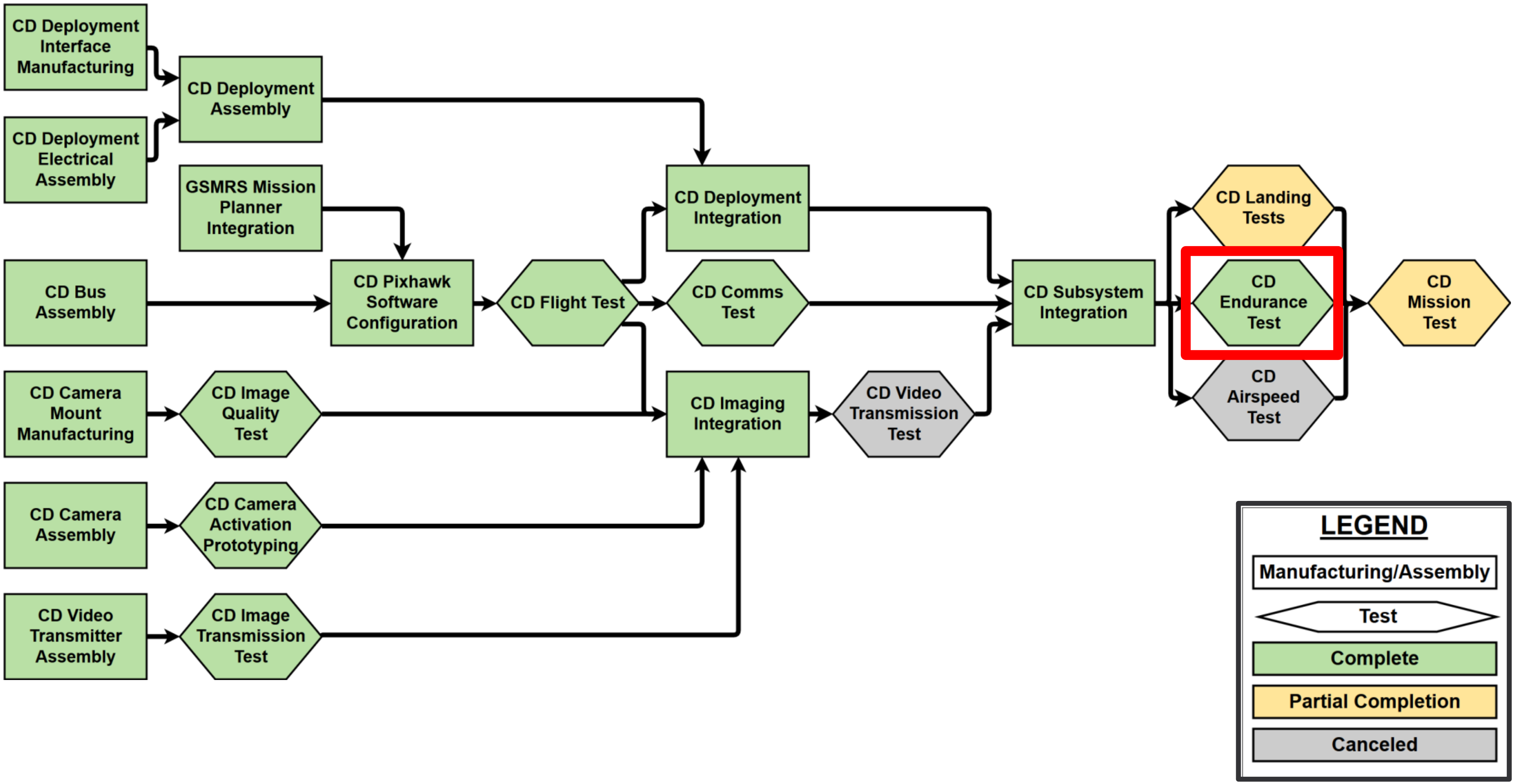
- Child Drone
  - Endurance Test
  - Communications Test
  - Landing Test
  - Validation Test
  - GPS Test
  - Airspeed Test
- Sensor Package
  - Thermal Test
  - Communication Test

CHILD DRONE TESTING

CHILD DRONE ASSEMBLY/TEST FLOW



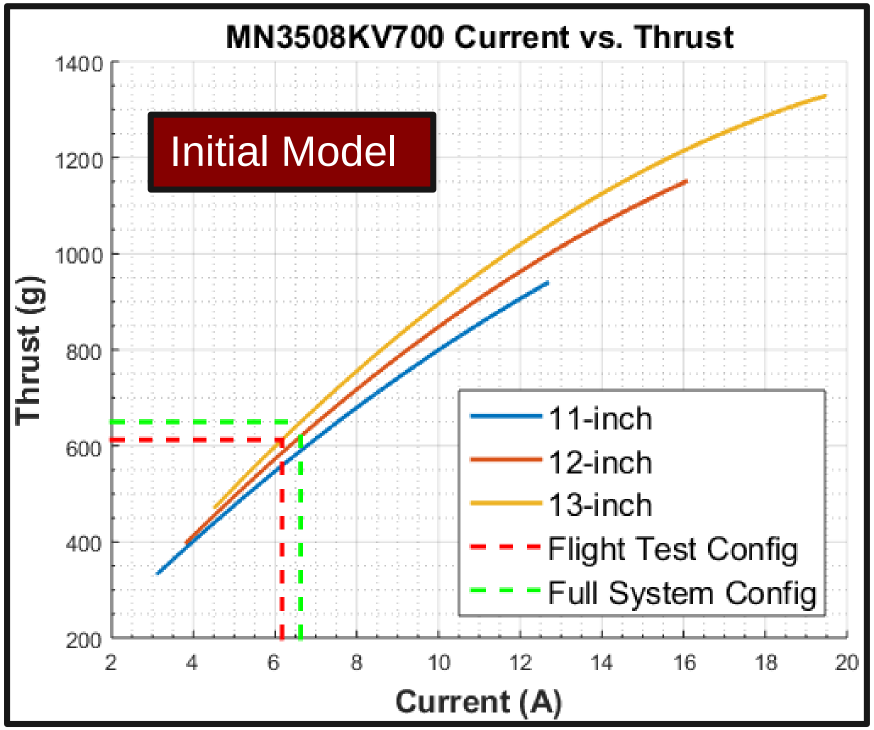
CHILD DRONE ENDURANCE TEST

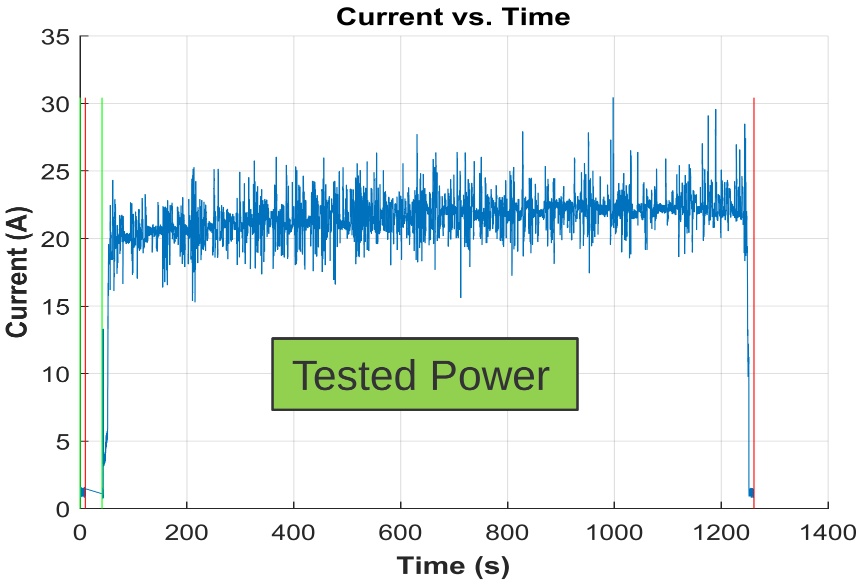


Project Context | Design Solution | **V&V** | Systems and Management

CHILD DRONE ENDURANCE TEST

- Verify flight endurance requirements *(FR 2.0)*
- Characterize drone thrust-power curves
- Determine mass/power budget



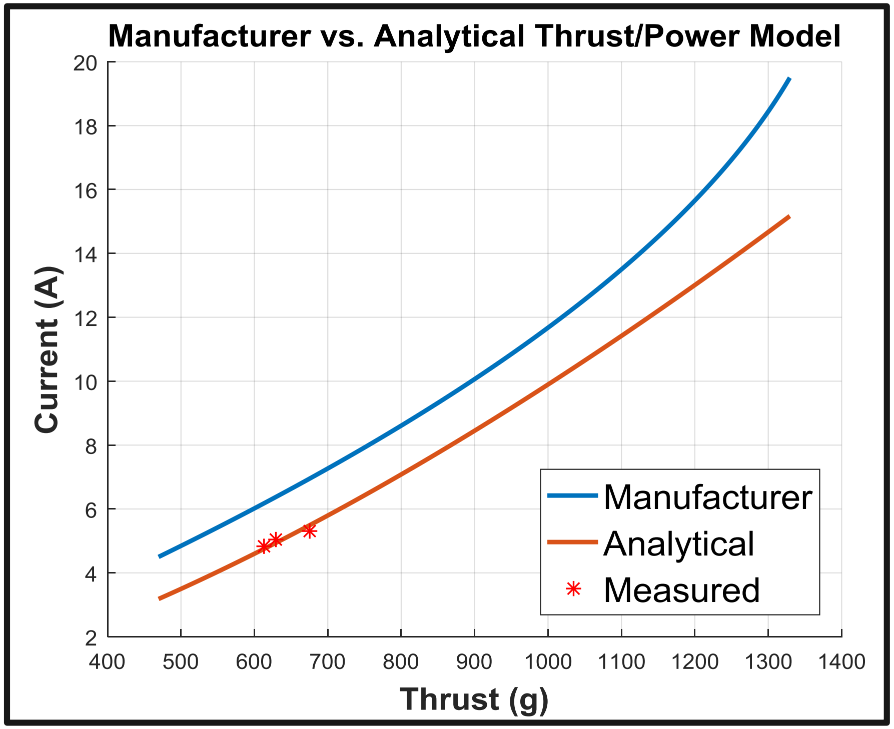


Endurance	Time (min)
Requirement	15
Target	18
Predicted	17.8
Tested	**23.1 ± 1.4**

Project Context | Design Solution | V&V | Systems and Management

CHILD DRONE ENDURANCE TEST

- Design model extrapolated from manufacturer specs
- Analytical model from PDR more accurate



Observed Endurance vs. Analytical Model

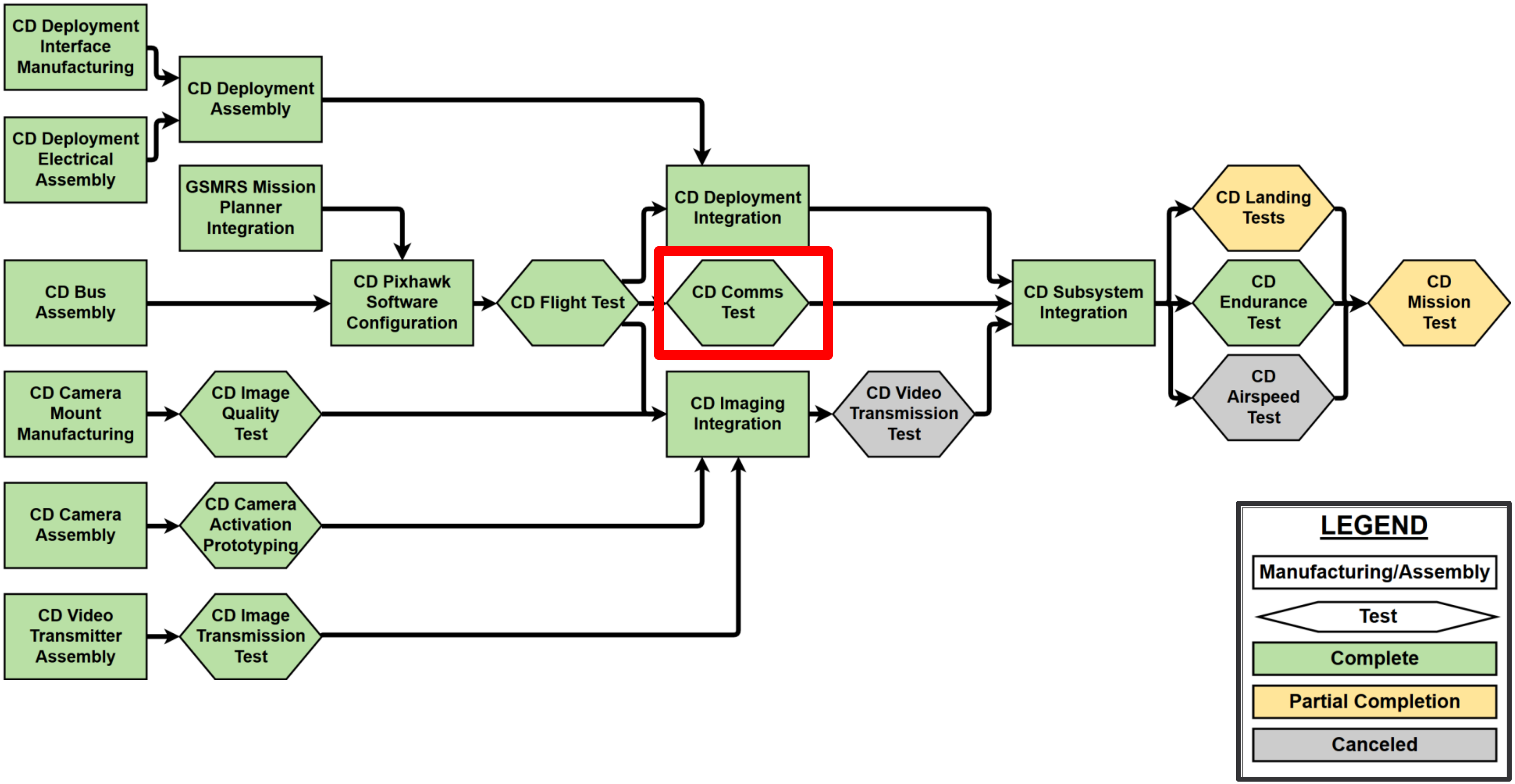
Mass (g)	Observed (min)	Modeled (min)
2450	25.5 ± 0.9	26.0
2520	24.5 ± 0.1	24.9
2700	23.1 ± 1.4	22.5

Possible Alternate System Configurations

Endurance (min)	Maximum Mass (g)
15	3530
18	3130
20	2910
25	2515

- Further testing required for full model verification

CHILD DRONE COMMUNICATIONS TEST

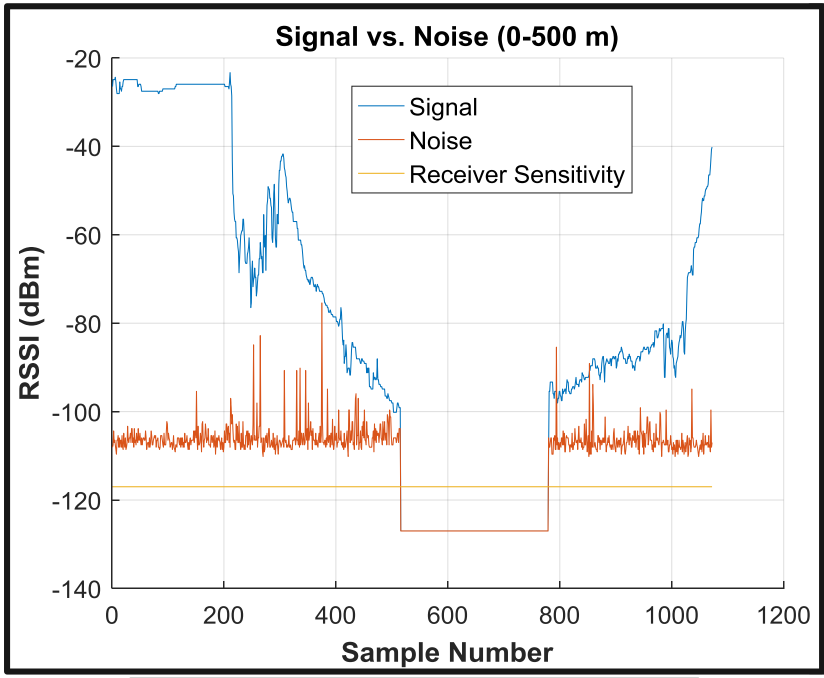


Project Context | Design Solution | V&V | Systems and Management

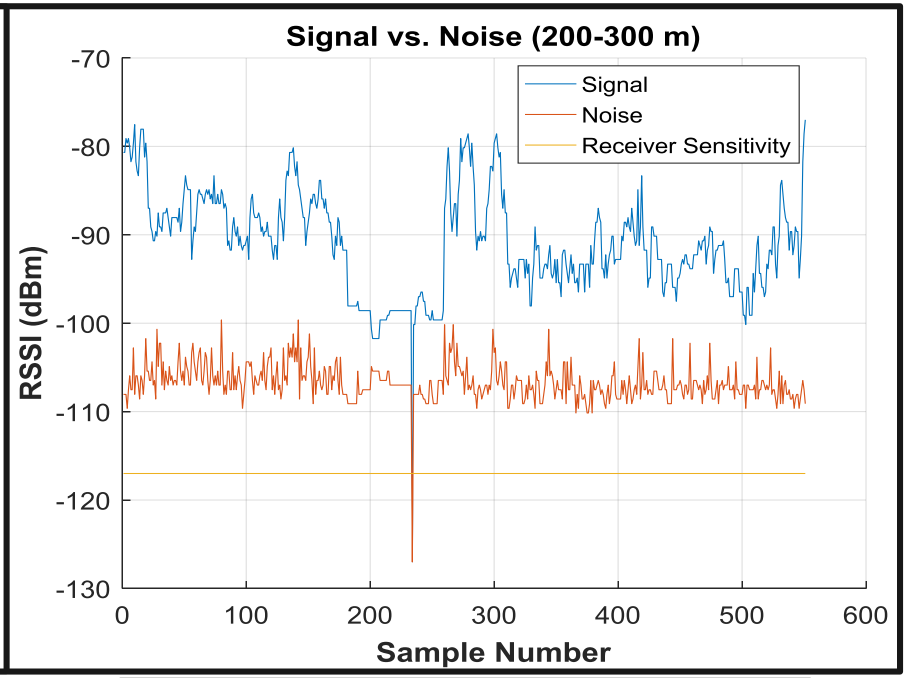
CHILD DRONE COMMUNICATIONS TEST

- Verify comm requirements (FRs 4.0, 5.0) and model
- Characterize comm performance and interference sources

- CD moved from 50-500 m from GSMRS
- Measured telemetry:
  - Signal strength (RSSI)
  - Noise power



Noise Comm Loss Example

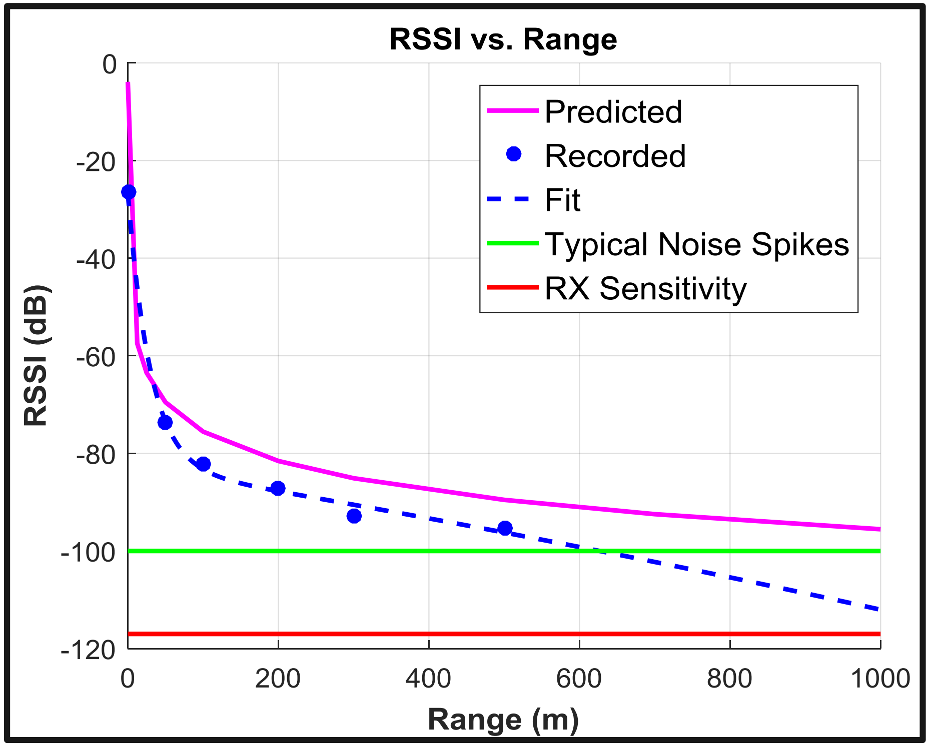


Ground-Level Comm Loss

Project Context | Design Solution | **V&V** | Systems and Management

CHILD DRONE COMMUNICATIONS TEST

- Model overestimated link budget by ~5-8 dB
- Ground effects and noise caused most comm loss

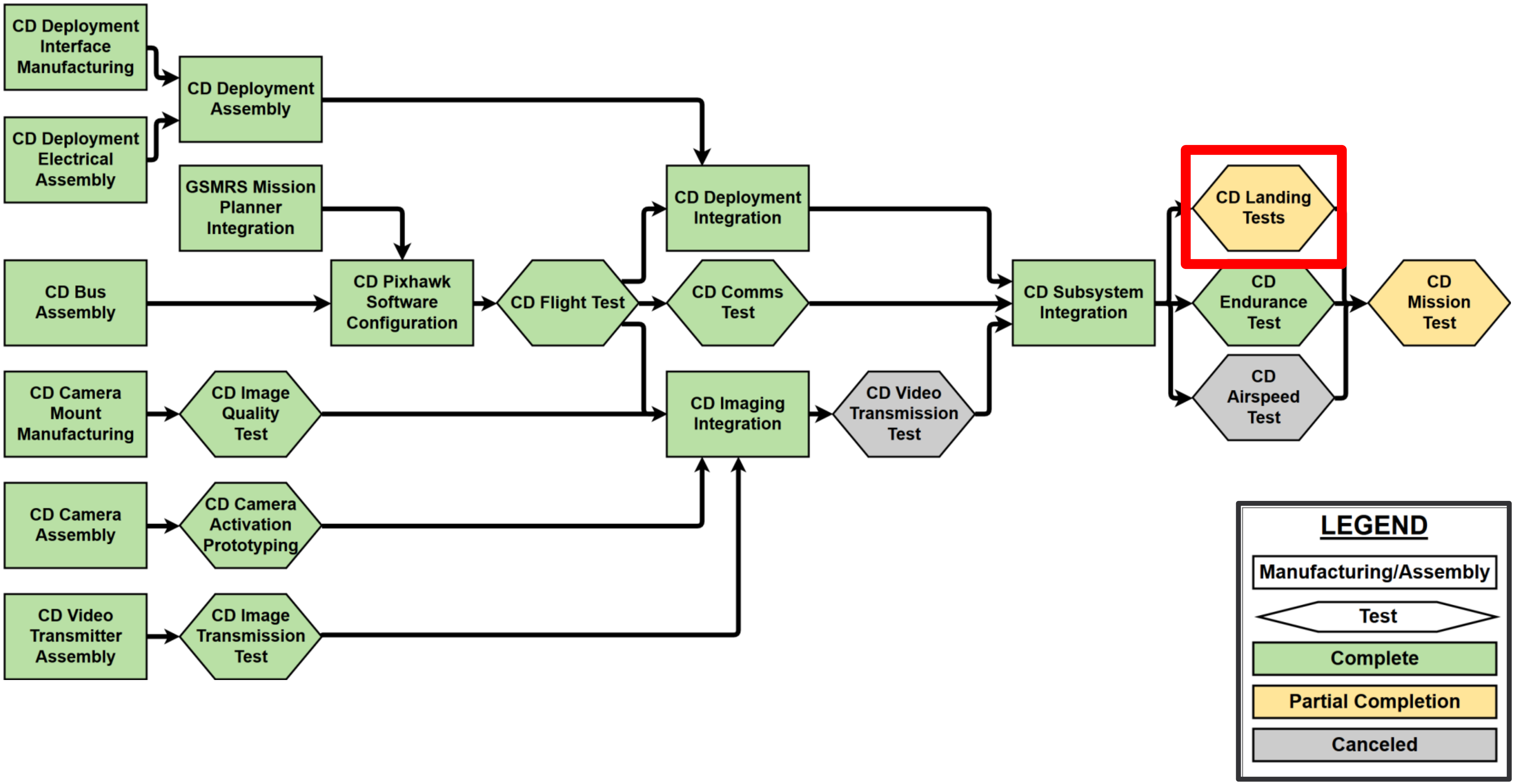


Predicted vs. Observed Link Budgets

Distance (m)	Predicted (dB)	Observed (dB)	Error (%)
50	47	43.2 ± 0.7	-8.1
100	41	34.7 ± 0.7	-15.4
200	35	30.0 ± 0.5	-14.2
300	32	24.2 ± 0.4	-24.4
500	27	21.6 ± 0.4	-20.0

- Acceptable communication except during deployment
- Possible Solutions
  - Higher gain antennas
  - More powerful communication system
  - Additional testing

CHILD DRONE LANDING TEST

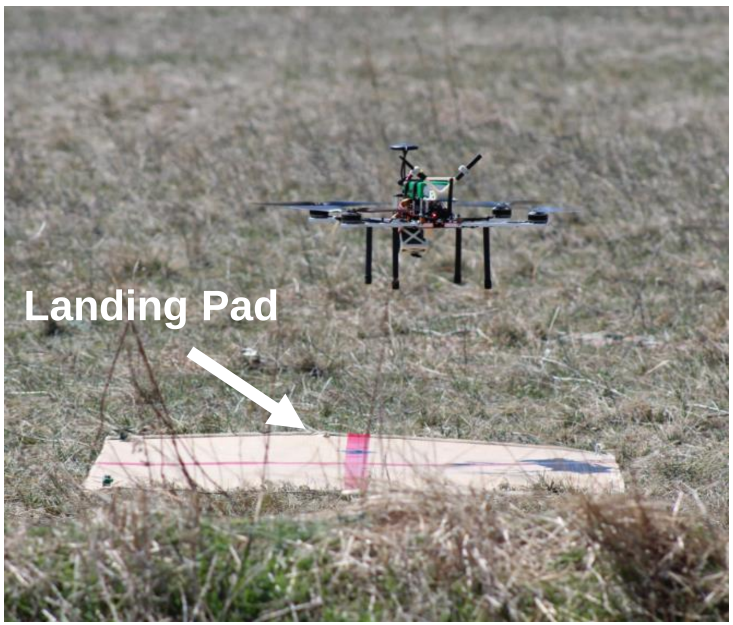


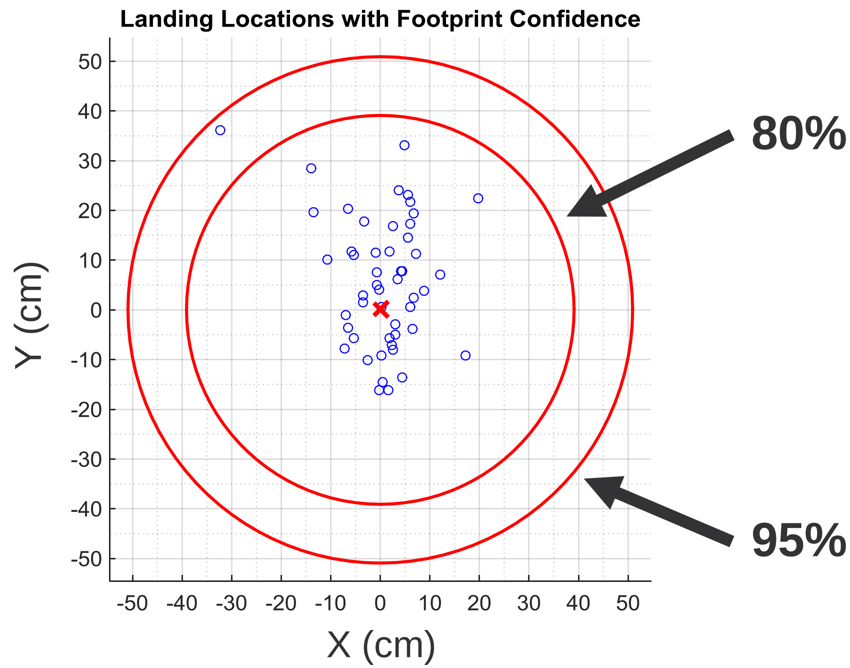
Project Context | Design Solution | V&V | Systems and Management

CHILD DRONE LANDING TEST

- Verify piloted landing capability *(FR 6.0)*
- Characterize landing pad size

Actual Landing Test



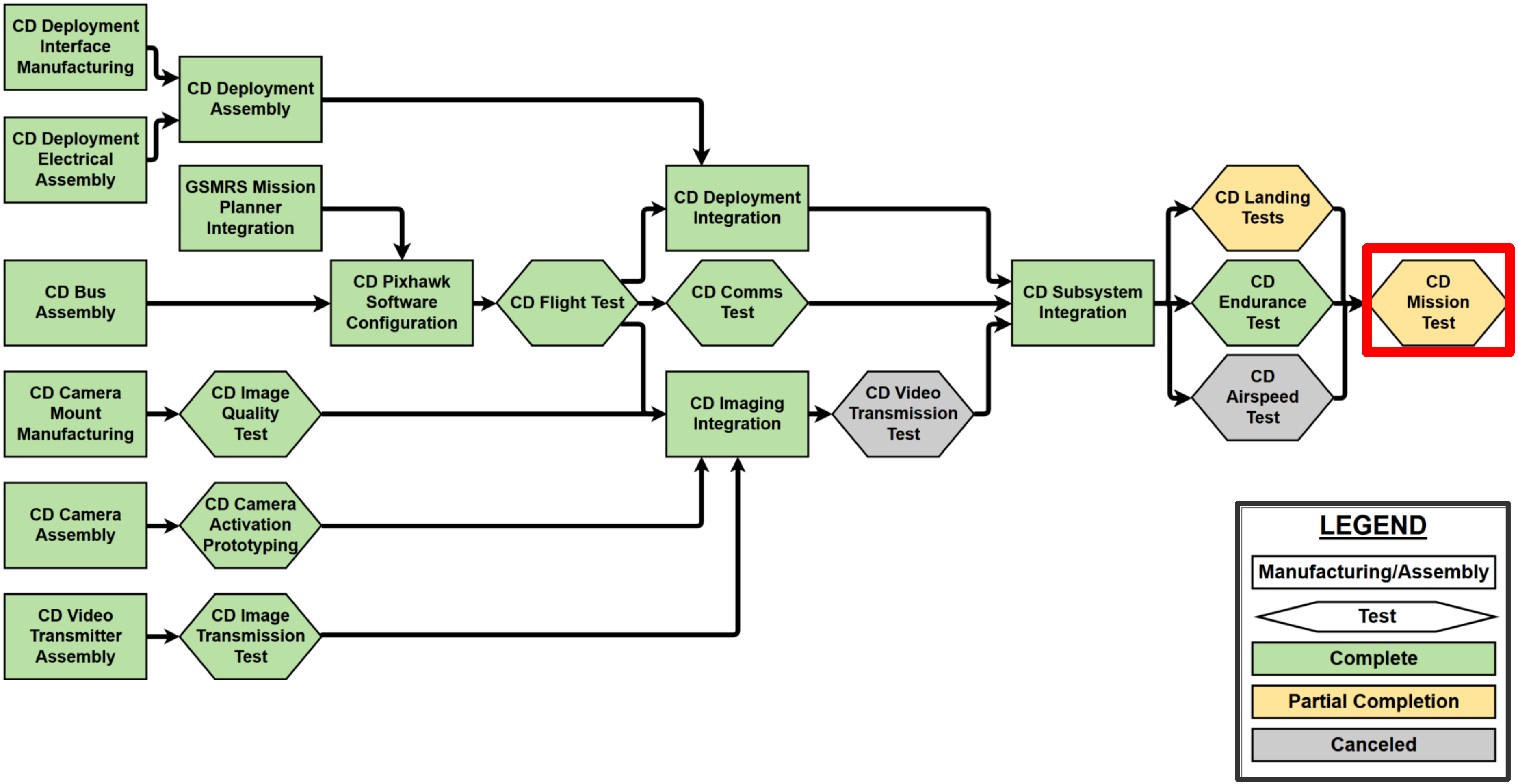


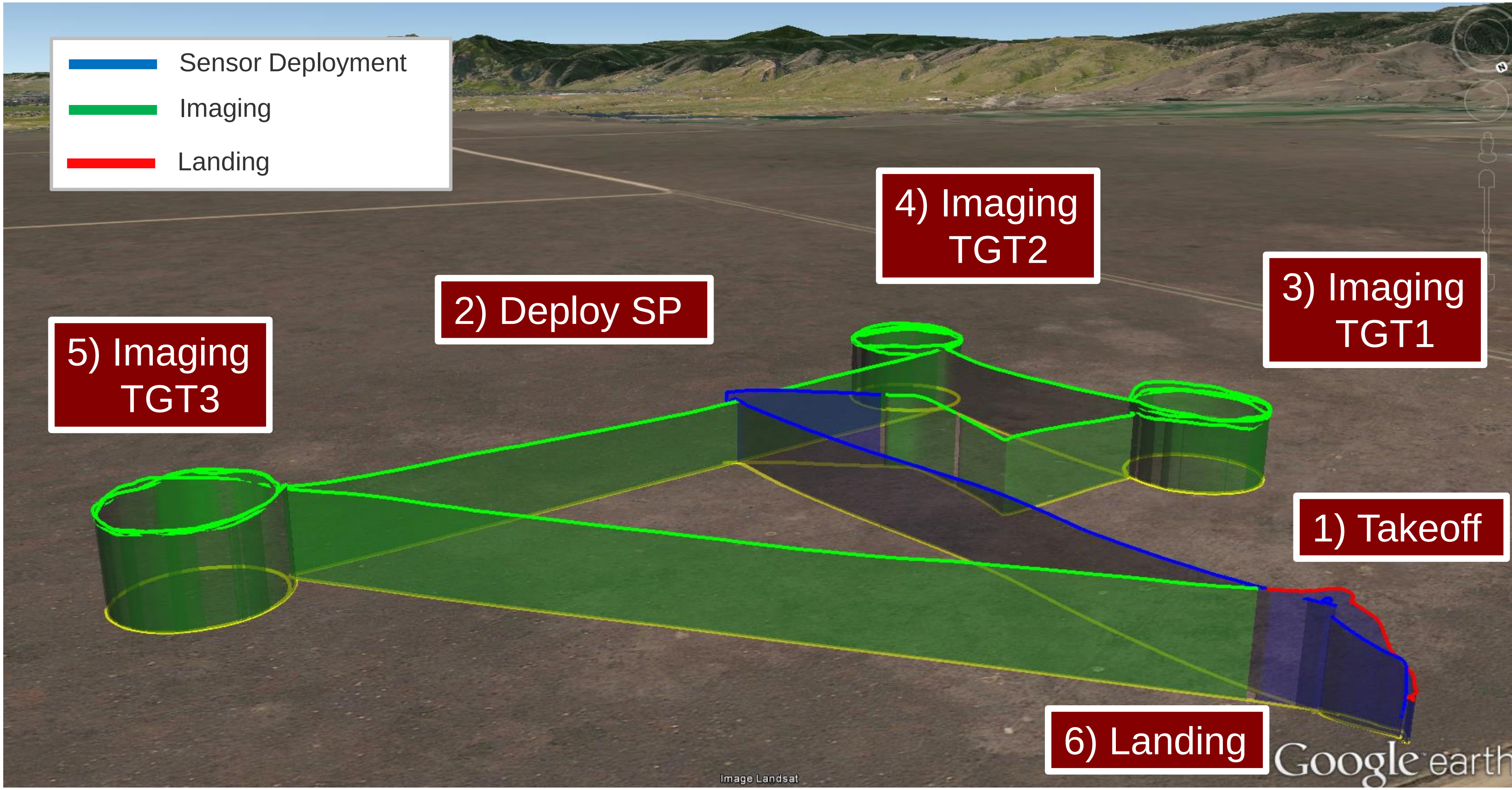
Pad Size	Dimensions (cm)
Requirement	110 x 110 *
Measured (Visual)	79 x 79
Measured (Video)	Future Testing Required

* 80% Confidence

Project Context | Design Solution | **V&V** | Systems and Management

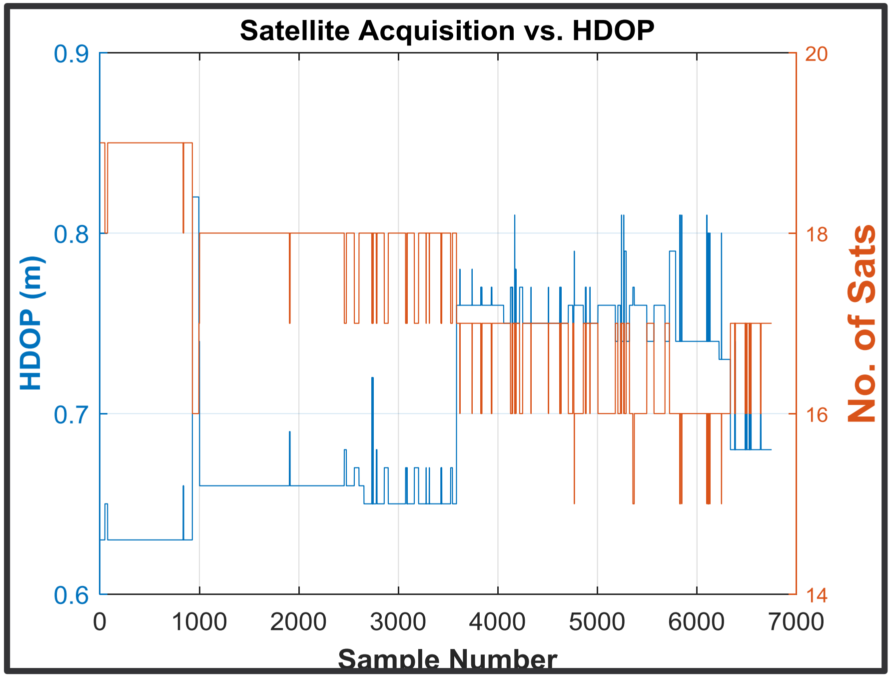
CHILD DRONE VALIDATION TESTS

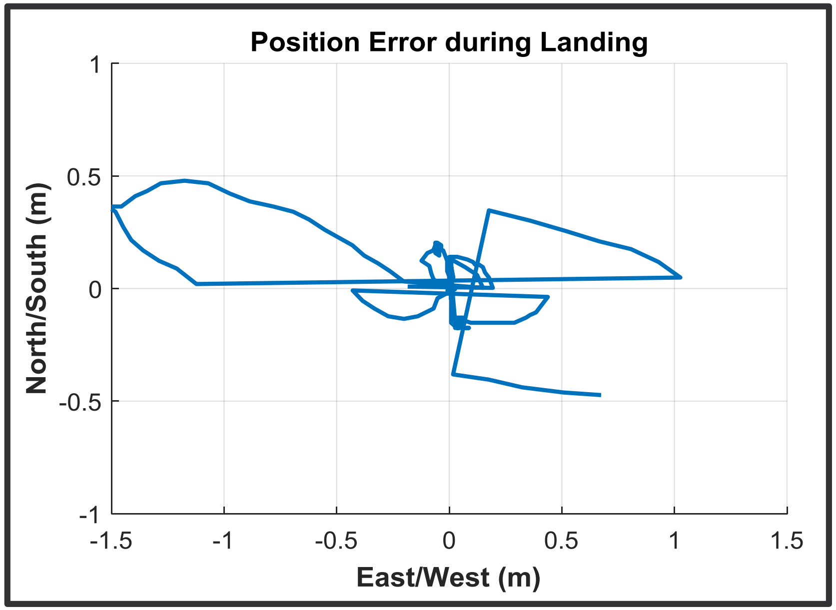



Sensor Deployment
Imaging
Landing
1) Takeoff
2) Deploy SP
3) Imaging TGT1
4) Imaging TGT2
5) Imaging TGT3
6) Landing
Image Landsat
Google earth

CHILD DRONE GPS TESTING

- Verify GPS receiver accuracy
- Verify ability to deploy SP within 5 m of target *(FR 1.0)*

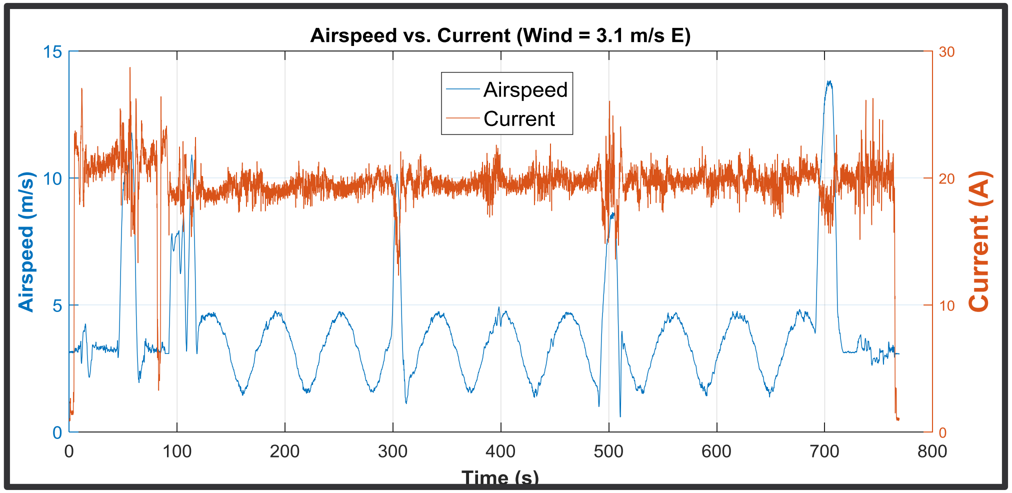


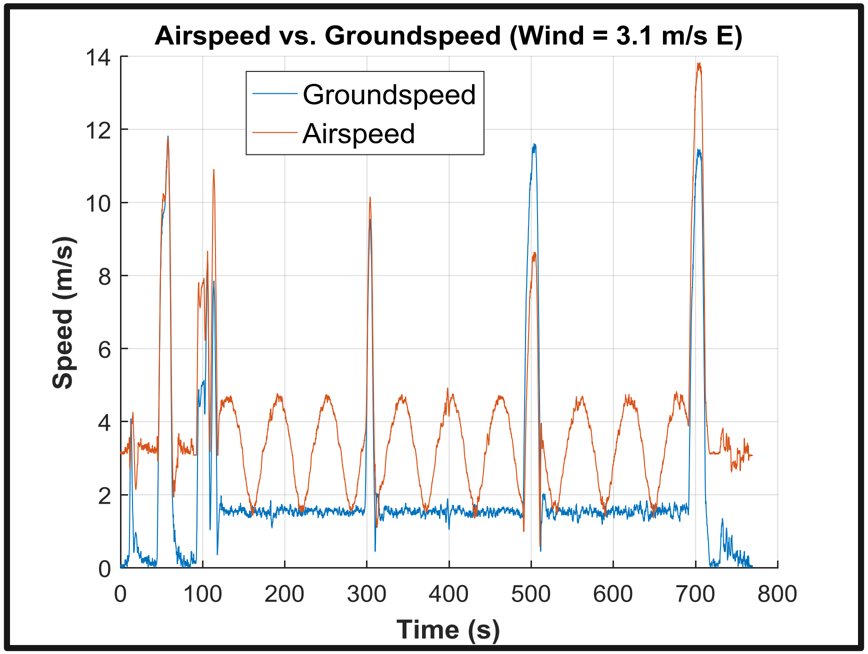


Accuracy	Mean Error (m)	Max Error (m)
Requirement	---	5
HDOP	0.70 ± 0.0007	0.82 ± 0.0007
Measured	0.38 ± 0.04	1.56 ± 0.04
Total	**0.79 ± 0.04**	**2.38 ± 0.04**

CHILD DRONE AIRSPEED TESTING

- Verify 10 m/s airspeed requirement *(FR 1.0)*
- Characterize power consumption vs. airspeed



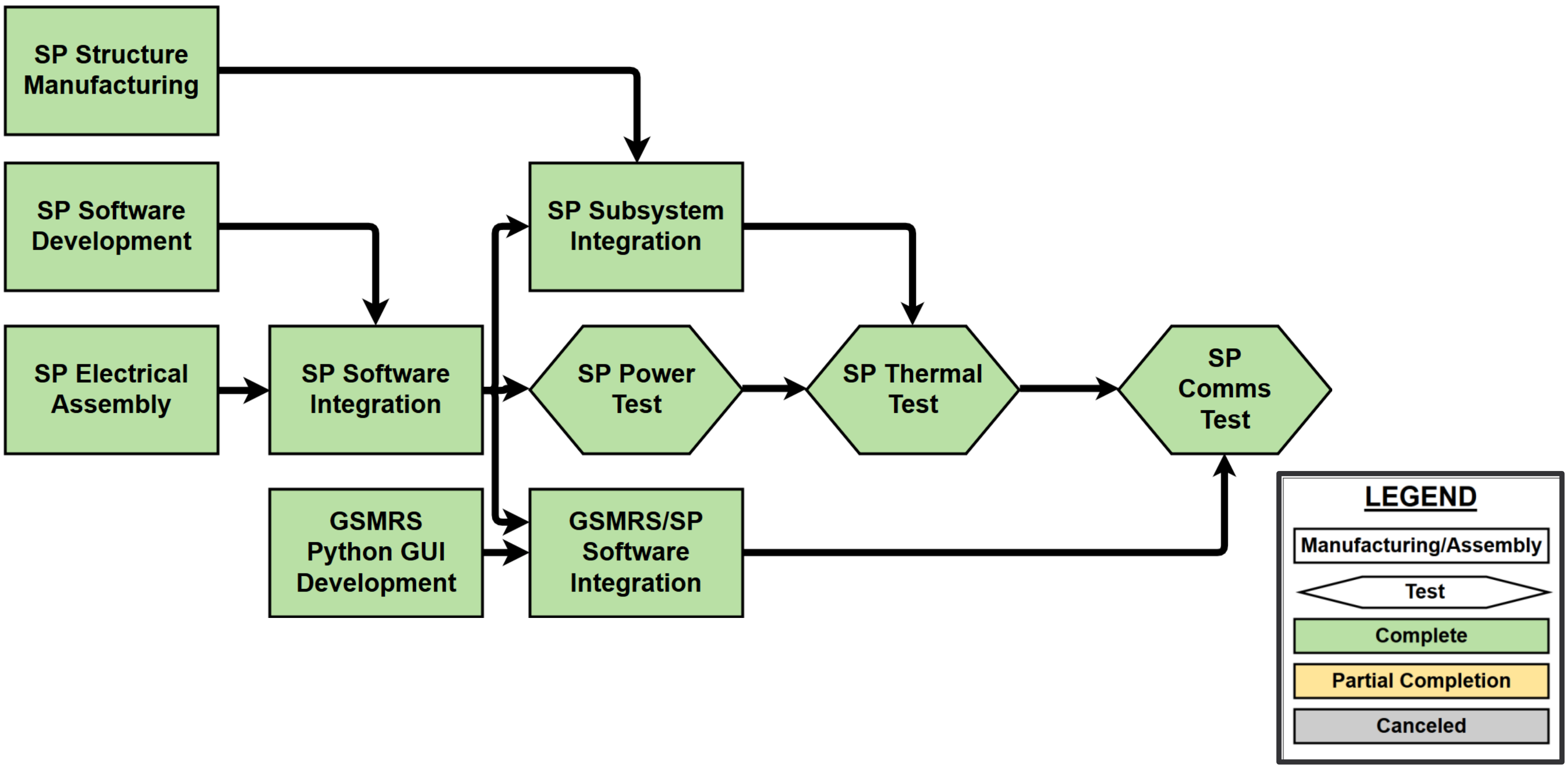


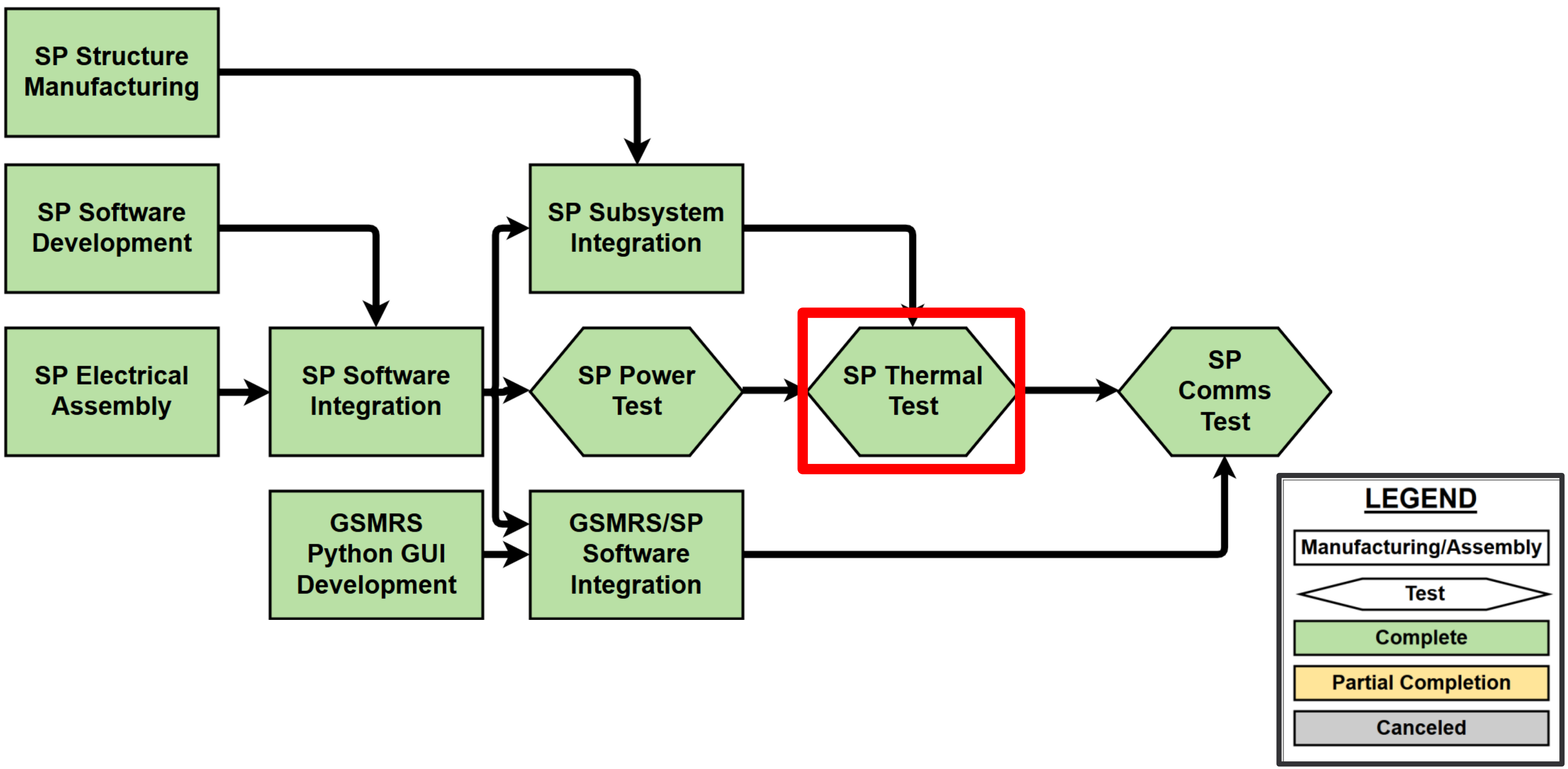
Airspeed	Speed (m/s)
Requirement	10
Tested	**13.8**

- CD exceeds airspeed requirement
- Further testing required for full performance characterization

SENSOR PACKAGE TESTING

SENSOR PACKAGE ASSEMBLY/TEST FLOW

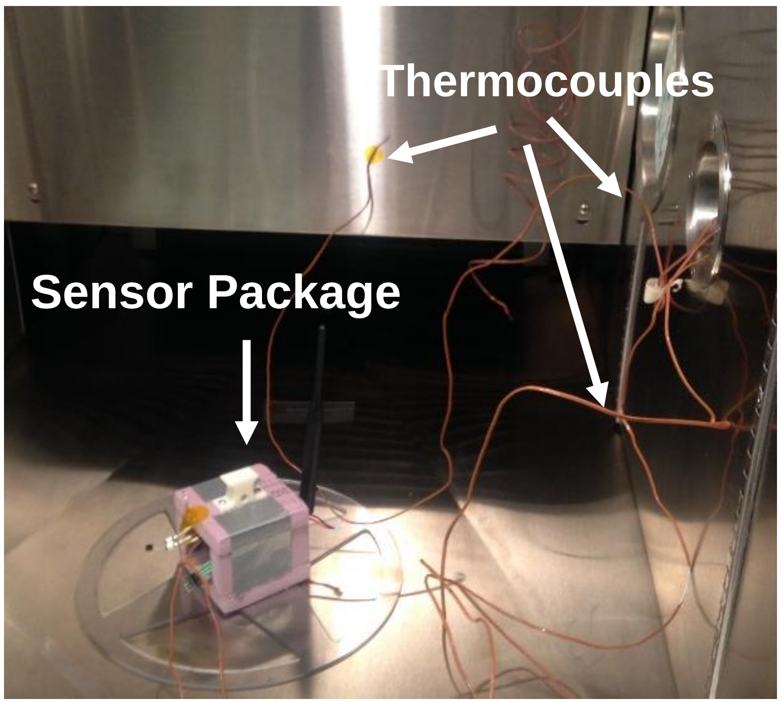




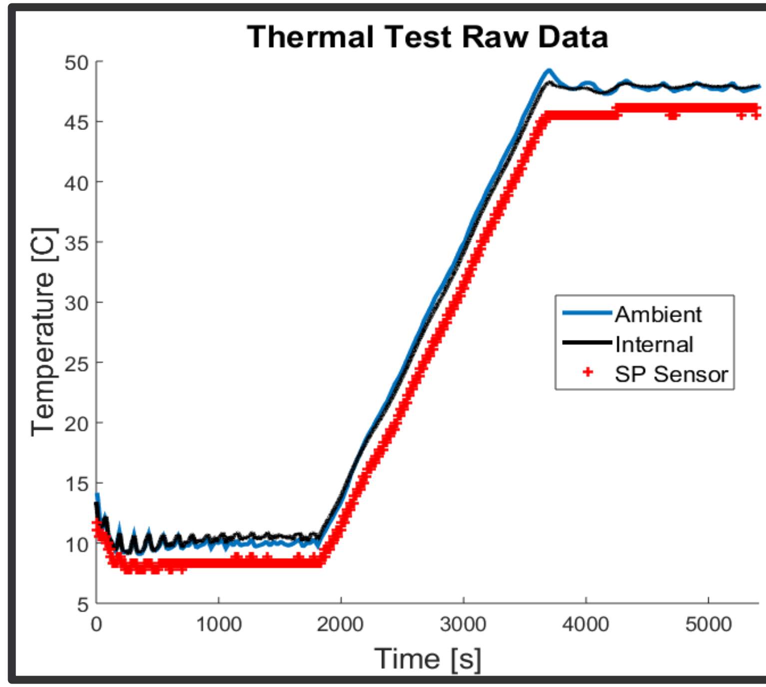
SP Structure Manufacturing
SP Software Development
SP Electrical Assembly
SP Software Integration
GSMRS Python GUI Development
SP Subsystem Integration
SP Power Test
GSMRS/SP Software Integration
SP Thermal Test
SP Comms Test
LEGEND
Manufacturing/Assembly
Test
Complete
Partial Completion
Canceled

- Verify SP sensor accuracy and range *(FR 1.0)*

Thermal Chamber Setup



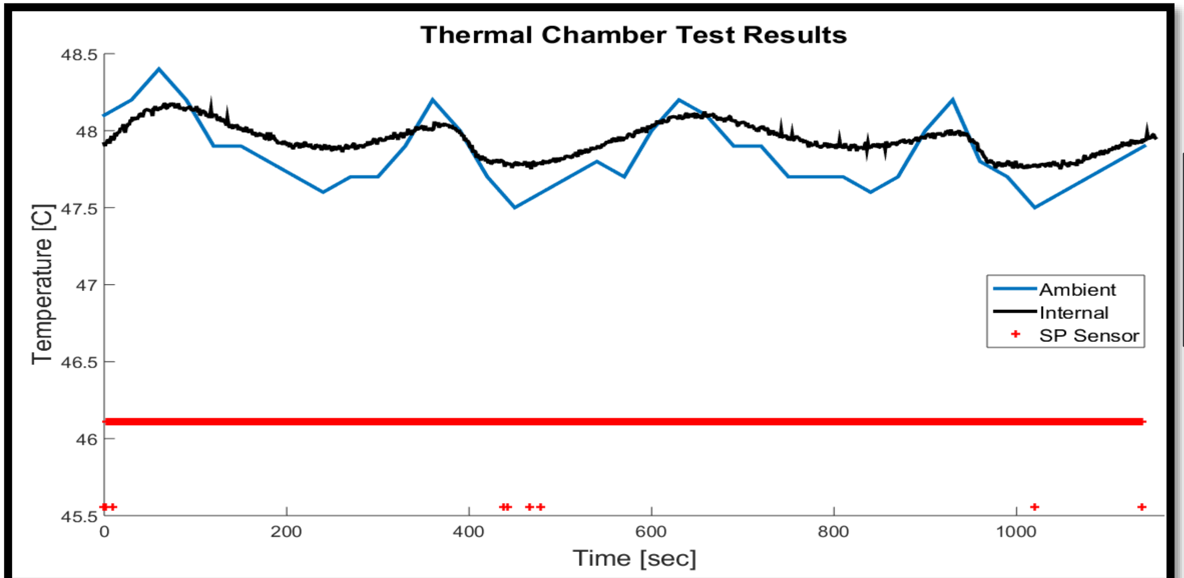
Recorded Data



Hold at 10°C for 30 minutes
Ramp to 47.8°C in 30 minutes
Hold at 47.8°C for 30 minutes

SENSOR PACKAGE THERMAL TEST

Primary Test: Hold at 47.8°C

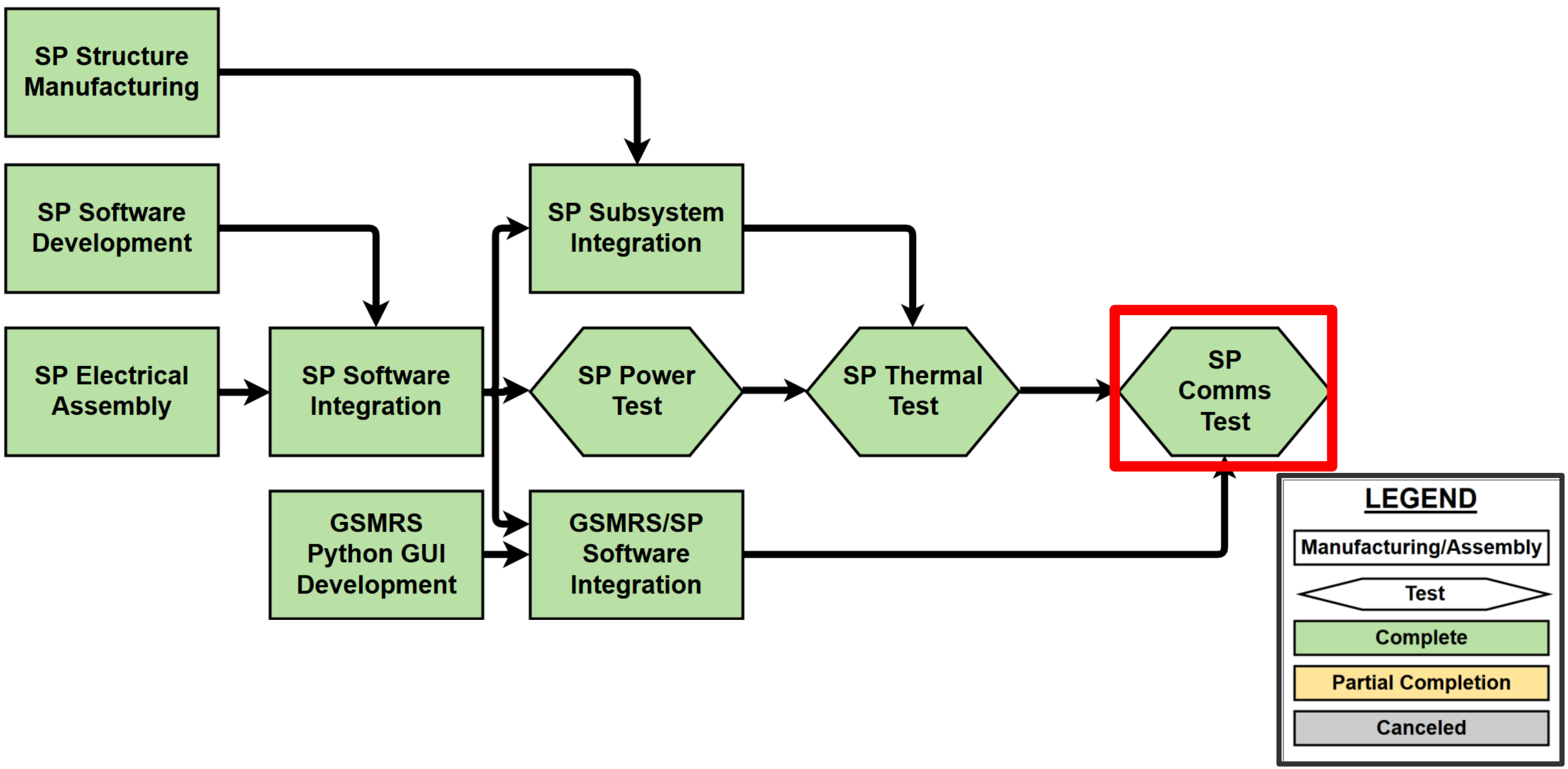


- Calibrate SP software to account for sensor bias
- Use more accurate sensor

- Mean required thermal sensor accuracy verified
  - Max required thermal sensor accuracy not verified
- Thermal sensor range verified

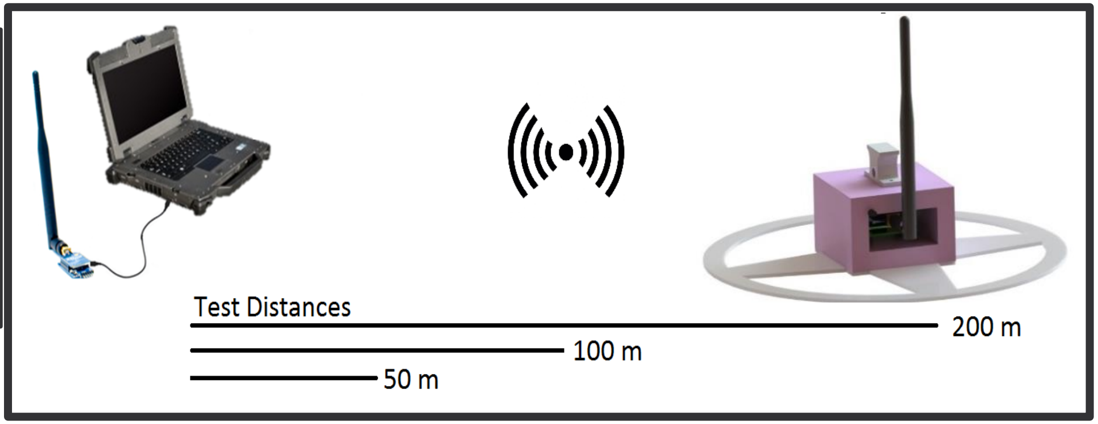
Sensor Error	Temperature (°C)
Requirement	< 2.78°C
Measured	1.74 ± 1.74
Max Measured	3.48

SENSOR PACKAGE COMMUNICATIONS TEST



SENSOR PACKAGE COMMUNICATIONS TEST

- Verify sensor package comm link up to 200m away *(FRs 4.0, 5.0)*
- Verify accuracy of wirelessly received data *(FR 5.0)*



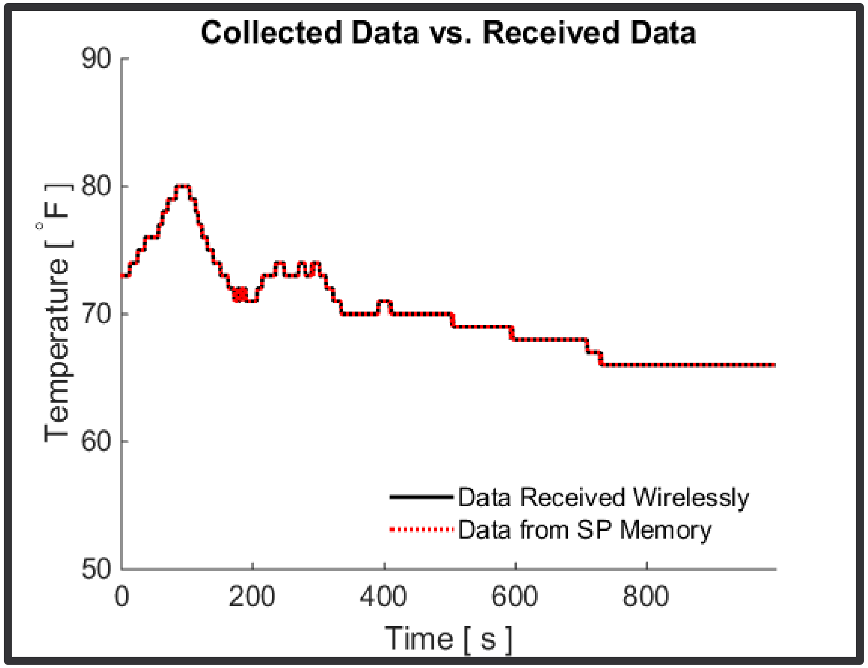
Testing Setup at South Campus:

- Place SP at measured distance from GSMRS
- Collect and timestamp temperature data of ambient air
- Transmit temperature data to GSMRS
- Repeat at new distance from GSMRS
- Data collected and transmitted for 5 minutes at 50m, 100m and 200m each
- GSMRS placed 1m AGL to simulate antenna mast

SENSOR PACKAGE COMMUNICATIONS TEST

- Comms link drops significantly at ground level
- Antenna mast may be required for Mother Rover

Received Data Accuracy Results



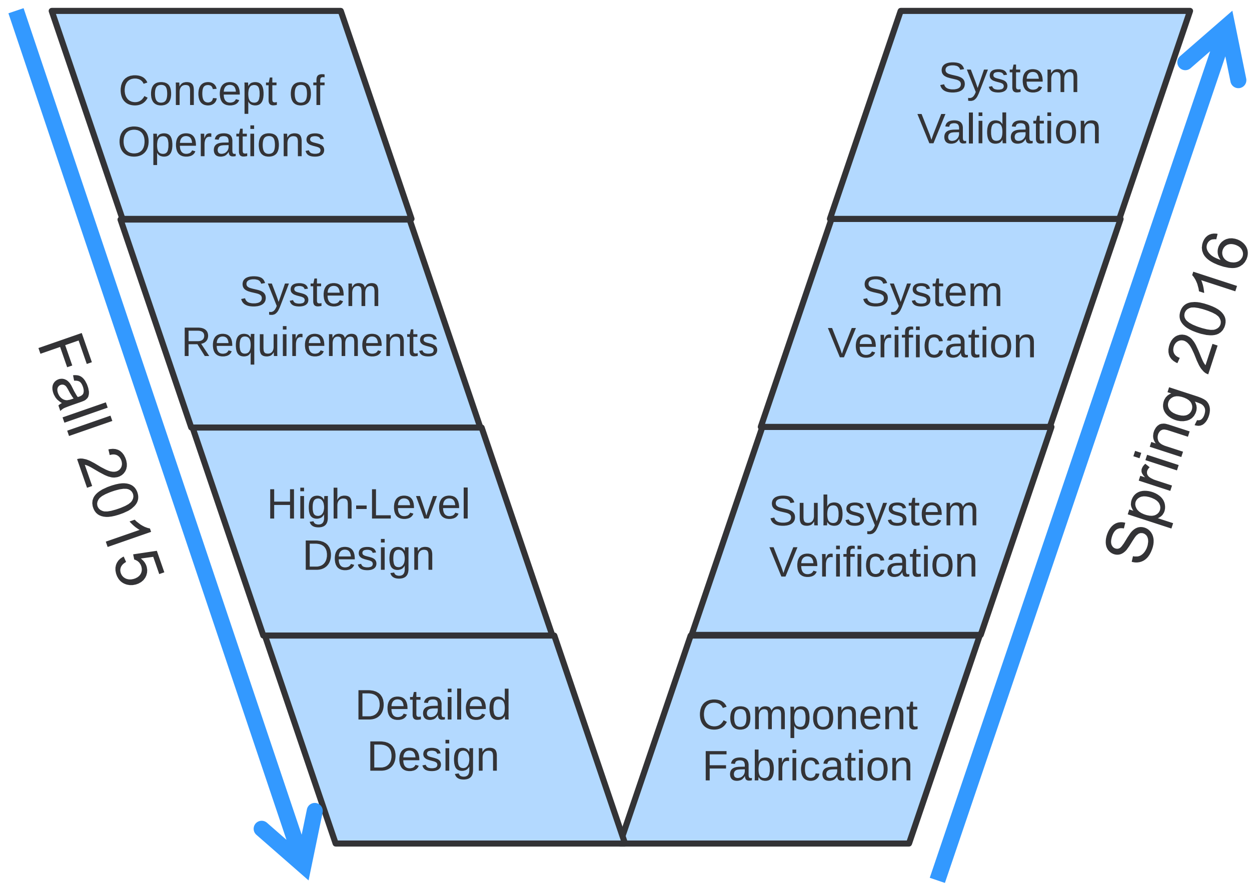
Predicted vs. Observed Link Budgets

Distance (m)	Predicted (dB)	Observed (dB)	% Error
50	63	59	6.78
100	57	53	7.04
200	51	44	16.6
200 @ 1 m AGL	51	55	7.27

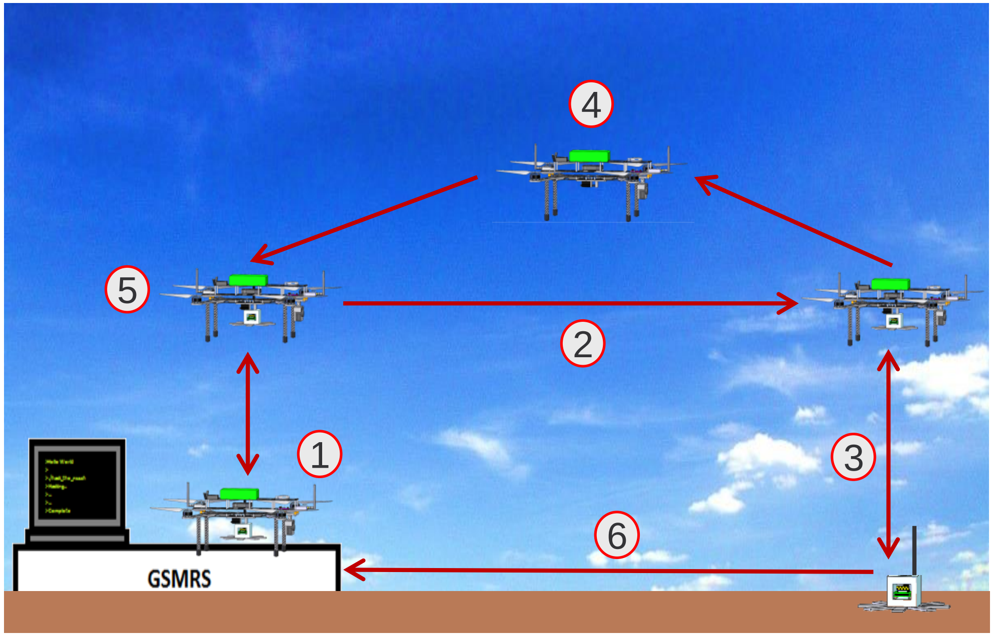
- Link budget exceeds system requirements
- 100% accuracy of data received vs. data stored on SP

SYSTEMS ENGINEERING APPROACH

SYSTEMS ENGINEERING OVERVIEW



SYSTEMS APPROACH: CONOPS



Finalized INFERNO CONOPS

Concept of Operations

CONOPS Development
- Two major possibilities for deployment carried through design
- Two major CONOPS changes due to design influence

Key Lessons
- Understanding of how CONOPS and design are interconnected
- Heritage project scope – simulate vs. build

SYSTEMS APPROACH: REQUIREMENTS

INFERNO Requirements Metrics		
Number of:	**Initial Draft**	**Final Draft**
Functional Requirements	13	6
Derived Requirements	63	27
Total Requirements Rewrites	4	

System Requirements

Requirements Definition

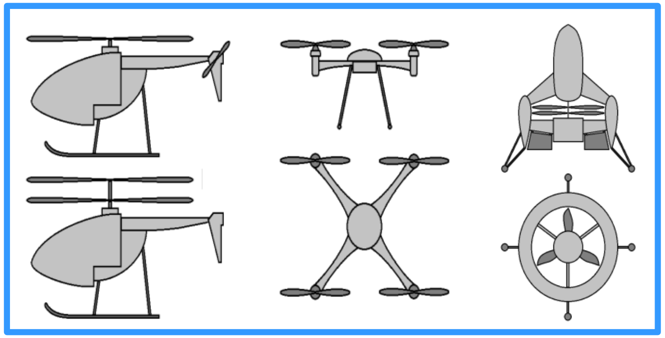
- **Customer negotiation on endurance requirements**
- **Four rewrites required to achieve acceptable requirements**

Key Lessons

- **Requirements negotiation with customer**
- **Use qualitative metrics to ensure testability**
- **Balance between specificity and constraining design**
- **Don't impose unnecessary requirements**

Project Context › **Design Solution** › **V&V** › **Systems and Management**

SYSTEMS APPROACH: SYSTEM DESIGN



Rotorcraft Solution Space

Integrated INFERNO Design

High-Level and Detailed Design

System Design

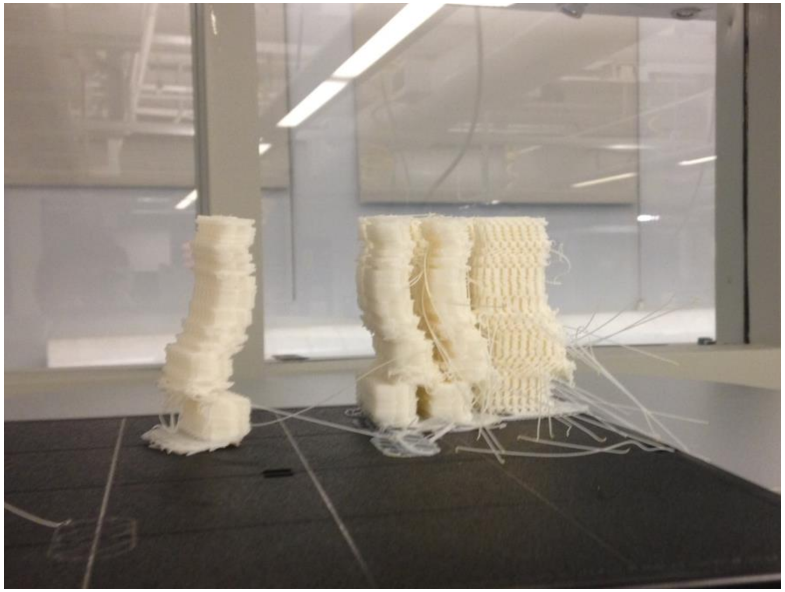
- **High-Level Trades: deployment method, CD aerial vehicle type, sensor carrying method**
- **Detailed Trades: rotorcraft selection, temperature sensor selection, SP shape**
- **Risk Mitigation: selected communications frequencies, SP shape drove CONOPS change**
- **Proof of Concept prototyping/testing for solution space down-selection**

Key Lessons

- **Design through context of both requirements and CONOPS**
- **Examine realistic design solution spaces**
- **Consider influence of all resources (time, financial, personnel) on design**

Project Context | **Design Solution** | **V&V** | **Systems and Management**

SYSTEMS APPROACH: COMPONENT FABRICATION



3D Printing Machine Failure

Component Fabrication

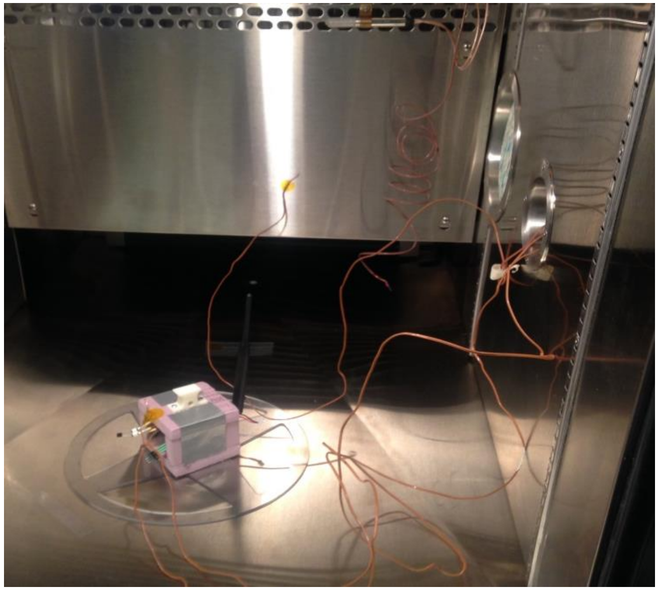
Component Fabrication

- **Risk Mitigation: early material testing for 3D printed ABS print grain effects**
- **Several iterations of manufactured components (baseplates, SP foam housing, 3D printed mounts)**
- **Many hours writing / debugging software**

Key Lessons

- **Software is most time consuming and difficult element**
- **Material testing required for unfamiliar mediums (ABS print grains)**
- **Plan for multiple iterations - 3D printed elements and SP structure**

SYSTEMS APPROACH: SUBSYSTEM VERIFICATION



SP Thermal Test Setup

Subsystem Verification

Subsystem Verification

- **Issues Identified: video transmission encoding, temperature sensor accuracy, SP software debugging**
- **Risk Mitigation: Used ICDs to track changing interfaces to ease airframe integration**

Key Lessons

- **Keep ICDs current to minimize difficulties with subsystem integration**
- **Ensure compatibility of major system interfaces (ex. deployment SP-CD 3D printed component)**

CD Landing Under Pilot Control

System Verification

System Verification

- **Issues Addressed: video transmission encoding, SP software debugging**
- **Issues Identified: RF interference with video transmission**
- **Risk Mitigation: stocked spare components to limit impact of CD crash**

Key Lessons

- **Address system level risk not mitigated at subsystem level**
- **Resource allocation is essential for successful verification**

SYSTEMS APPROACH: SYSTEM VALIDATION

Preparing CD in System Validation Testing

System Validation

System Validation
- Issues Identified: flight controller limitations on autonomous landing hold during deployment
- Risk Mitigation: Secured COA months before System Validation
- Successful completion of all other mission elements

Key Lessons
- Successful proof of concept of INFERNO scope
- Test critical functionalities during system verification

SYSTEMS APPROACH: SUMMARY

Anticipated Risk Description	Prevented	Realized
Crashing Child Drone		✓
Software Development Delay		✓
Camera Mount Structural Failure	✓	
Improper SP Orientation	✓	
Failure to Obtain COA	✓	
Airframe Integration Difficulties		✓

- **Realized risks had greatest likelihood, most difficult to directly prevent**
- **Minimize realized risk impact via schedule margin, extra component procurement, personnel allocation**

<u>Final Systems Engineering Lessons</u>

- **Customer involvement is key – negotiation, understanding of ultimate goal**
- **Invest time in developing clear, testable requirements**
- **Interface control is critical to mission success**
- **Maintain traceability throughout design and testing**
- **"Start with your eye on the finish line"**

Project Context | Design Solution | V&V | **Systems and Management**

PROJECT MANAGEMENT

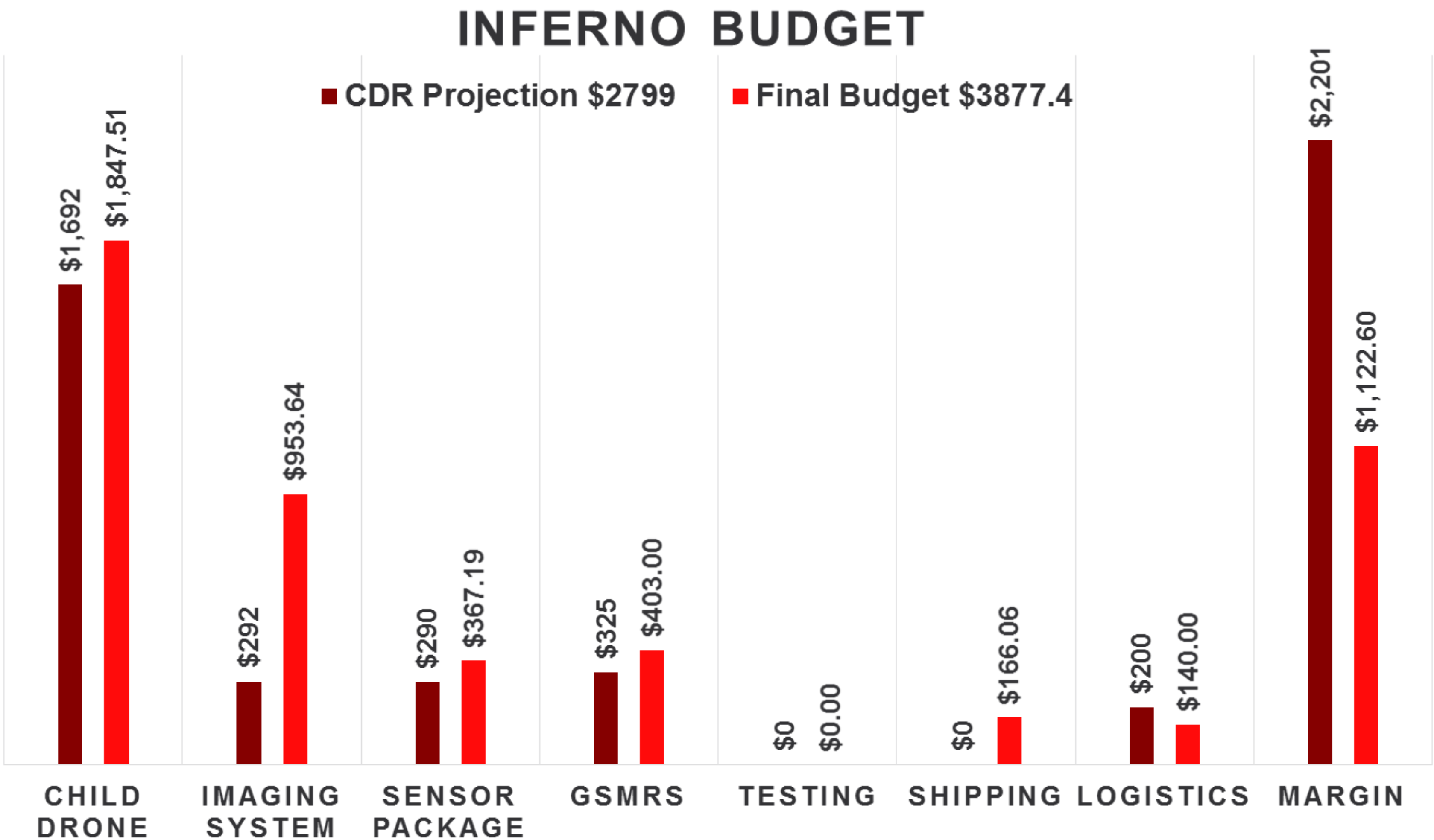
MANAGEMENT APPROACH

- Maintain the long term view
  - Schedule Impact, logistics, workload…
- Anticipate issues, preemptively address
  - Spare parts, scheduling conflicts…
- Employ team in accordance with their capabilities
  - Diverse talents on the team
- Let the team focus of their work
  - Interface with JPL, the PAB, and others…
- Focus the team as necessary
  - Identify tasks critical to the project
- Support individuals as needed

MANAGEMENT LESSONS LEARNED

- Communication can always be better
  - Early Difficulties: Keeping the team apprised
  - Later Successes: Standardized methods
- Detailed yet flexible schedule
  - Early Difficulties: Switching from following class milestones to setting our own schedule.
  - Later Successes: Detailed schedule which can be easily referenced and updated.
- Transitioning from "Steering" the team to "Pushing"
  - Easy when the team is highly motivated
  - Keeping people accountable as motivation waned
  - Schedule is an important reference

BUDGET



INFERNO BUDGET
CDR Projection $2799
Final Budget $3877.4
$1,692
$1,847.51
$292
$953.64
$290
$367.19
$325
$403.00
$0
$0.00
$0
$166.06
$200
$140.00
$2,201
$1,122.60
CHILD DRONE
IMAGING SYSTEM
SENSOR PACKAGE
GSMRS
TESTING
SHIPPING
LOGISTICS
MARGIN

RELATIVE INDUSTRY COST

Item	Hours	Rate	Total
Work Hours	3871.3	$31.25 per hour	$120,978.13
Project Supplies		$5000	$5000.00
RIFLE Range	30	$200 per hour	$6000.00
Table Mountain Access		$5000 per year	$5000.00
Pilot/Spotter	40	$40 per hour	$1600.00
Subtotal			$138,578.13
Overhead		200%	$277,156.25
Total			**$415,734.38**

QUESTIONS

BACKUP SLIDES

BACKUP SLIDES CONTENT

- Levels of Success
- Requirements
- Thermal Sensor Analysis
- SP Internal Temperature Analysis
- Human Factors Testing
- Mass and Power Model Updates
- Tensile Strength Testing
- CD Airspeed
- CD EMI

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

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.

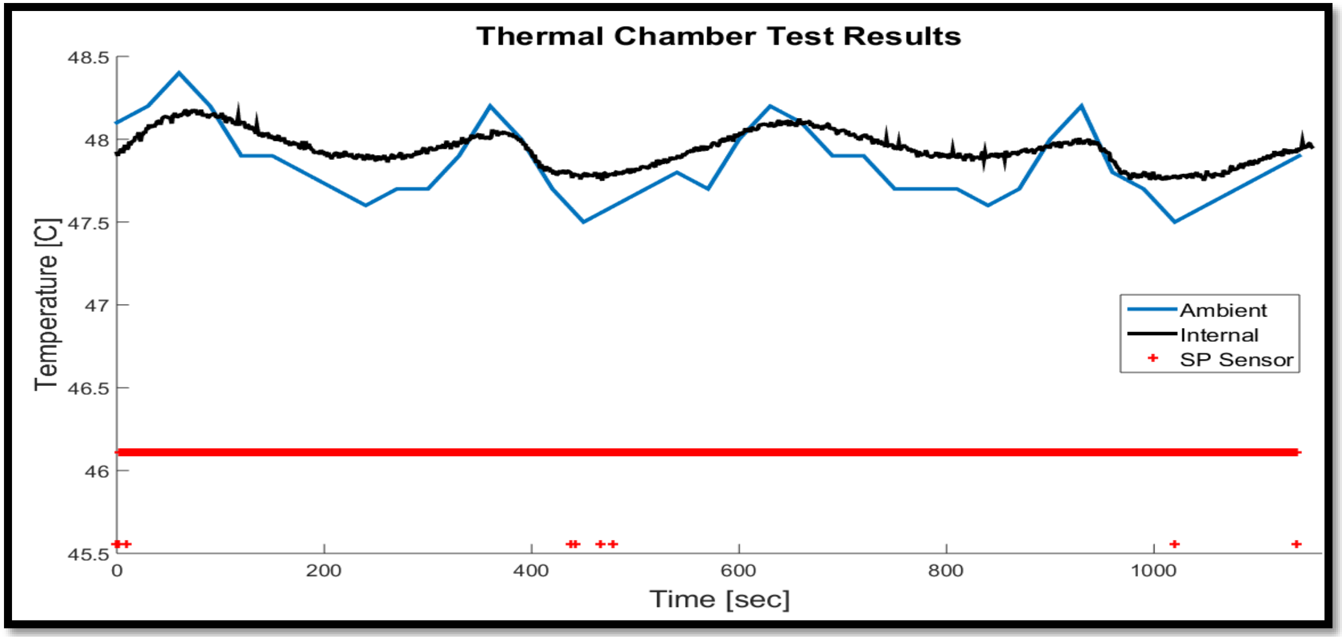
REQUIREMENTS

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.

SP THERMAL SENSOR ANALYSIS

Primary Test:
Hold at 47.8°C



	Mean (°C)	Confidence Interval (°C)	System Error (°C)	Bin Error (°C)	Mean Error (°C)	Max Error (°C)
Ambient	47.85	±0.072	±1	-	-	-
SP Sensor	46.11	-	-	0.67	1.74	3.48

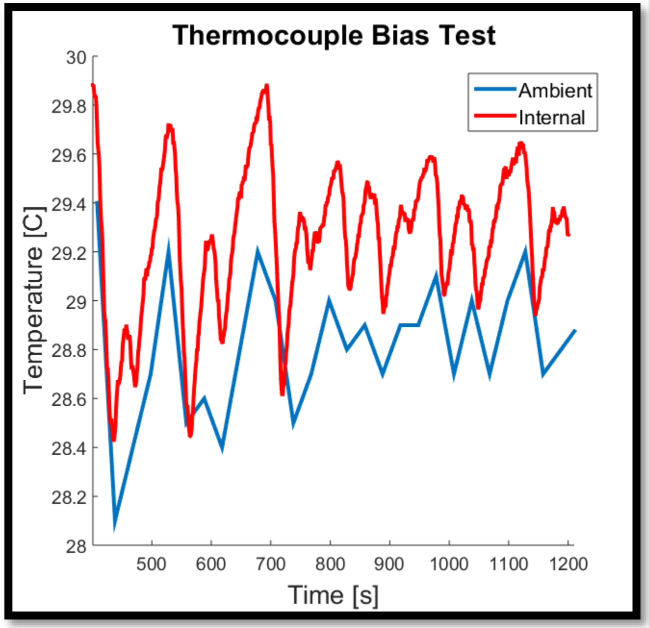
- Unable to verify the thermal sensor error is < 2.78°C
- Range of thermal sensor verified during ramp from 10-47.8°C
- Visible bias in the SP thermal sensor reading.
  - Calibrate SP software to account for the bias

SP INTERNAL TEMPERATURE ANALYSIS

	Mean (°C)	Confidence Interval (°C)	System Error (°C)	Bias Offset (°C)	Bias Error (°C)
Ambient	47.85	±0.072	±1	-	-
Internal	47.94	±0.006	±2	+0.43	±0.11

	Mean Temperature Difference (°C)	Temperature Difference Range (°C)
Modeled	2.70	0.90-3.40
Experimental	0.52	0-3.71

Bias Test

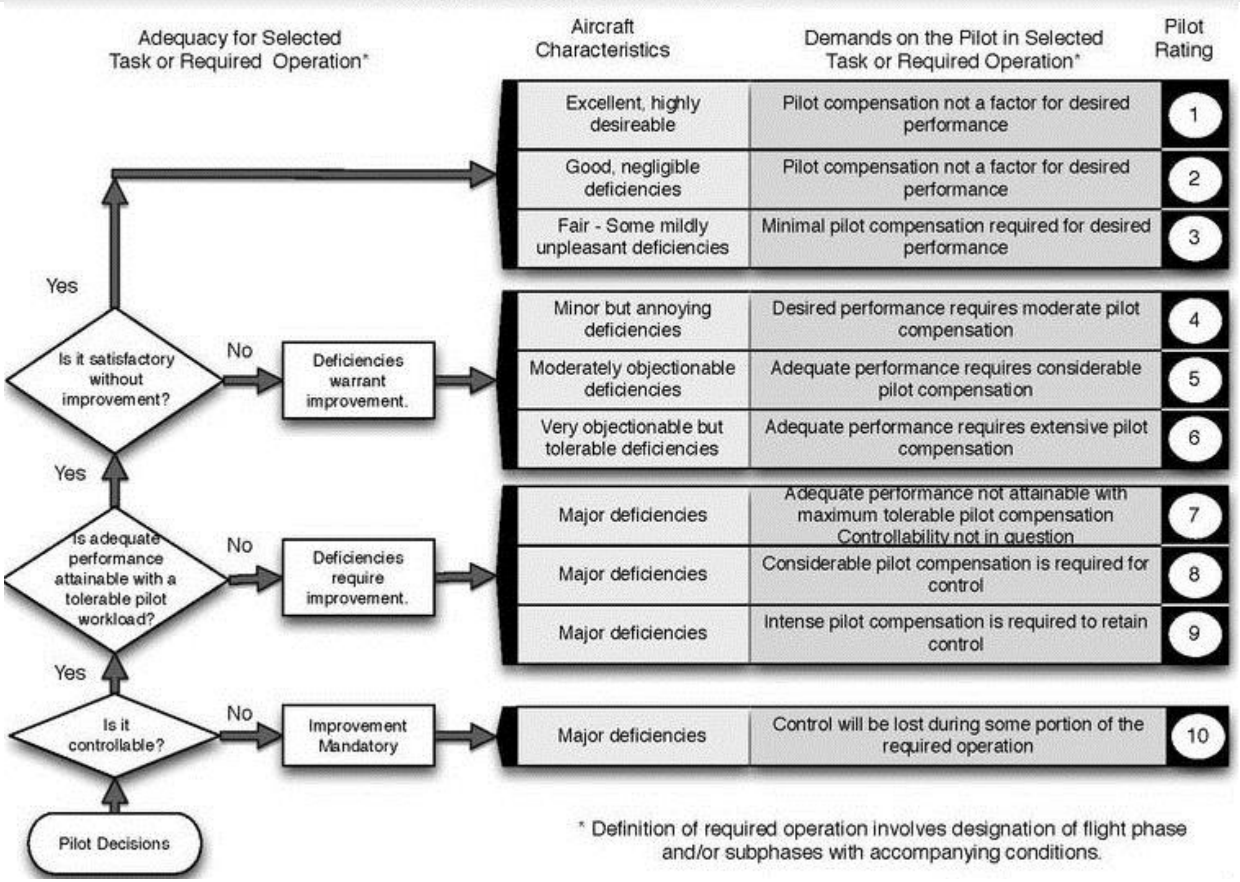


- Inconclusive results due to large system errors.
- Model over predicts actual internal temperature.
- Error Sources:
  - Free convection modeled using vertical plate
    - Ignores internal convection
    - Decreases conduction area
  - Assumes all power is dissipated as heat

TEST READINESS: COOPER HARPER CRITERIA / HUMAN FACTORS ANALYSIS

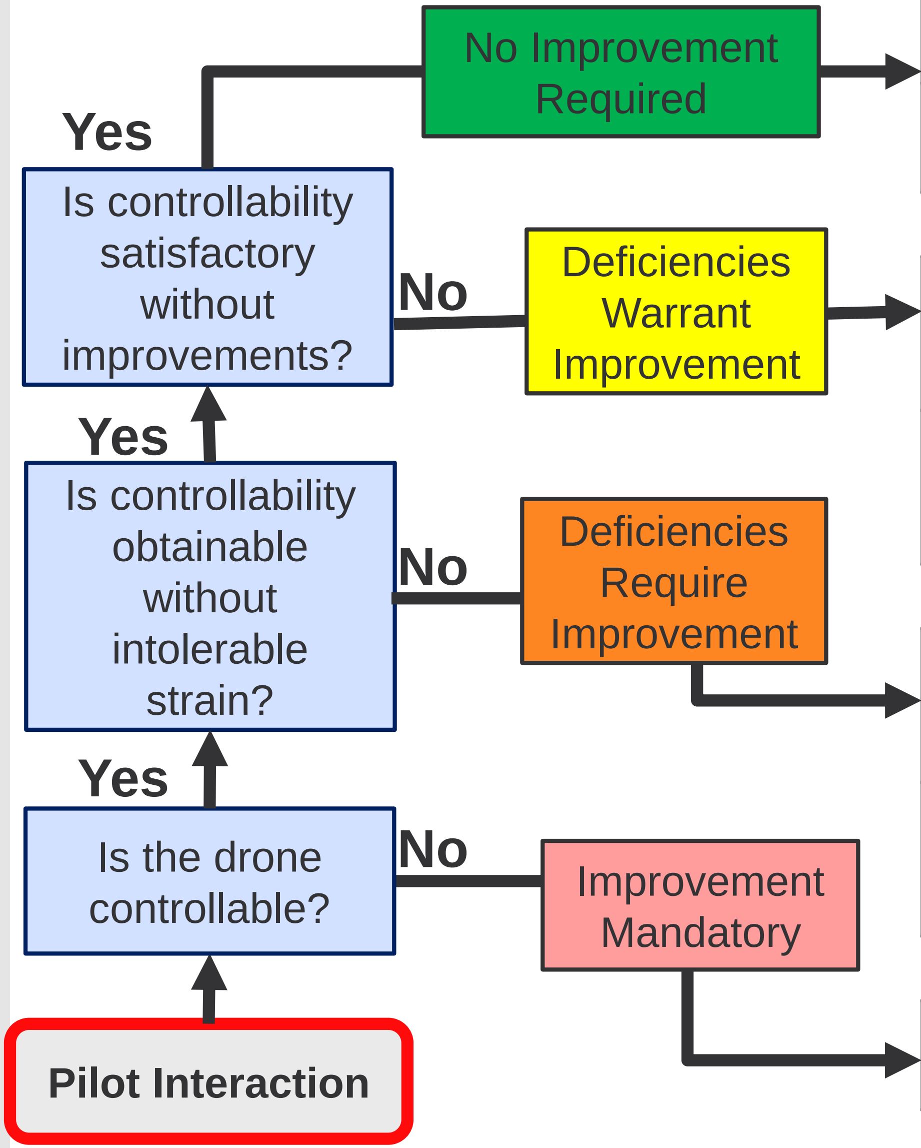
- No automated landing on GSMRS
- Piloted control
- Cannot predict the effects of flight on the transmitted image
  - Dr. Frew: We don't have the time, expertise, or resources to build a model
- Using human factors testing
- Backup plan: Use a COTS gimbal
  - 2000 Hz control frequency
  - 0.1° pointing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



Excellent, highly desirable	*Pilot strain is not a factor*	1
Good, negligible deficiencies	*Minimal pilot strain is required*	2
Minor but tolerable deficiencies	*Desired performance requires moderate pilot strain*	3
Moderately unpleasant deficiencies	*Adequate performance requires considerable pilot strain*	4
Major deficiencies	*Maintaining control requires considerable pilot strain*	5
Major deficiencies	*Maintaining control requires maximum pilot strain*	6
Major deficiencies	*Control will be lost*	7

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)

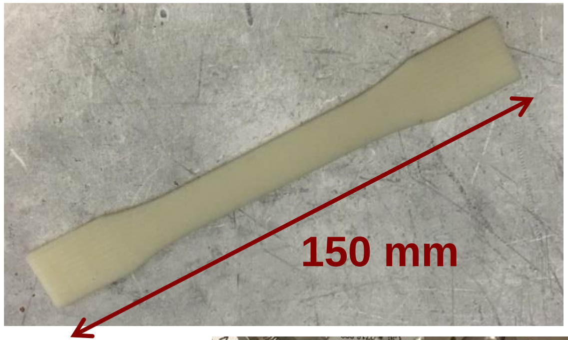
Component	Current [A]	Charge Used [mAh]	Change [mAh]
Propulsion @ Hover	26.6	6,650	+460
Flight Electronics	0.18	45	0
Video Transmitter	0.20	50	-125
Deployment System	0.04	~0	0
Total	**26.0**	**6,745**	**+335**
Margin vs. Endurance	**6.0**	**1,255**	**-335**

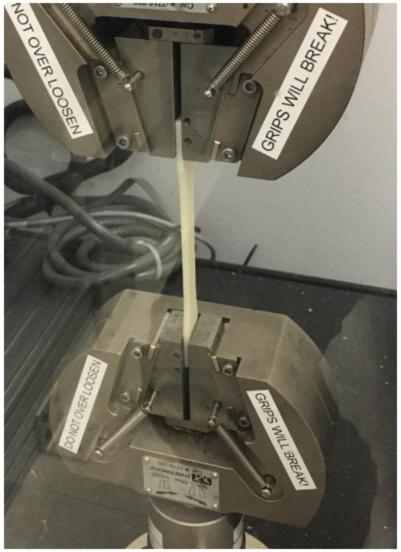
Summary

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

Tensile Strength Testing

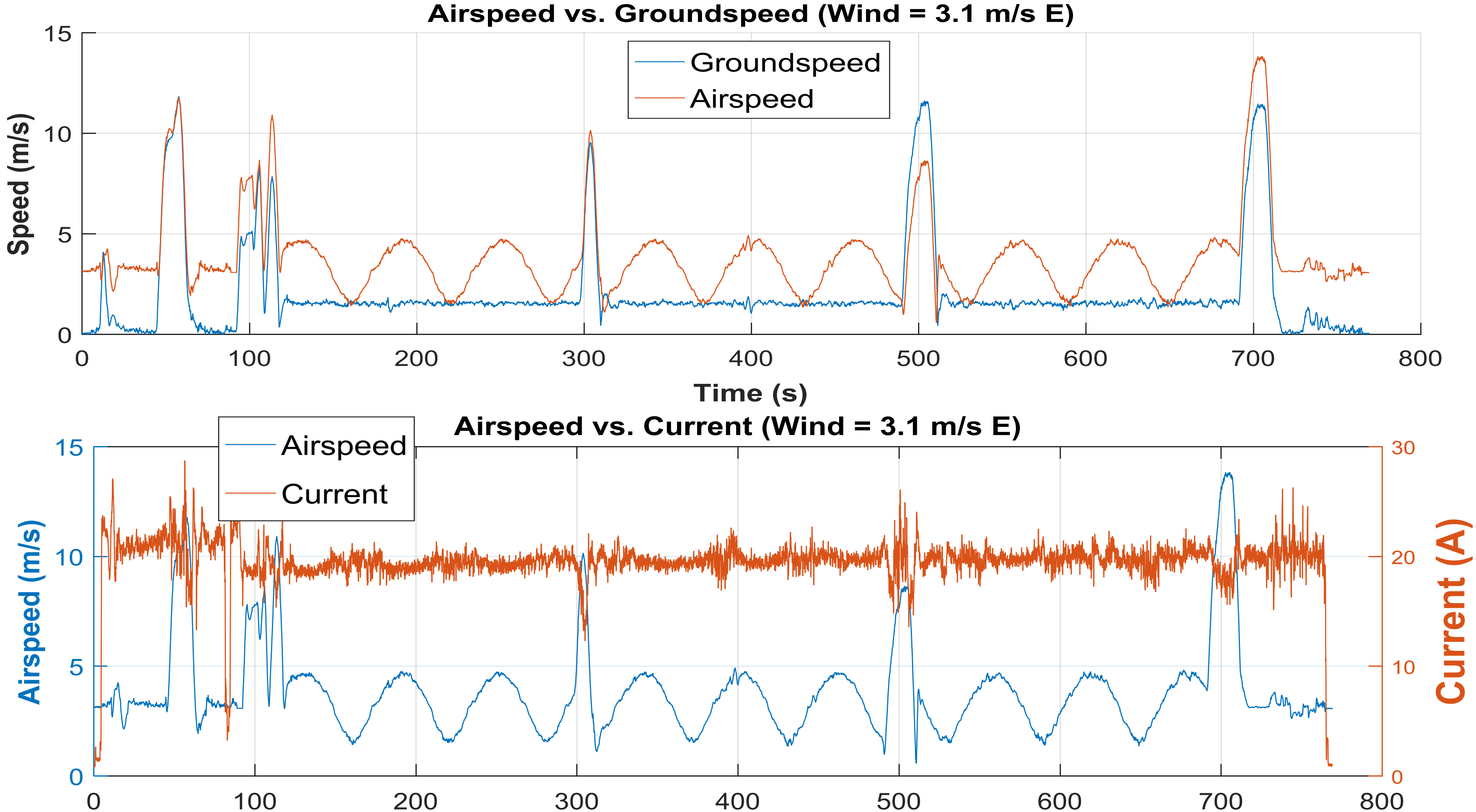
- Instron machine used to determine Young's Modulus and failure stress
- ASTM D638 Standard with Type 1 specimen used for tests



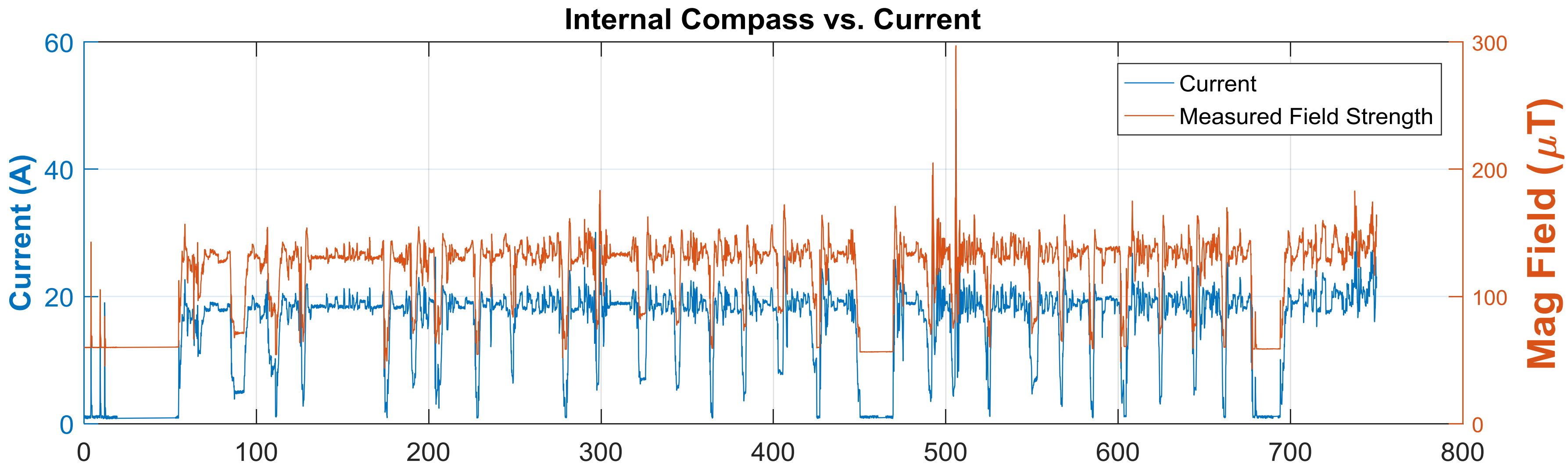


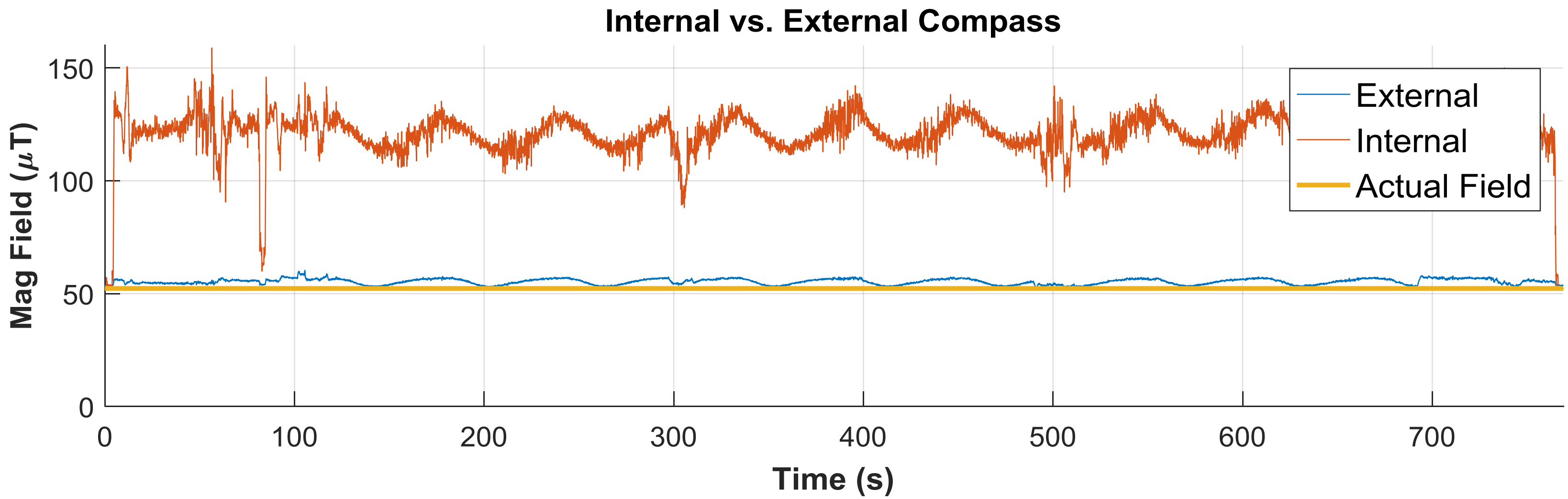
	Failure Stress (MPa)	Young's Modulus (GPa)
Tested	12.87	1.82
Specified	33	2.2

CHILD DRONE POWER VS. AIRSPEED



CHILD DRONE EMI TESTING





CHILD DRONE EMI TESTING