Raytheon

Spring Final Review

REPTAR

REcoverable ProTection After Reentry

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Customer: Steve Thilker, Collin Baukol, Cody Humbargar, Jason Latimer (Raytheon)

Advisor: Dr. Brian Argrow, Dr. James Nabity

University of Colorado Boulder

Project Statement & Motivation

REPTAR shall assist in the recovery of a de-orbited 1U Raytheon Payload. The mission begins once the SmallSat has re-entered the atmosphere and has reached subsonic velocity. REPTAR shall facilitate the subsonic deceleration, landing, location determination, and location transmission portions of the mission.

Recovery of payload enables:

- Lower mission costs by re-using the payload
- Obtain samples collected by payload on-board

Mission Concept of Operations

1) Launch
REPTAR components survive launch conditions as payload attached to a bus.

2) Orbit/Standby
REPTAR Components survive on orbit conditions. Batteries charged by bus.

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3) De-orbit
Receive command from bus to power REPTAR systems. Re-entry burn.

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4) Re-entry
Receive command from bus to power REPTAR systems. REPTAR separation from bus. Re-entry completed by Raytheon System.

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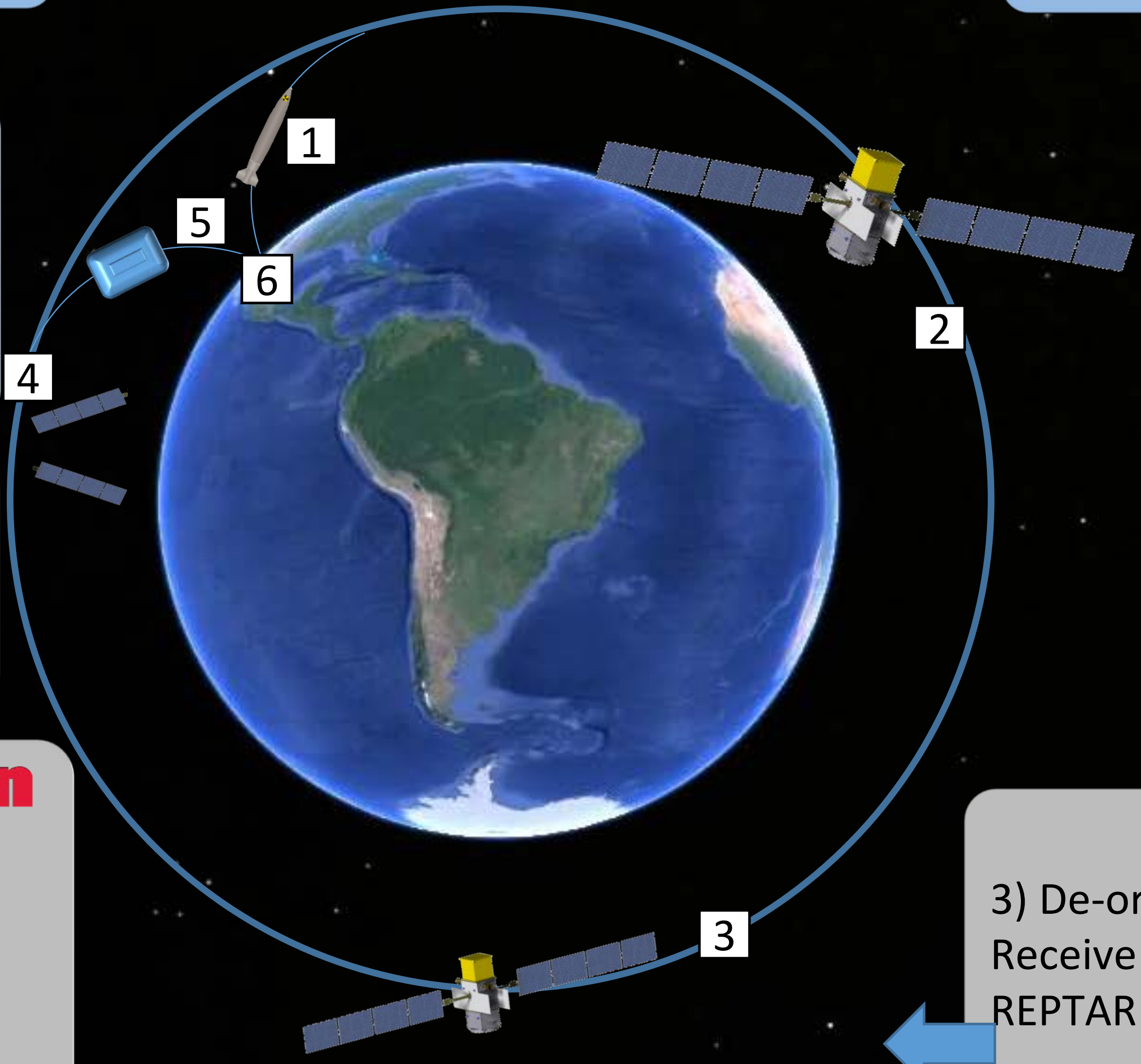
5) Deceleration
Decelerate to subsonic speeds.

6) Land and Recovery
REPTAR protects payload during ground contact and transmit location.



Legend

- REPTAR Solution
- Raytheon Solution

Concept of Operations(CONOPS)

Entry

After being decelerated to subsonic speeds, REPTAR activates atmospheric deceleration systems to protect the payload

Descent

Slows to safe landing speeds by deploying a parachute. Transmits location during descent

Land

Lands payload safely within launch loading requirements

Receive Location

Recovery team receives location

Transmit Location

Transmits location to recovery element

Levels of Success

Criteria	Form Factor – DR 1.1	Instantaneous G-Loading – DR 2.1	Communication – DR 3.1
Level 1	The form factor of REPTAR including payload shall be 6U Standard	The payload shall endure a maximum instantaneous loading of less than 40 G	REPTAR shall beacon its location over a range of 20 miles
Level 2	The form factor of REPTAR including payload shall be 4U Standard	--	REPTAR shall beacon its location over a range of 30 miles
Level 3	The form factor of REPTAR including payload shall be 3U Standard	--	REPTAR shall beacon its location over a range of 45 miles

Executive Summary

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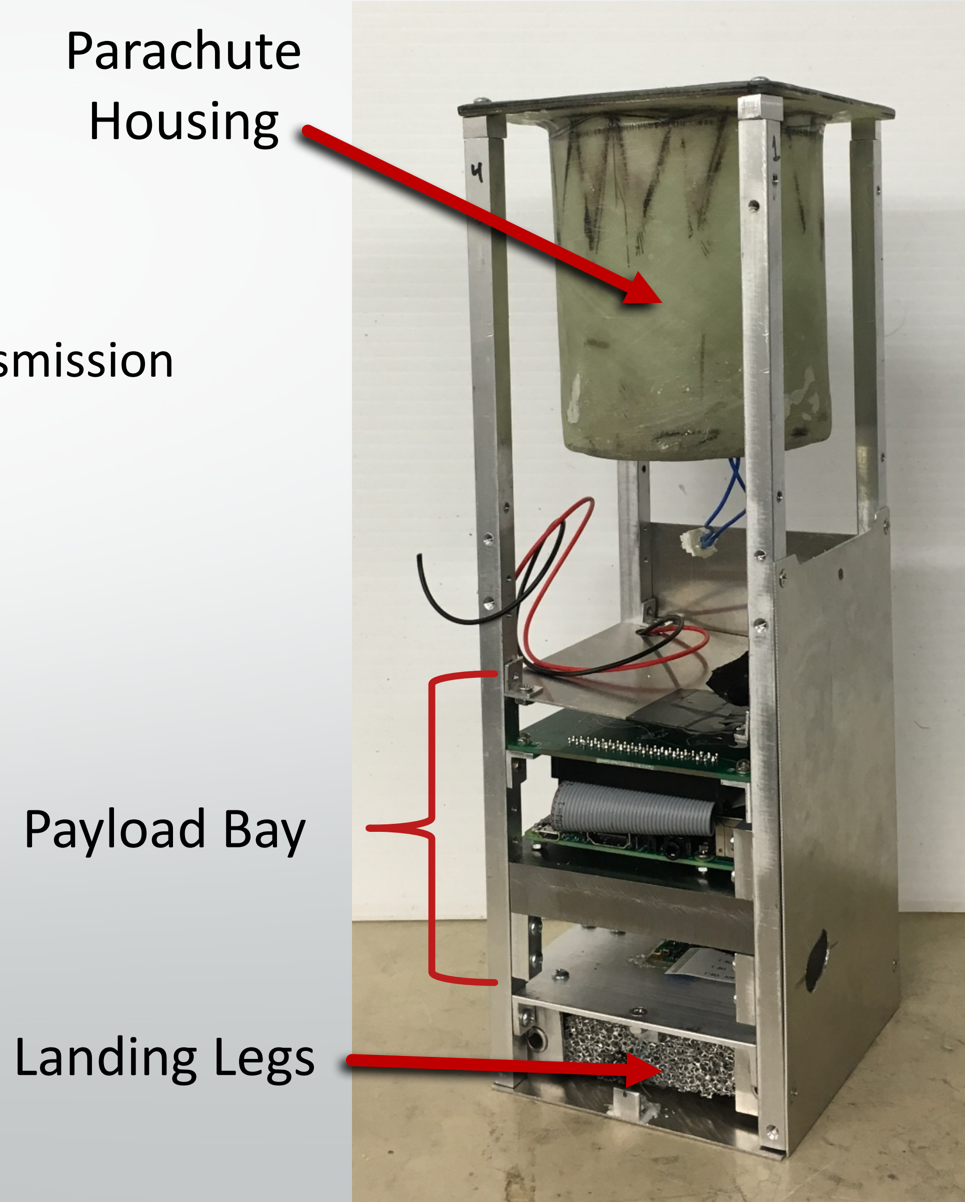
- Designed and constructed 3U Recovery Vehicle
  - Parachute for deceleration
  - Aluminum foam for impact absorption
  - GPS and Iridium for location determination and transmission
- Performed thorough subsystem-level validation
- Full system integration incomplete
  - Drop from aircraft not performed
- Performed drop test from a fire tower



Design Description

Key Components

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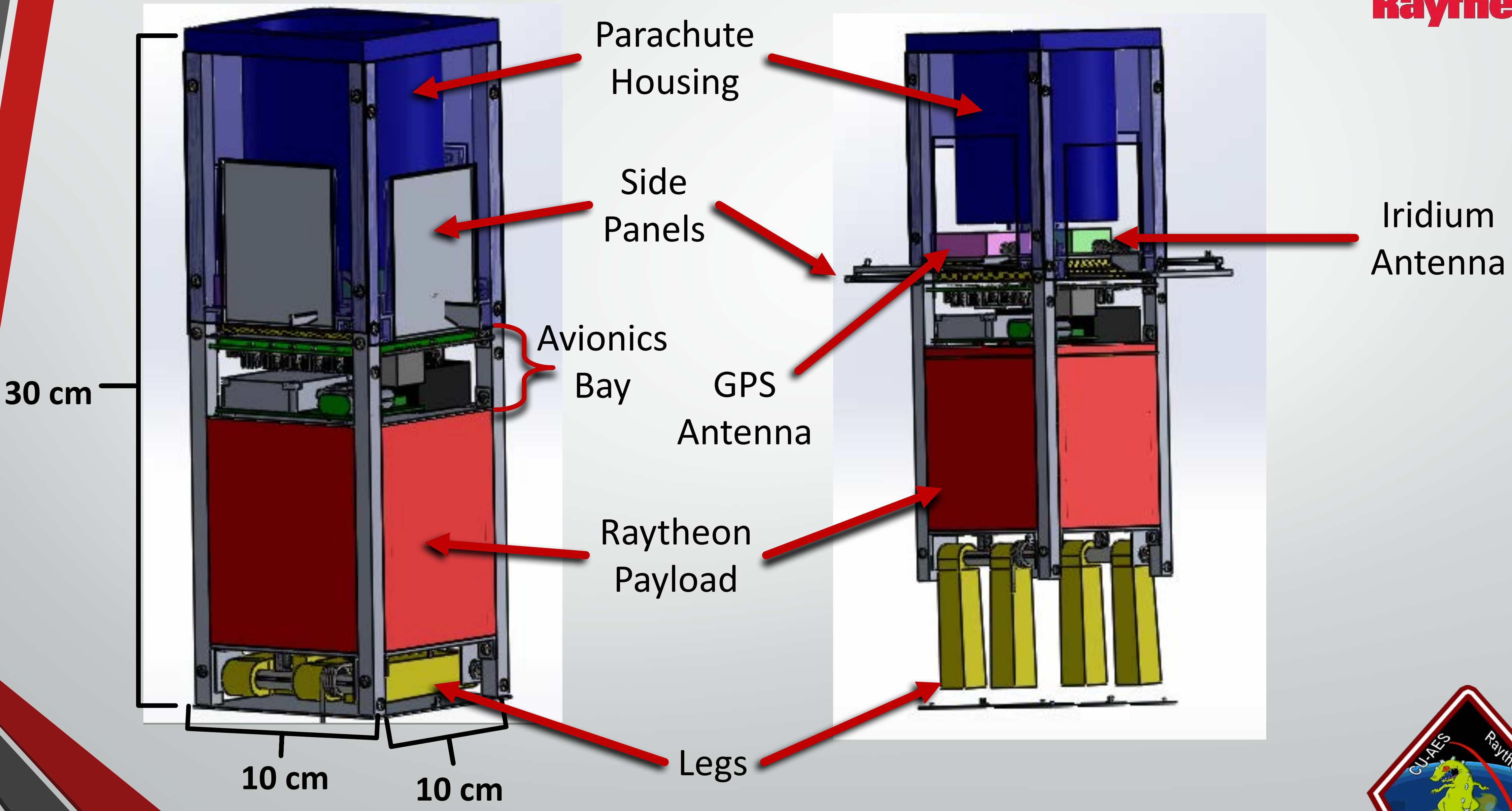
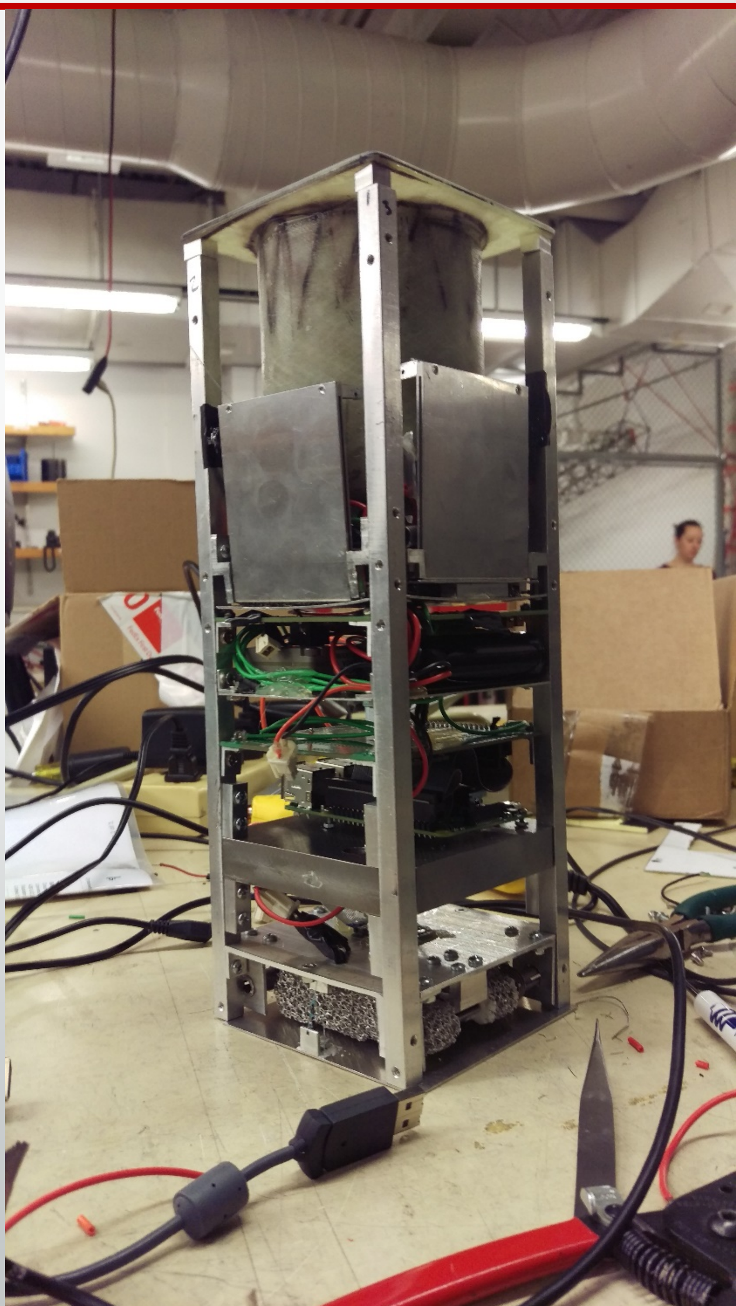


Mass and Volume Budget

Item	Mass (g)	Volume (U)
Descent Subsystem	383	1.23
Landing Subsystem	512	0.41
Avionics Subsystem	518	0.36
Frame	437	-
System Wiring	50	-
Test Payload and Added Ballast	1300	1.00
SYSTEM TOTAL	**3200**	**3.00**
SYSTEM MAX	**4000**	**3.00**
Margin	**800**	**-**



Mission Timeline and FBD

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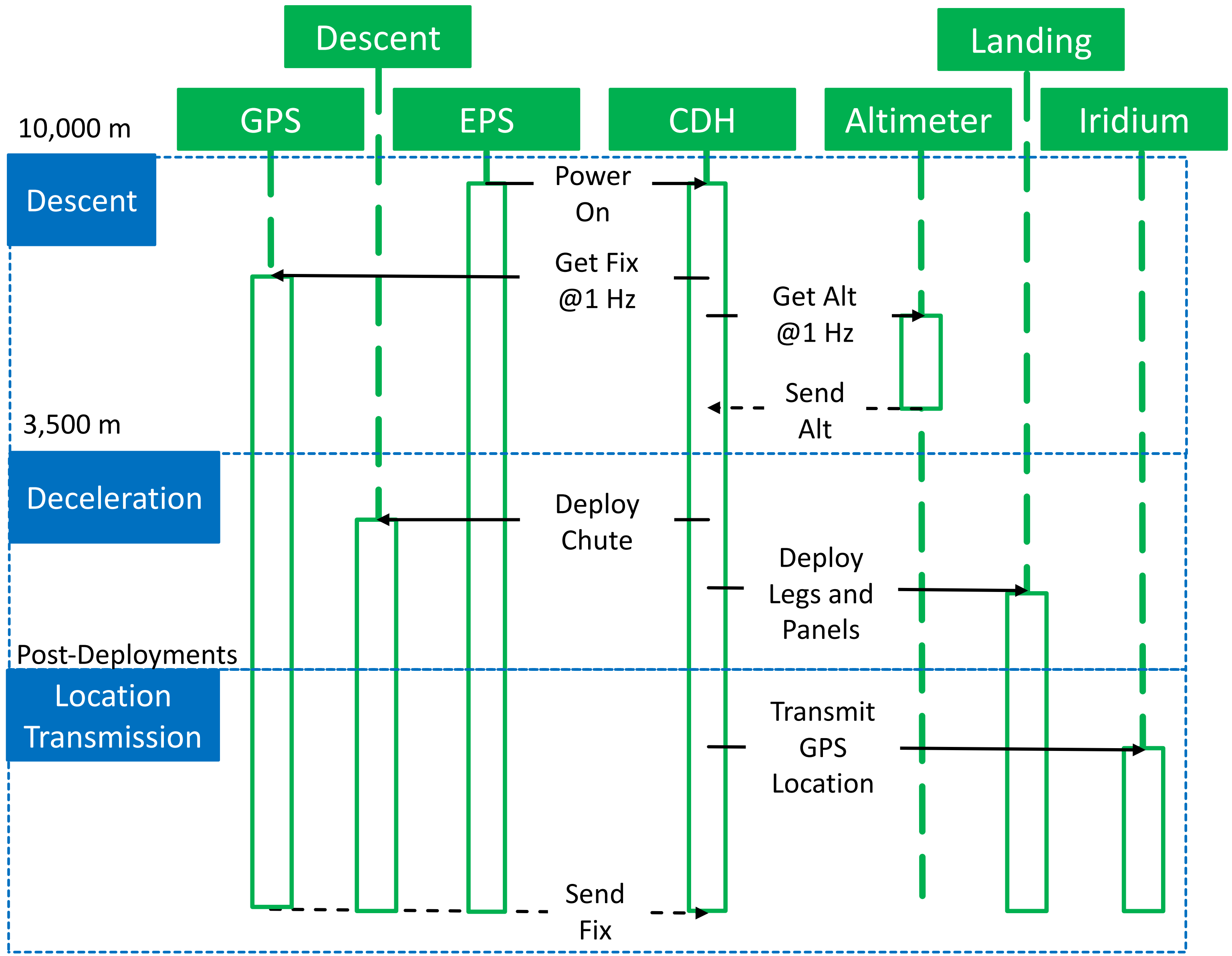

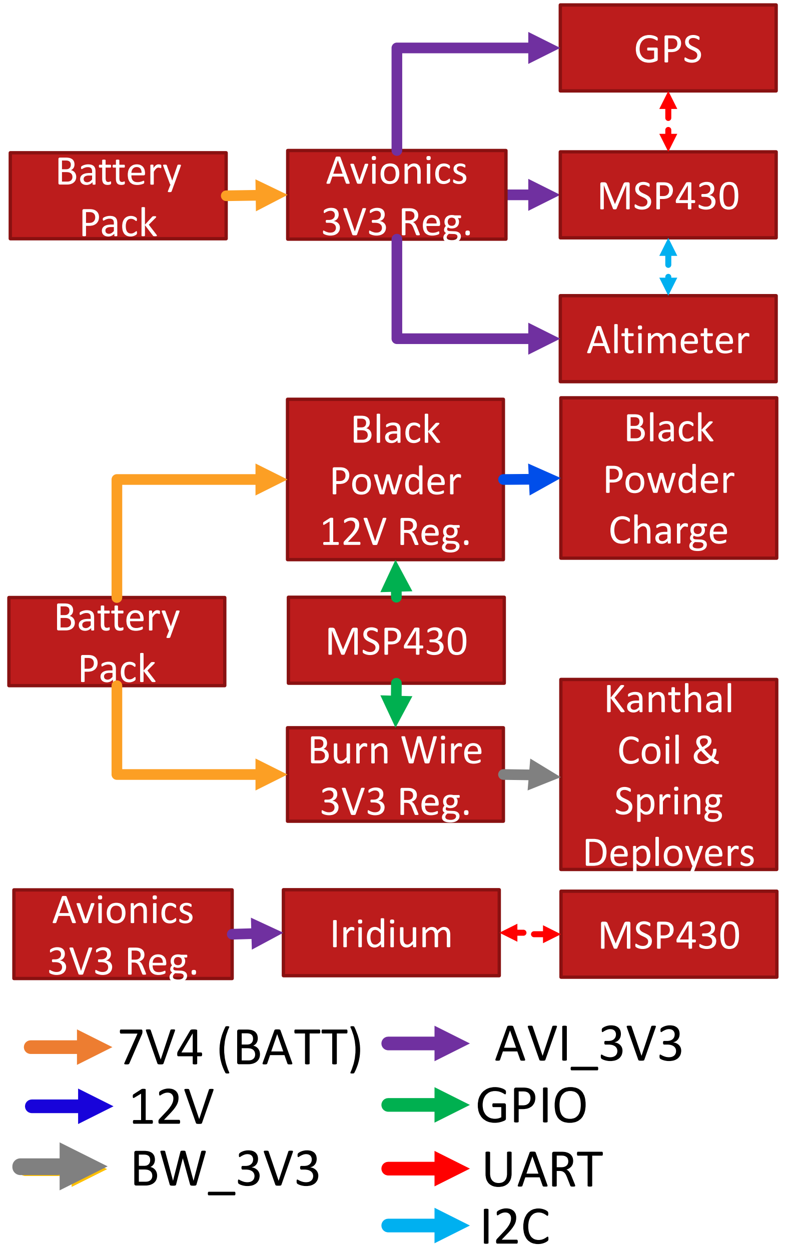

Critical Project Elements

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Critical Project Element	Description
Parachute Deployment	Without chute deployment, vehicle hits ground at 90 m/s
Landing Leg and Side Panel Deployment	Without leg and side panel deployment, vehicle experiences more than 40 G upon landing
Avionics Internal Power	Provides sufficient power at a reasonable line and load configuration to all avionics components
FET Deployment Triggers	Allows triggering of deployable elements
Battery Charge - Discharge	Safely provides sufficient power to avionics
Full System Integration	All components work together in form factor

Testing

Parachute Ejection Modeling

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- Pressure Gauge:
  - Measured 24 PSI, expected 20 PSI
- Friction Force:
  - 5.29 J of energy: 1079 g dropped from 50 cm
- Parachute Exit Velocity:
  - Velocity measured over 5 inches at 59 FPS
  - Averaged from 3-5 m/s

*Tests performed in Aerospace Welding Shop and Senior Projects Work Shop

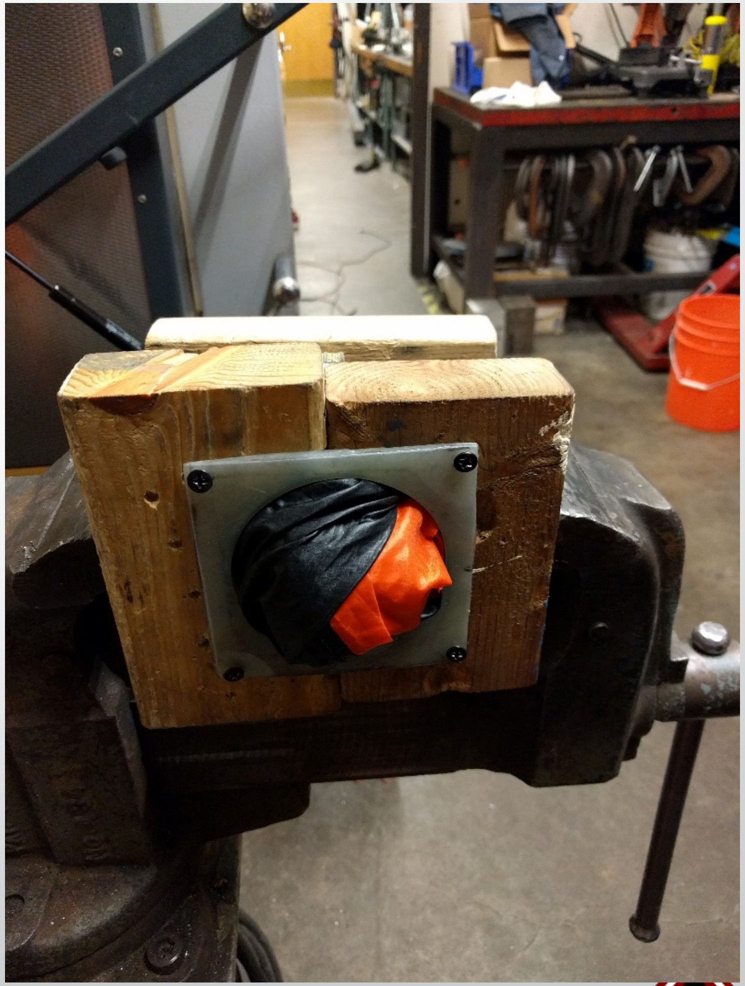
Parachute Ejection Testing

- Final Testing with Fiberglass Housing:
  - Ignite black powder for successful ejection
- Purpose:
  - Validate strength of fiberglass
  - Validate parachute ejected
- Results:
  - 9/9 successful ejections
  - No damage to fiberglass

*Test Performed in Aerospace Welding Shop

Parachute Ejection Conclusion

- Parachute ejection from fiberglass housing:
  - 0.55 g of black powder with cotton sheet protection
- DR 3.2:
  - Parachute helps slow to reduce impact on landing
- Slow REPTAR to safe landing velocity:
  - 4.9 m/s landing velocity with selected parachute



Leg Deployment Testing

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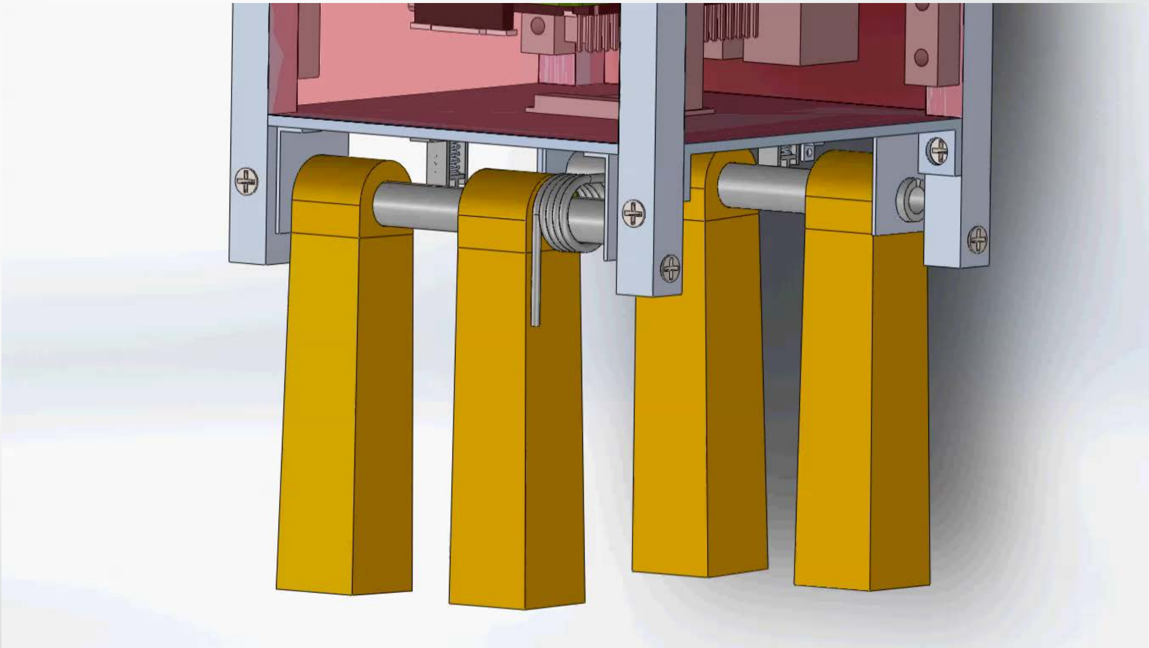
- Full Leg System Deployment
  - Power sent to Kanthal coil, system deploys
- DR 2.1
  - 3U volume constraint
- DR 3.1
  - Survive 40 G
- Purpose
  - Validate Kanthal coil cuts wire
  - Validate springs rotate legs into place
  - Validate locking mechanism locks into place
- Model
  - Torque required in 6 m/s wind: 0.065 in-lbs
  - Torque provided: 2.76 in-lbs



Model of Leg System

Leg Deployment Testing Results

- Simplified system deployed successfully 40/40 times in both no-wind and 6 m/s wind scenarios
- System successfully deployed 7/7 times with full system with final Kanthal coil setup
- Kanthal coils trigger deployments with 3V3 and 4A4

Leg Crushability Testing

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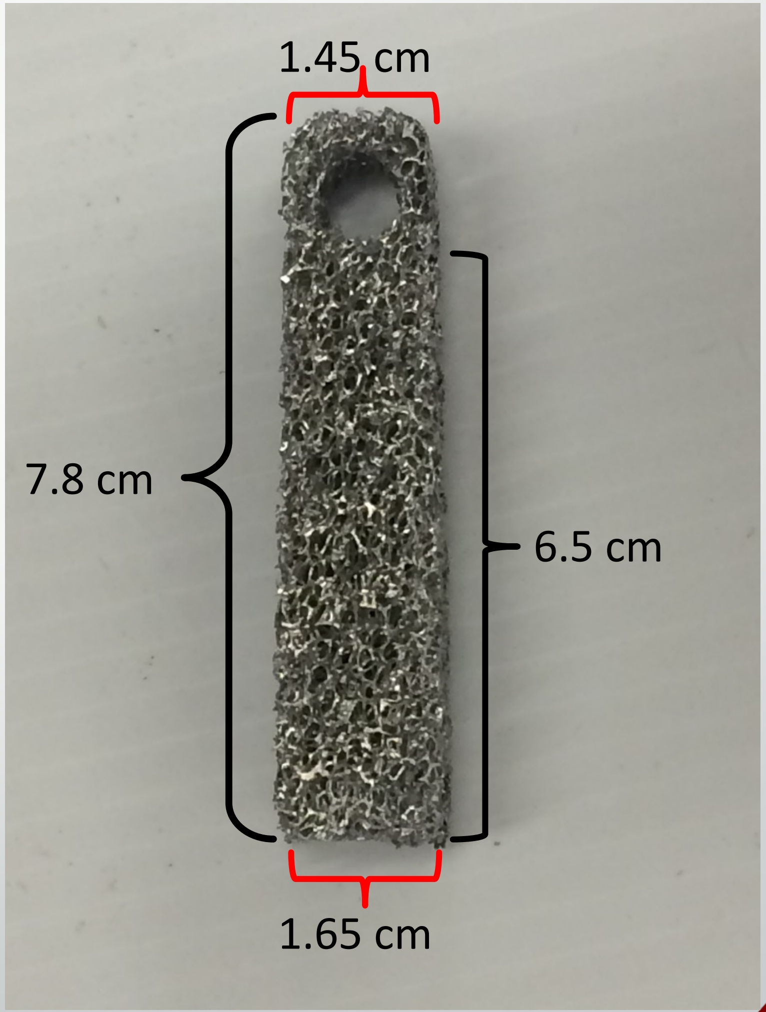
- Single Leg Crushability
  - Simulate ¼ expected system energy – 16.25 J
- Derived Requirement 3.1
  - Survive 40 G
- Purpose
  - Validates 65% compression of leg
  - Validate G-loading
- Model
  - Equating kinetic energy into expected work of leg deformation



Leg Crushability Testing

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- Dropped 1 kg mass on single leg from 1.66 m, to achieve ¼ of expected energy
- Tested 5 times
- Estimated G-loading using frame by frame estimate of deceleration

Test Results

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Building Drop Test Purpose

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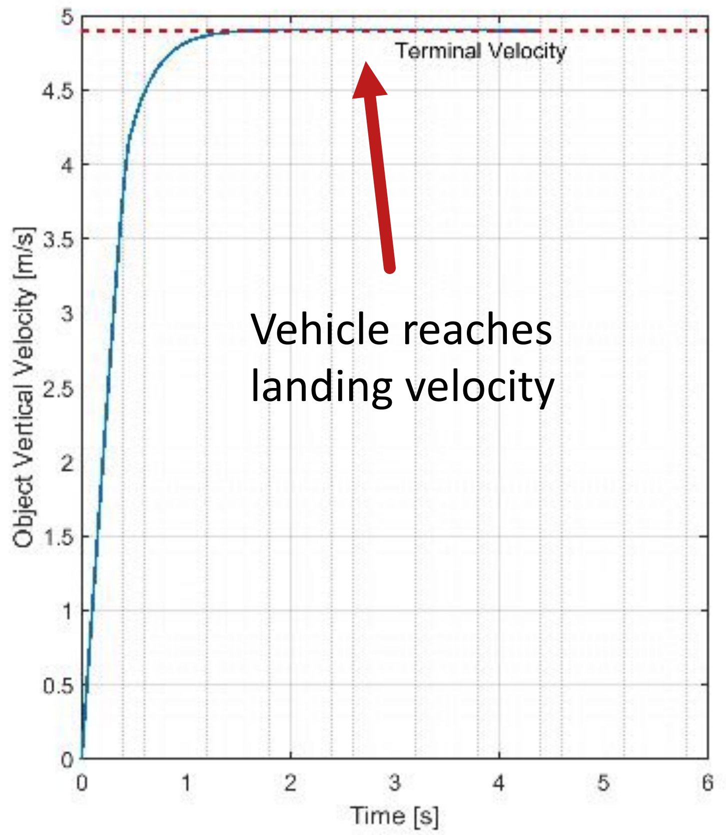
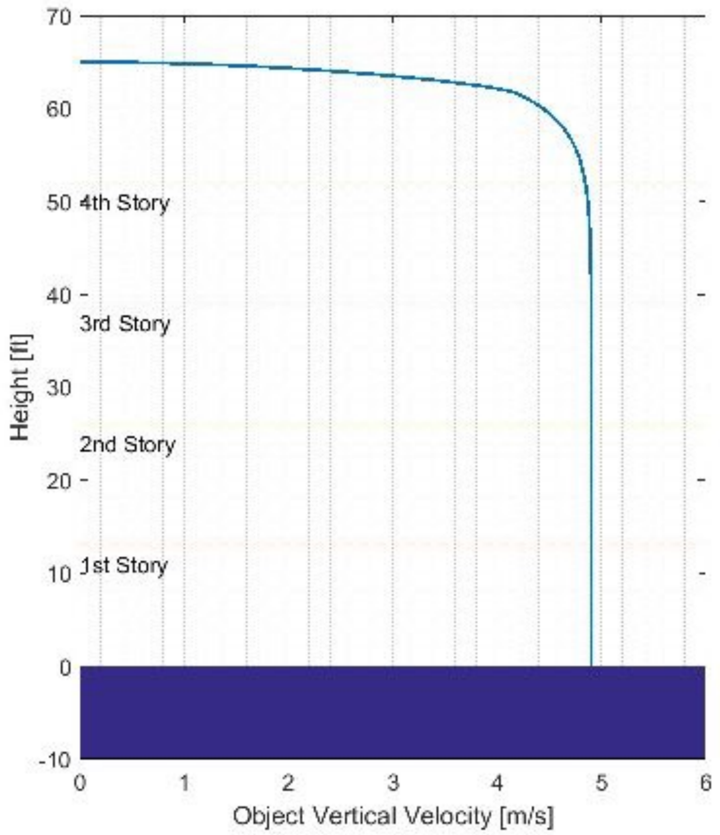
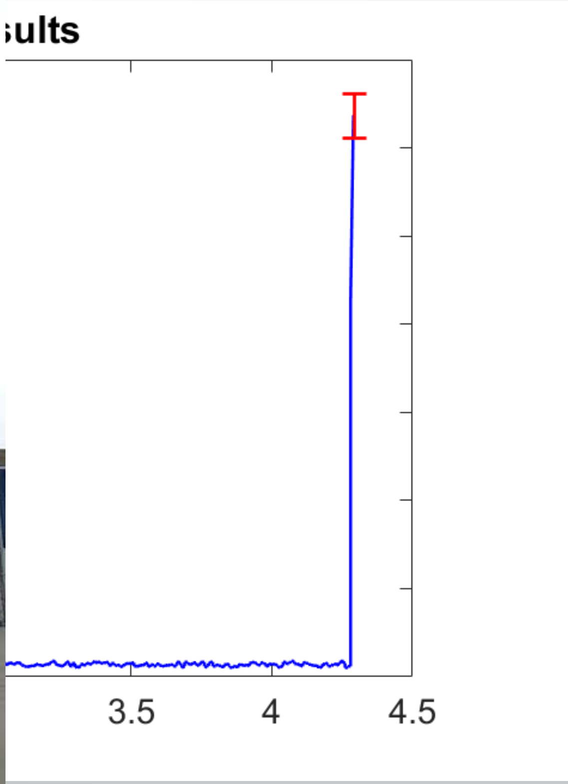
- Purpose:
  - Test impact absorption qualities of landing system in dynamic environment
  - DR 2.1 – Keep payload below 40 G of loading





esults

- V … cted ground as
  c … exceeding
- V … ted landing
  p … due to pendular
  t … n



Building Drop Test Impact on Project

- Side panels need a redesign, they did not act as intended
  - Panels need a locking mechanism and stronger springs
- Necessity of landing system needs to be reinvestigated
  - Stemming from mass tradeoffs
- Chute inflation time needs further testing
  - 10 G upon chute inflation was higher than expected
- Further testing is needed from higher altitudes
  - Allows system to reach steady state before landing, reduces sensitivity to wind upon landing

3V3 Internal Regulator Performance Verification

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Test Scope:

- Fundamental Voltage Component
- Ripple
- Line/Load Regulation

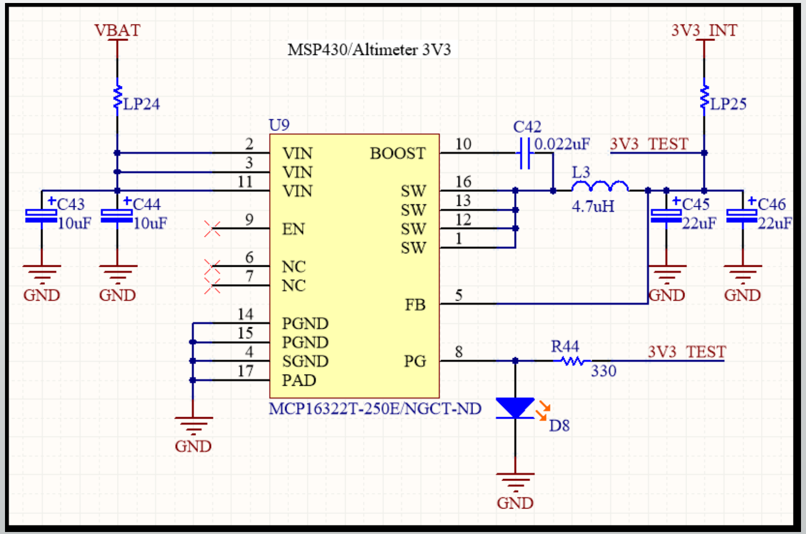
Design Requirements:

- 3.3V Output to within 5%
- Less than 300 [mV] of ripple
- Less than 300 [mV] of combined line and load regulation

Importance of Validation:

The 3V3 Internal Regulator is responsible for providing power to:

- MSP430FR – Microcontroller
- Iridium RockBlock Unit
- Venus GPS Unit
- MS5607 – Pressure Altimeter



Initial Subsystem V&V and Integration

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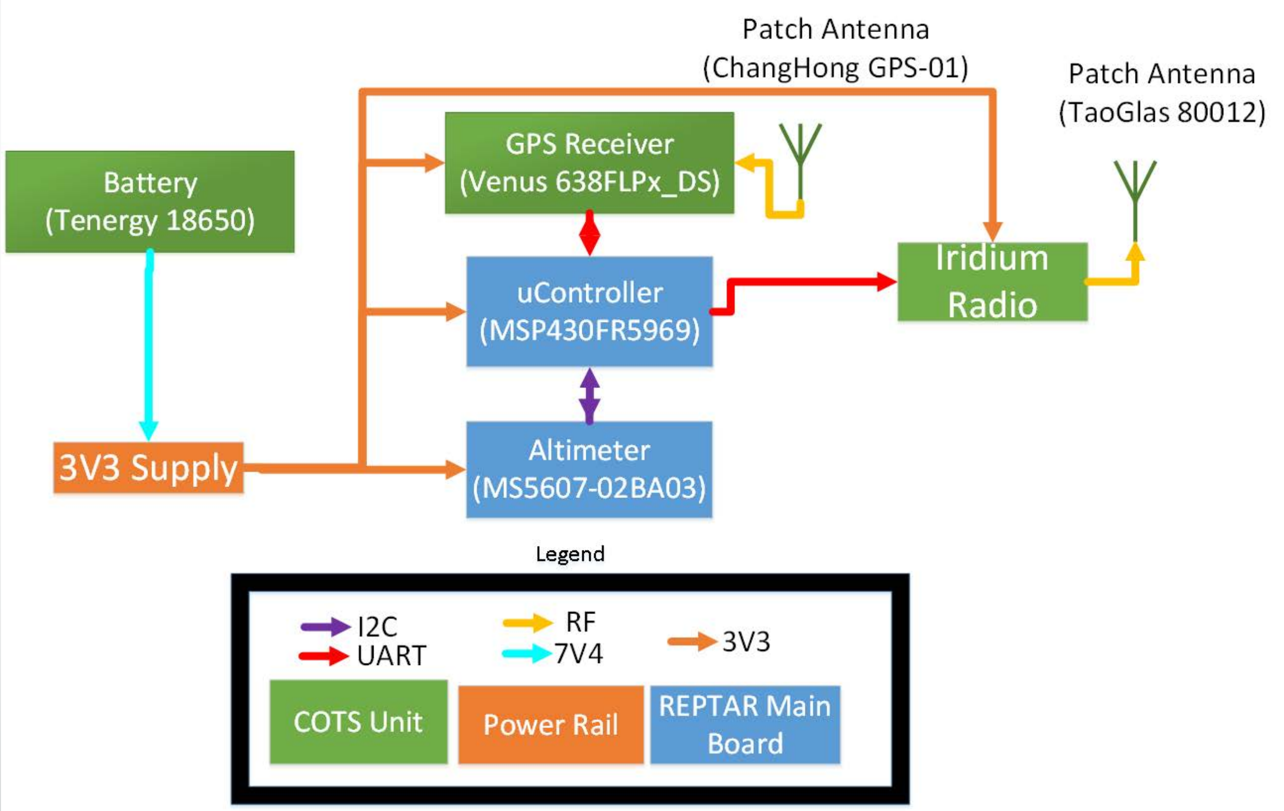
Subsystem Level Validation:

- 3.34 [V] Realized (Unloaded)
- 160 [mV] Ripple (Unloaded)
- 40 [mV] Load Regulation
- 10 [mV] Line Regulation

Integration:

- 1.5 [V] of ripple observed when RockBLOCK Iridium Module is attached and in a non-transmitting state.
- SPICE Model does not explain performance – issue lies at RF



Microwave Model in ADS

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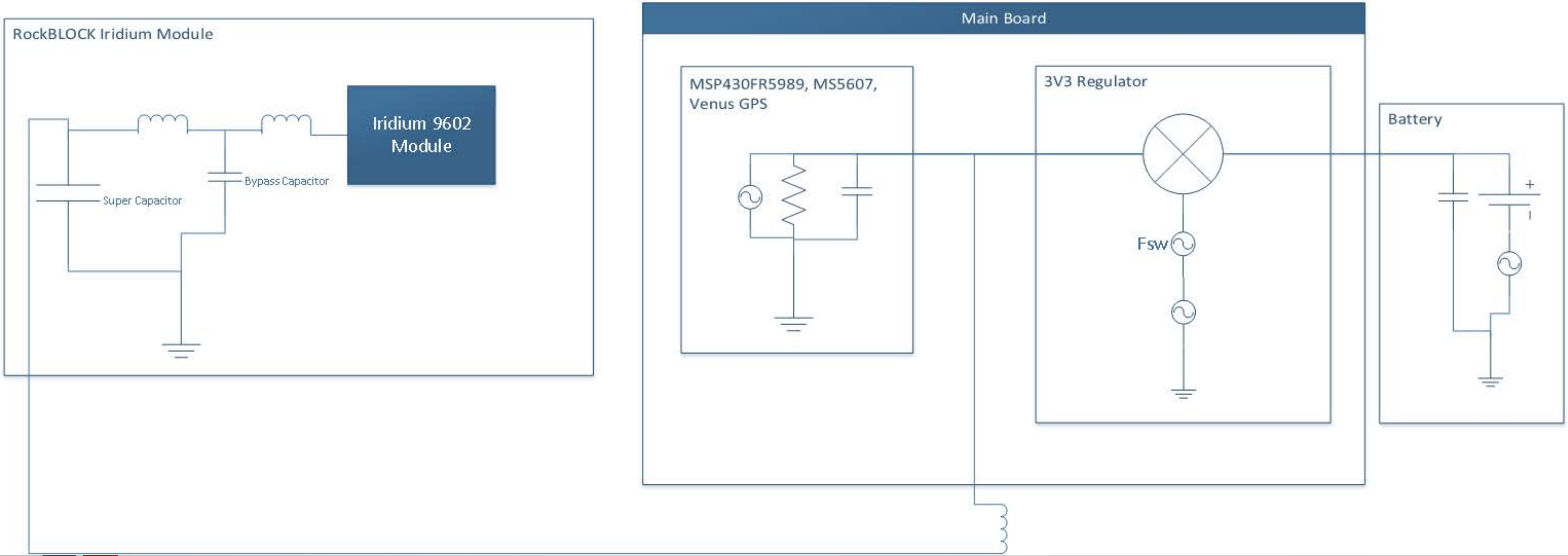

Mitigation and Results

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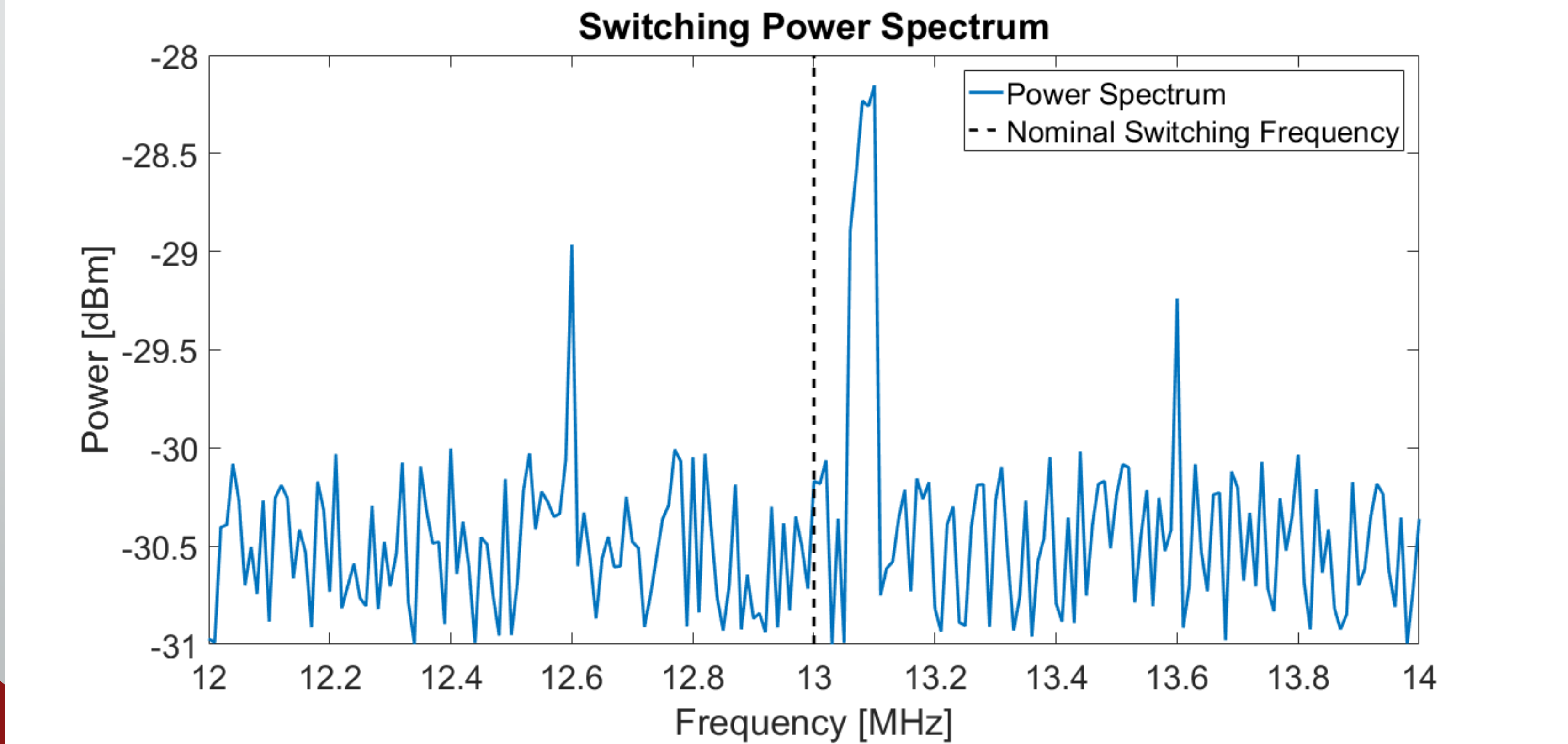
Issues Identified:

- RockBLOCK bias line incorrectly implemented by manufacturer
- Injection locking regulator switching frequency

Mitigation:

- Adjust RF drain Capacitor to 10pF
- Add 180 Ohm Ferrite to board wiring
- 200 [mV] Measured Ripple (from 1.5 [V])



12V and 3V3 Deployment FETs

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Test Scope:

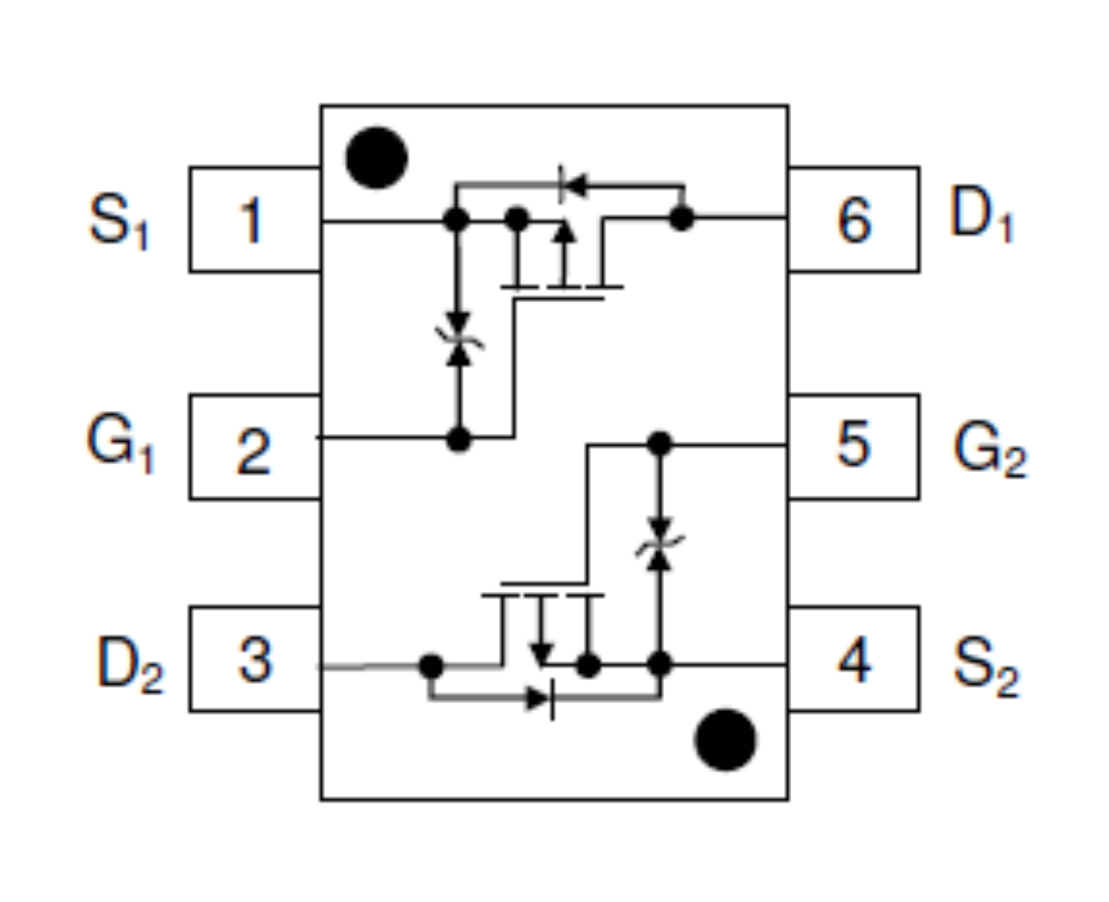
- Determine power handling capability of deployment FETs

Design Requirements:

- Handle 28.4 [W] power transfer to black powder charge
- Handle 12.21 [W] power transfer to each Kanthal coil

Importance of Validation:

Critical to ensuring deployment activities can occur



Initial Subsystem V&V and Integration

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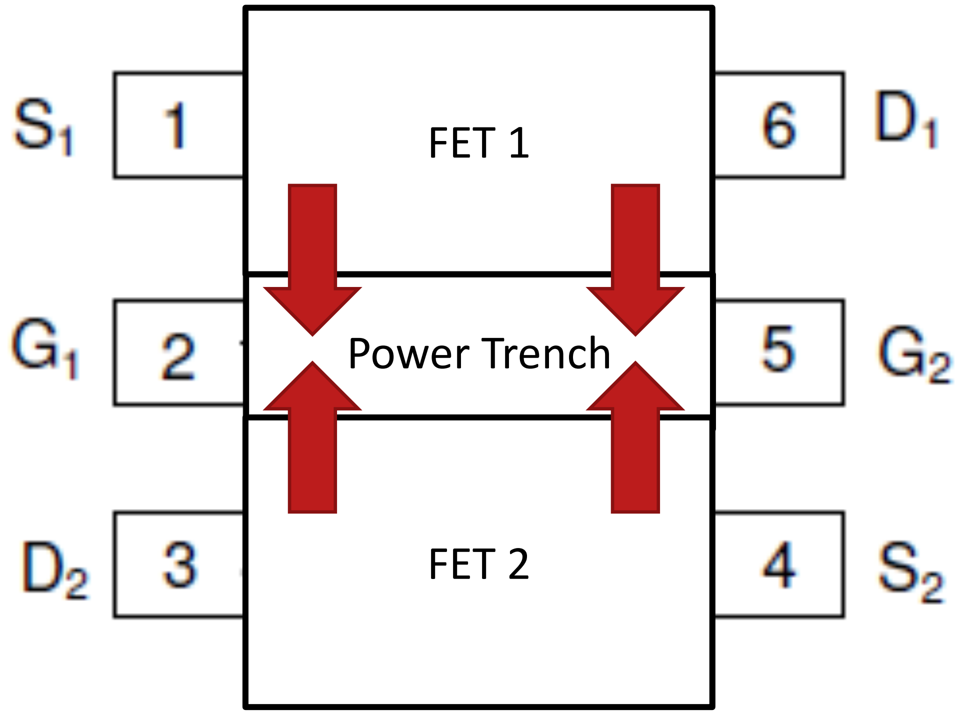
Subsystem Level Validation:

- Handled both Black Powder and Kanthal Coil Deployments successfully [10/10] times with representative load

Integration:

- Failure of the Black Powder Charge FET on test trigger with representative load
- Datasheet assumed one FET grounded for all measurements
- Breakout FET Controller off-ramp used to resolve issue

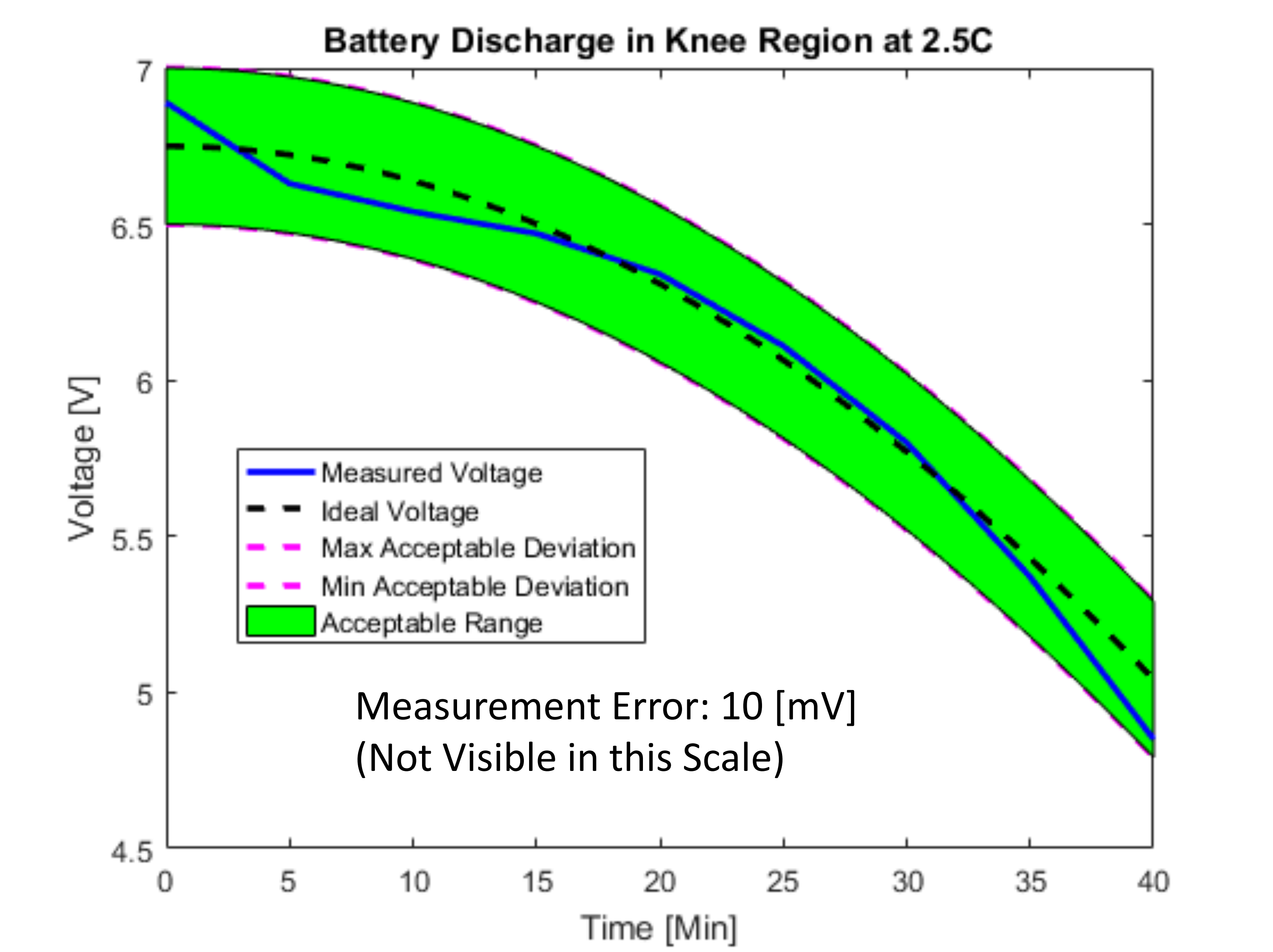
Thermal Expansion of Die Wafers



Final Trench Gap: ~ 2-3 microns

Trench Air Gap Voltage: 6-9 Volts

Battery Performance



Test Scope:

- Li-Ion Battery Stability

Design Requirements:

- Charge-Discharge voltage curve stays within 0.25V of modelled

Importance of Validation:

Battery unit is responsible for providing power to all flight avionics and deployers.

Flight UART and I2C Communication Tests

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Test Scope:

Verify Communication from MSP430FR to the following:

- RockBLOCK Iridium Unit
- Venus GPS Unit
- Power Monitor [x2]
- MS5607 – Pressure Altimeter

Importance of Validation:

- I2C must work to allow altitude and deployment determination
- UART must work to all location determination and transmission

Design Requirements:

- I2C must provide 1Hz Altimeter update rate
- I2C must read power delivered through monitor
- UART Bus 1 must read GPGGA sentence from Venus GPS Unit
- UART Bus 2 must transmit correctly formed packet to Iridium module

Results:

All systems performed according to initial MSP430FR emulator model.

Day-In-The-Life (DITL) – Flight Dress Rehearsal

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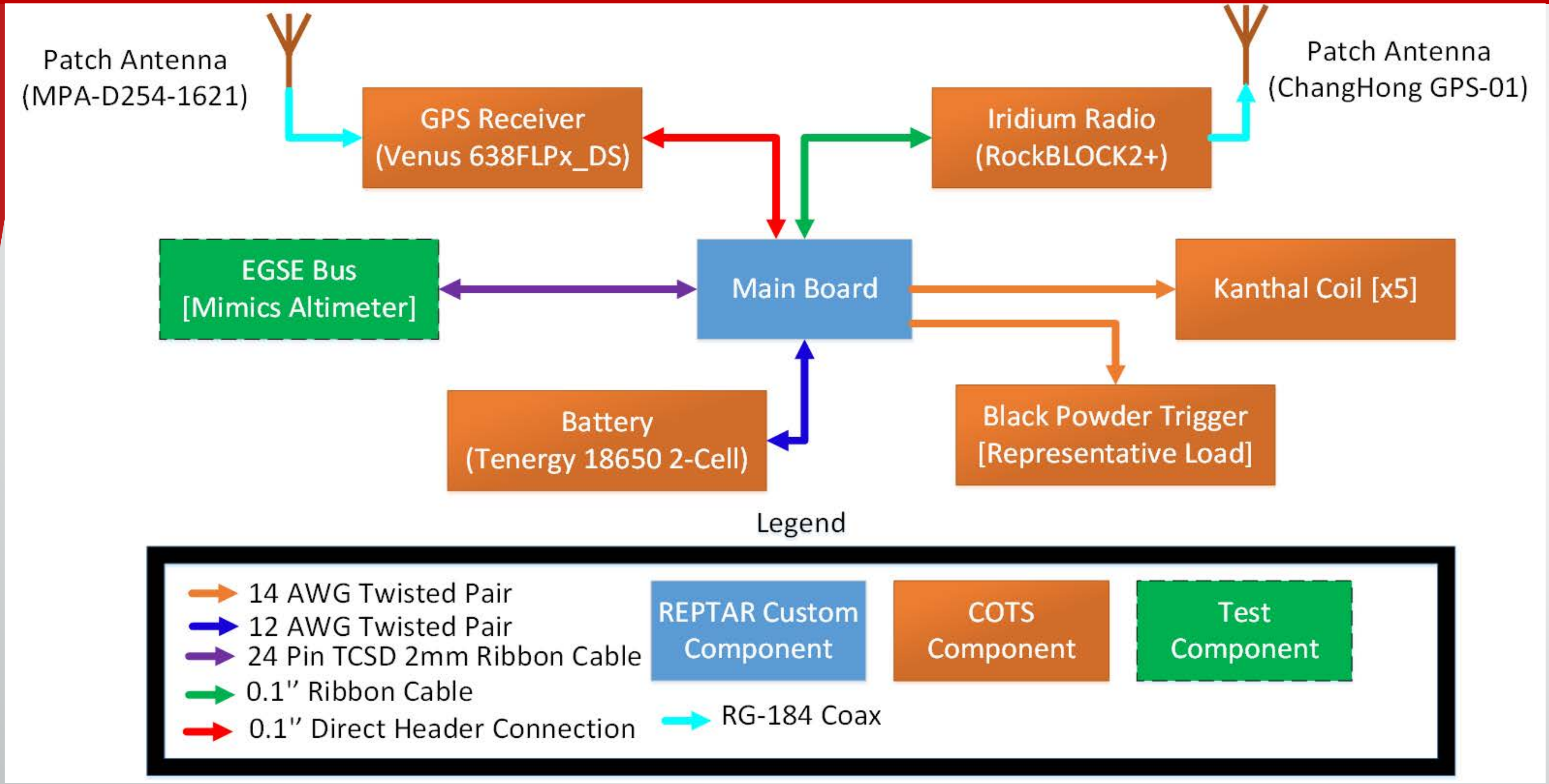


Purpose:

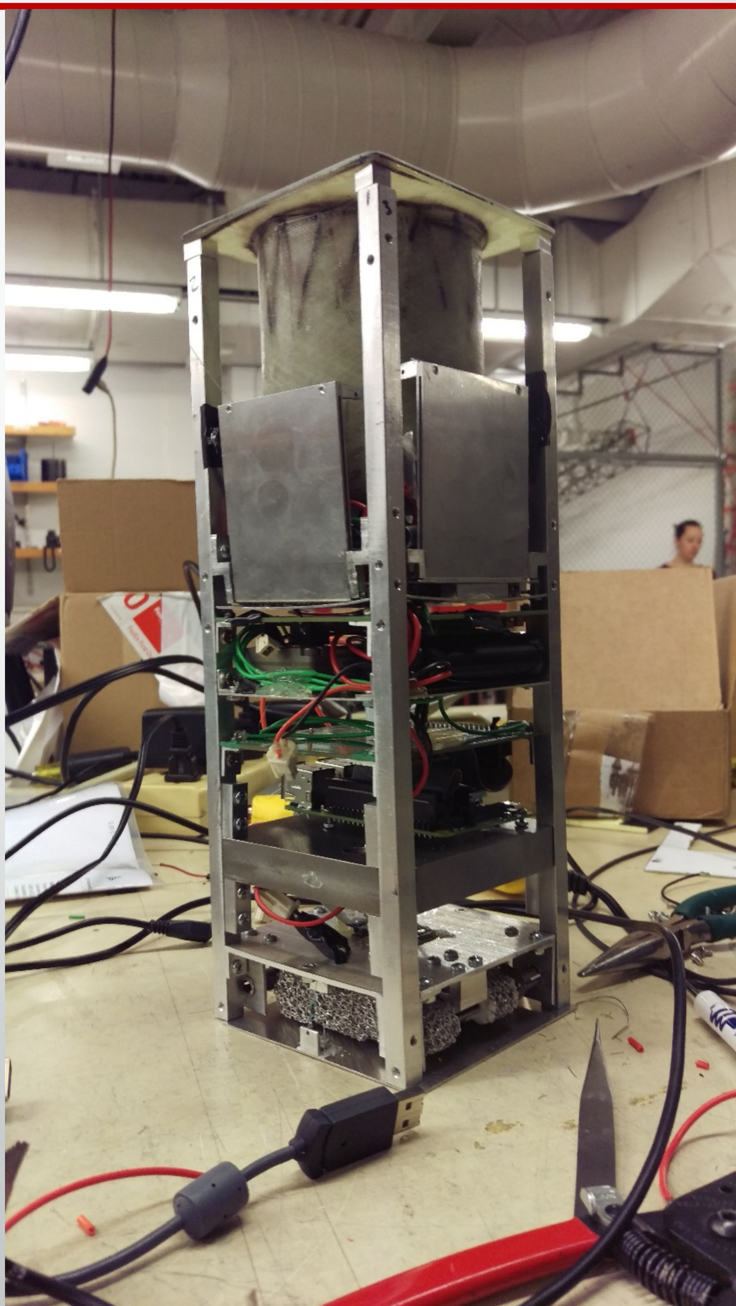
To verify the integrated performance of the Avionics Hardware and Software

Deviations From Test Flight:

- Black powder ignition without parachute
- Altimeter readings from EGSE

DITL Results

- Avionics Day in the Life test performed without incident
  - All components performed as expected after mitigation
- Full System Day in the Life test was not run due to complications
  - Control FET triggers mounted incorrectly
  - 12V grounding through structure
    - Iridium suffered from power supply errors following integration



DITL Impact on Project

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- Not yet proven system as a flight unit
- Sufficient testing validating each subsystem
  - All deployments functioned properly after trigger FET mitigation
- System not yet proven to meet DR 3.1 (Location Transmission)
  - A functional Iridium module would allow DR 3.1 to be met

Systems Engineering

Functional Requirement Flow Down

- **FR.2:** REPTAR shall conform to industry CubeSat Standards
  - Target form factor is a standard 3U CubeSat
  - Volume becomes the constraining factor in design
- **FR.3:** REPTAR shall keep the payload safe during descent and landing phases
  - Assuming a 40 G loading limit as defined by military standard specifications
  - Landing is the clear critical event, other critical events arise dependent on design
- **FR.4:** REPTAR shall be locatable upon landing
  - REPTAR should be locatable for a search team in the UTTR
  - Reliability of communication is prioritized

Systems Engineering Approach

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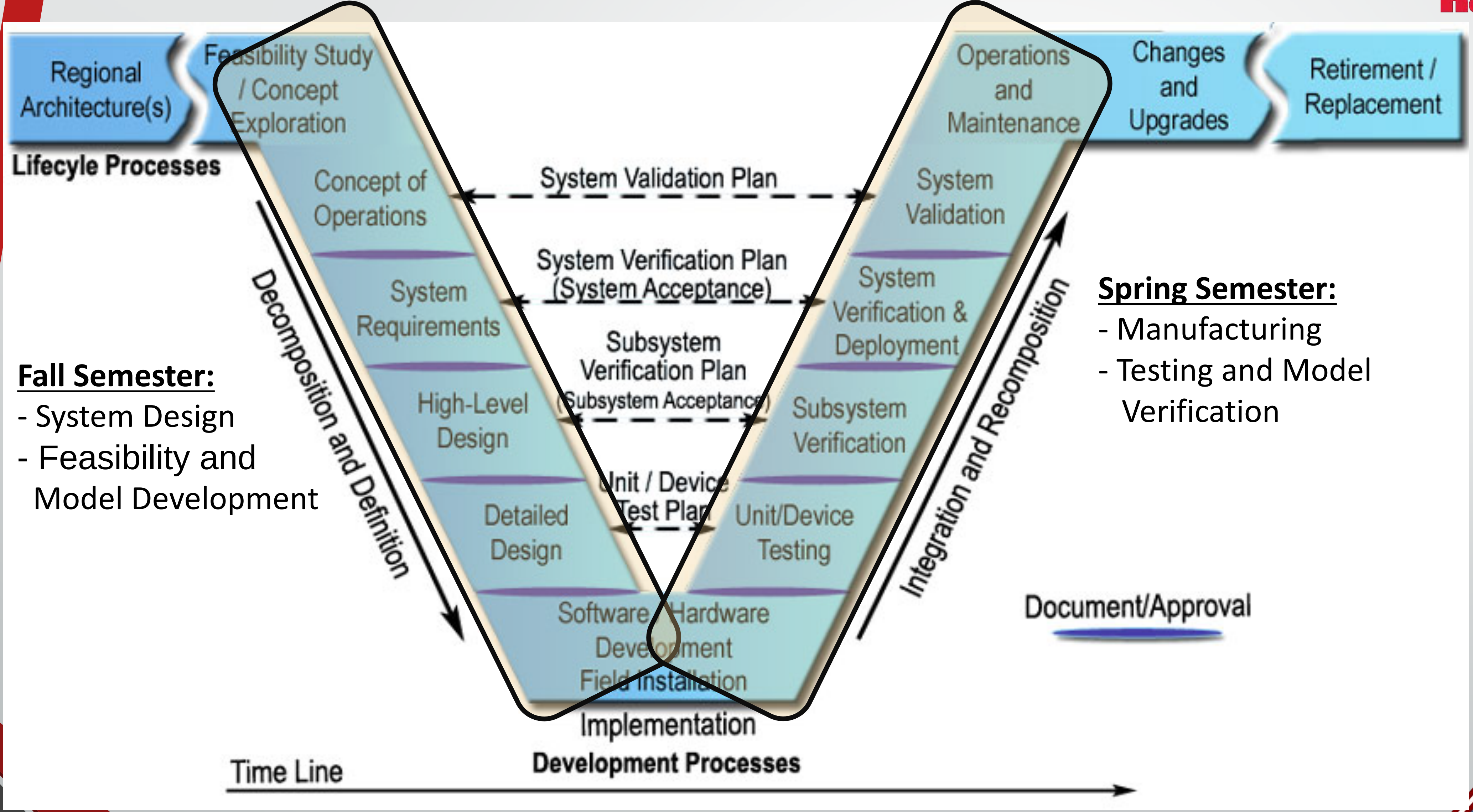

Fall Semester:
- System Design
- Feasibility and Model Development

Spring Semester:
- Manufacturing
- Testing and Model Verification

Fall Semester

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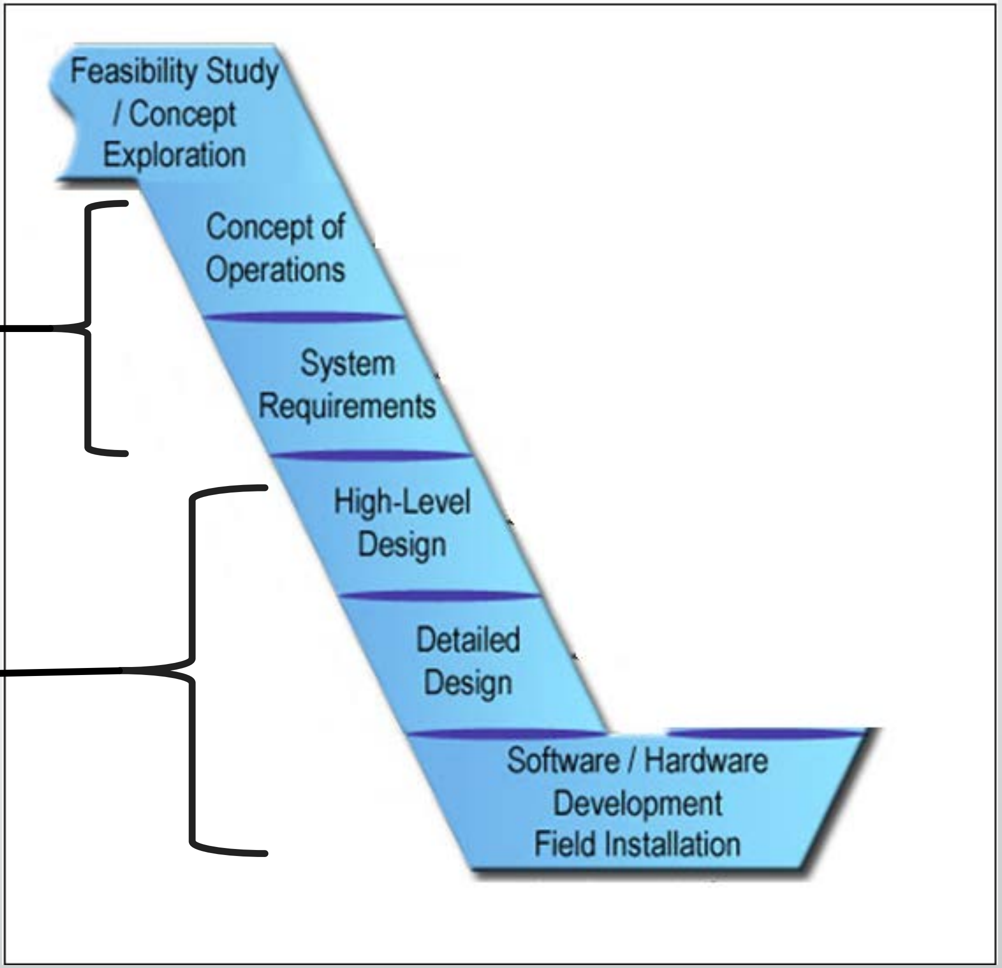
Major Tasks
Define appropriate project requirements and scope
Determine levels of success
Identify feasible designs to accomplish design requirements
Major Issues Encountered
Project initially significantly over-scoped
Customer unclear on project desires and payload interface

Major Tasks
Model parachute black powder ejection
Model antennae characteristics
Model landing impact scenario
Major Issues Encountered
Ensuring proper antennae communication
Meeting volume constraints
Managing work amongst team



Spring Semester

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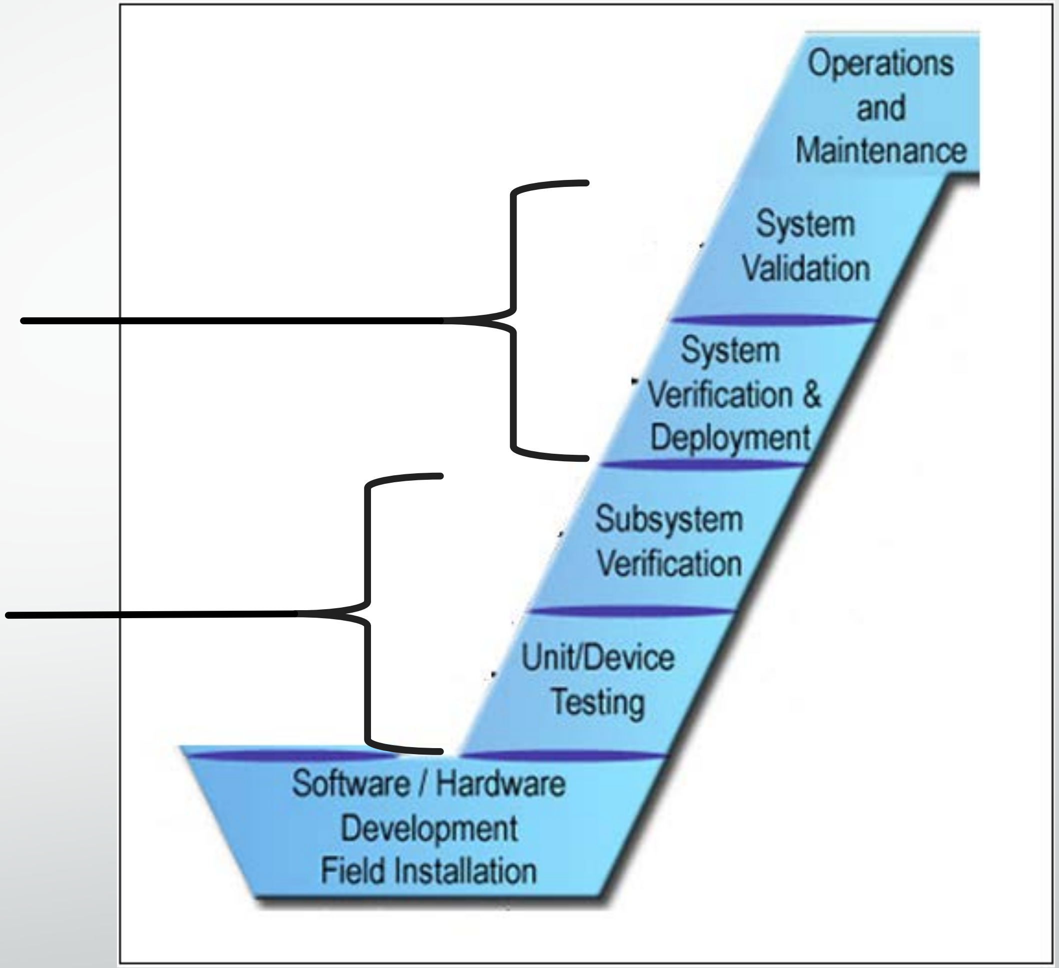
Major Tasks
Integrate full system
Full system test
Major Issues Encountered
Full system integration
Differences between mock system and actual system for avionics

Major Tasks
Manufacture system and test rigs
Perform subsystem testing
Compare and reiterate models to test data
Major Issues Encountered
Difficulties modeling parachute ejection
Failure or lack of backup stock for components



Risk Outcomes

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Risk	Mitigated	Realized
RD1: Black Powder Ignition	✔	
RD2: Insufficient Top Break		✔
RL1: Bottom Leg Fails to Lock	✔	
RL2: Side Panels Fail to Orient		✔
RA1: Antennae Failure	✔	
RA2: Regulator / Battery Overdraw	✔	

- The realized risks were most difficult to mitigate
- Severity of realized risks had minimal impact to project schedule due to design
- Unforeseen risks were the most impactful on schedule

Challenges and Lessons Learned

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- Well defined requirements are necessary
  - Poorly defined requirements introduces confusion to system requirements
- Integration and interfacing must be accounted for in design
  - Unaccounted for components can lead to significant redesign
  - Reduces risk as project approaches full system testing
- Off-ramps are critical to project success
  - Multiple issues at subsystem level caused various schedule slips
- Characterize component reliability and complexity
  - COTS components may not perform as expected
  - Custom components may introduce unnecessary complexity

Project Management

Management Approach

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Technical Management

Aaron McCusker – Project Manager
Craig Wenkheimer – Modelling Lead
Himanshi Singhal – Testing Lead

Descent Subsystem

Cody Gondek – Descent Lead
Dustin Fishelman -- Financial Lead

Landing Subsystem

Calvin Beuchler – Landing Lead
Kevin Faggiano – Manufacturing Lead
Lee Huynh – Systems Lead

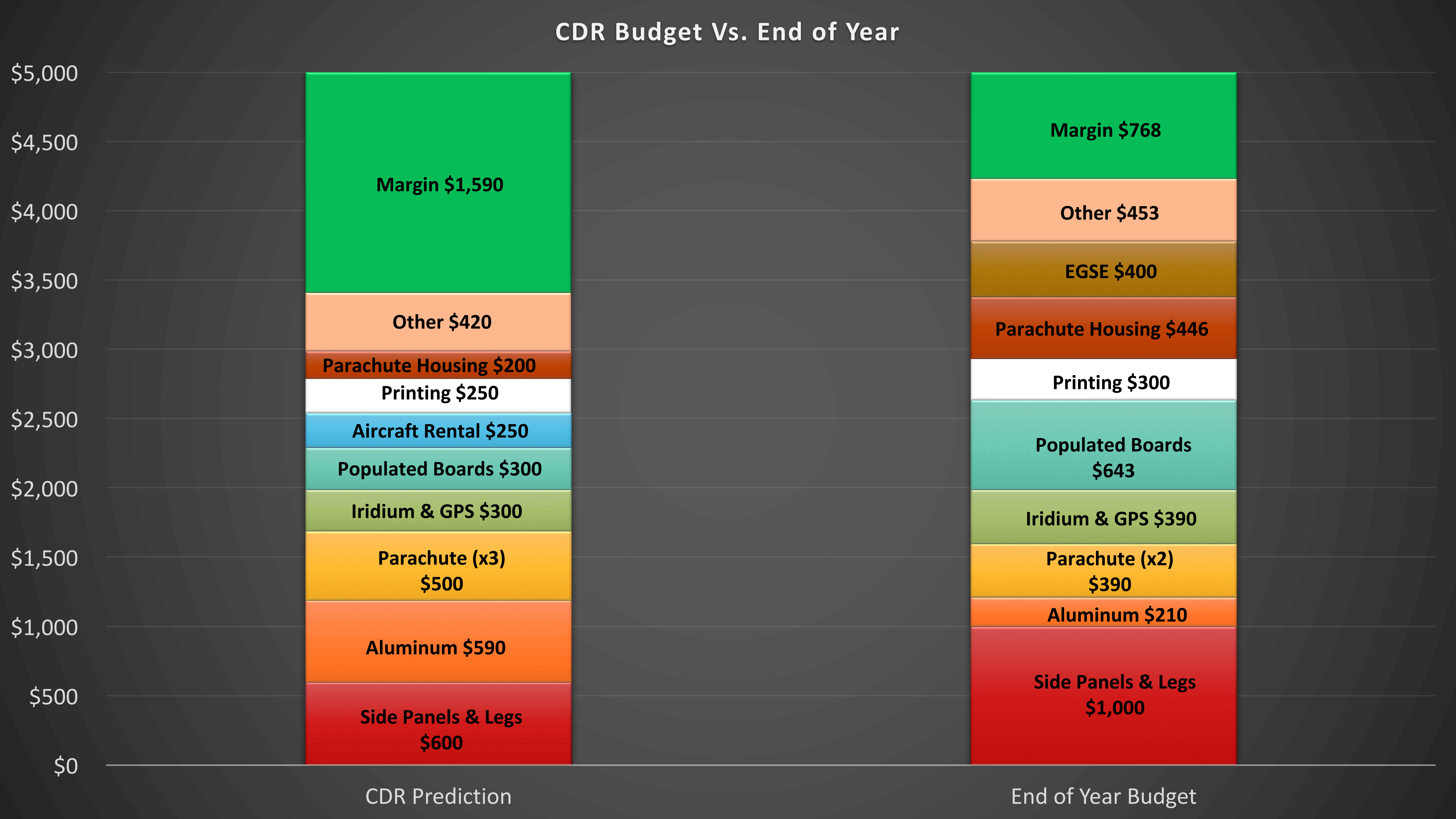
Avionics Subsystem

Will Sear – Avionics Lead
Nathan Yeo – Software Lead
Lee Huynh – Systems Lead

- Break team into 3 subsystem teams
  - Mission had 3 unique tasks, allowed team members to focus on single mission task
- Identify and assign team members to critical tasks
  - Primarily allows autonomy while still accomplishing critical tasks
- Employ team members in accordance with their talents
  - Let each team member work to their own strengths

Management Lessons Learned

- Scheduling can be extremely difficult to predict
  - Some tasks were accomplished much quicker than anticipated, some took weeks longer than anticipated
- Tasks must be defined in a way where help can be supplied if needed
  - Team members became knowledgeable about their complex systems, but outside help could not be supplied if needed due to lack of experience with system
- Specific tasks need to be assigned to individuals, not to subsystem teams
  - Tasks were not accomplished efficiently because teams took time determining who would do which task



CDR Budget Vs. End of Year
$5,000
$4,500
$4,000
$3,500
$3,000
$2,500
$2,000
$1,500
$1,000
$500
$0
Margin $1,590
Other $420
Parachute Housing $200
Printing $250
Aircraft Rental $250
Populated Boards $300
Iridium & GPS $300
Parachute (x3) $500
Aluminum $590
Side Panels & Legs $600
Margin $768
Other $453
EGSE $400
Parachute Housing $446
Printing $300
Populated Boards $643
Iridium & GPS $390
Parachute (x2) $390
Aluminum $210
Side Panels & Legs $1,000
CDR Prediction
End of Year Budget

Industry Cost

Assumptions:

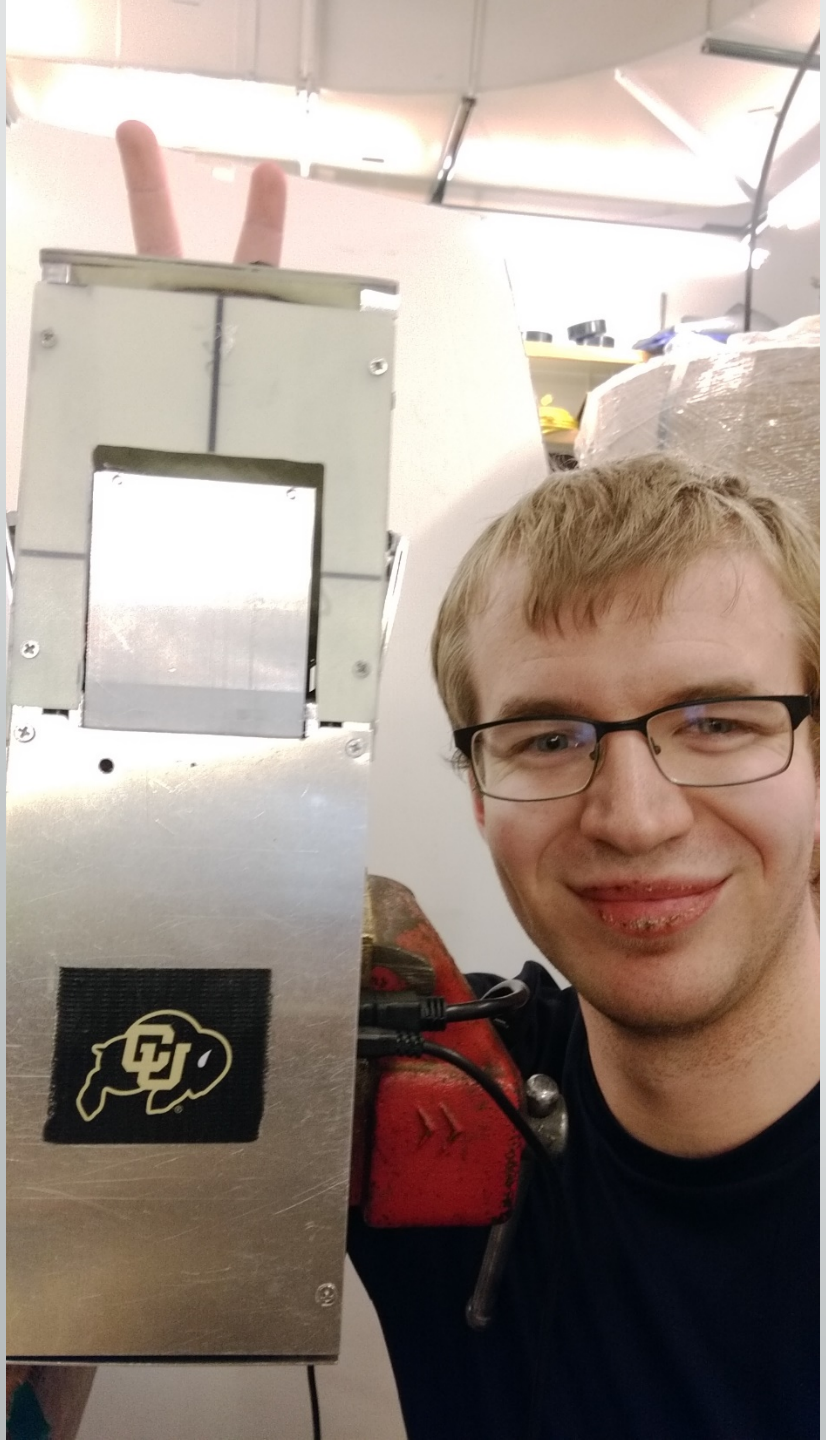
- $65,000 annual salary of entry-level aerospace engineers, 2080 hours per year
- Overhead rate of 200%

Total Hours	4,560 hours
Total Direct Labor Cost	$143,500
Overheard Percentage	200%
Overhead Cost	$285,000
Materials Cost	$4,000
Total Industry Cost	**$432,500**

Acknowledgments

REPTAR would like to thank:

- Steve Thilker, Collin Baukol, Cody Humbargar, and Raytheon Company
- Dr. Brian Argrow
- Dr. James Nabity
- Trudy Schwartz, Matt Rhode, Bobby Hodgkinson
- Dave Zader
- The Project Advisory Board



Questions?

Budget Comparison

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CDR Prediction	Cost	Actual Purchases	Cost
Parachute (x3)	$500	Parachute (x2)	$390
Fiberglass Tubing	$100	Fiberglass Tubing	$293
Ejection Canister (x25)	$100	Ejection Canister (x75)	$153
Aluminum Sheets	$190	Aluminum Sheets	$110
Side Panel and Leg Manufacturing	$600	Side Panel and Leg Manufacturing	$1000
Aluminum Foam	$400	Aluminum Foam	$100
Iridium RockBlock2+ and GPS	$300	Iridium RockBlock2+ and GPS	$390
Populated Boards	$300	Populated Boards	$643
Aircraft Rental	$250	Aircraft Rental	$0
Printing	$250	Printing	$300
Other	$420	Other	$853
Total	**$3,410**	**Total**	**$4,232**

Battery and Regulator Statistics

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Parameter	Battery
Pack Configuration	2 Panasonic NCR18650BF cells in series
Pack Voltage	7.2 V (3.6V per cell)
Max Discharge	10 A
Internal Resistance	154 mOhm (77 mOhm per cell)
Capacity	3350 mAHr

Parameter	3V3 Avionics	3V3 Deployer	12V Deployer
Efficiency	80%	93%	92%
Max Current	1.2 A	8 A	10 A
Junction Temperature Max	100 C	125 C	120 C
Part Number	MCP1632	LTC1775	LTC3786

Battery and Regulator Performance

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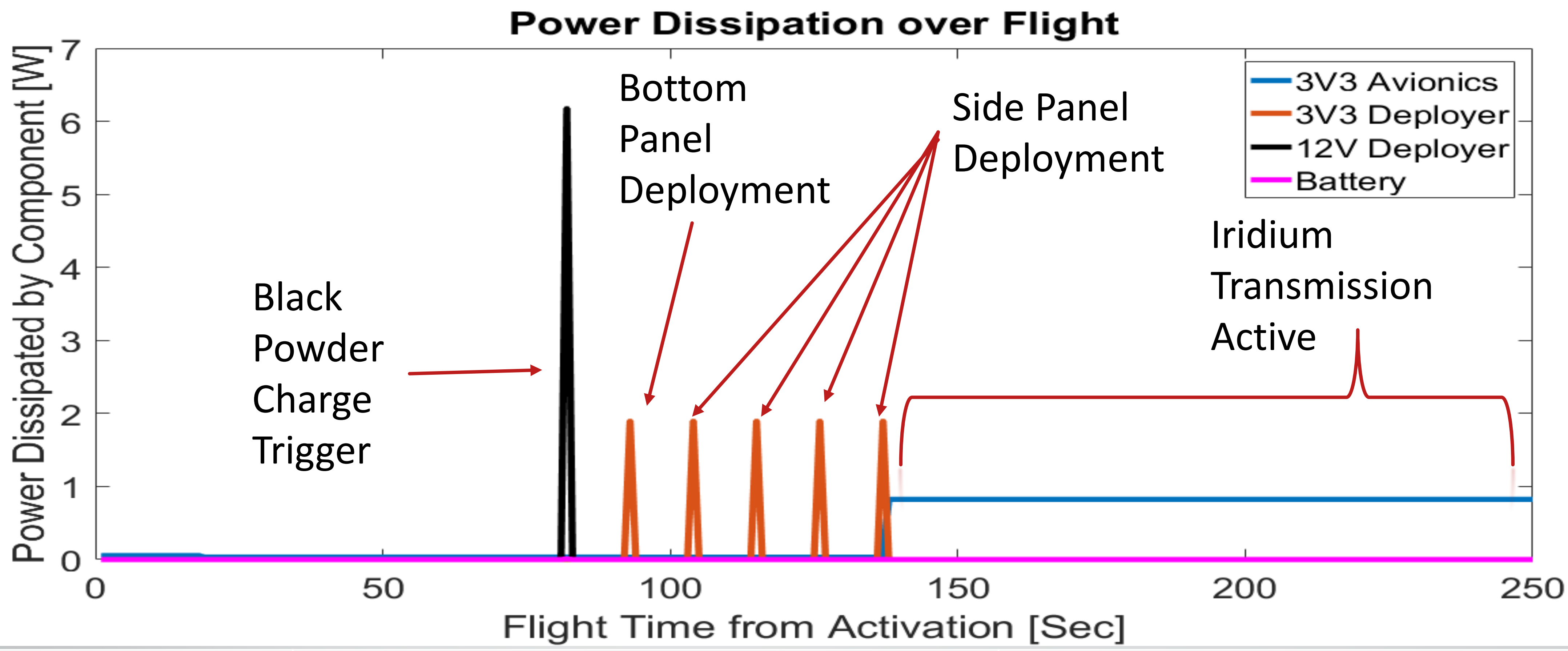

Regulator	Max Rated Junction Temp. [C]	Max Modelled Junction Temp. [C]
3V3 Avionics	125	85
3V3 Burn Wire	125	100
12V Black Powder	125	120

Full System Drop Test

Full System Drop Test

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Scope	Drop REPTAR from airplane in controlled environment	• Requires aircraft, large drop zone
Rationale	Full system drop test is the culminating test that provides proof of concept and full integration testing	• Testing high speed parachute deployment • Location determination during descent • G-Loading profile
Risk Reduction	Reduces risk by validating in-flight performance before real flight with expensive payload	

Drop Test Logistics

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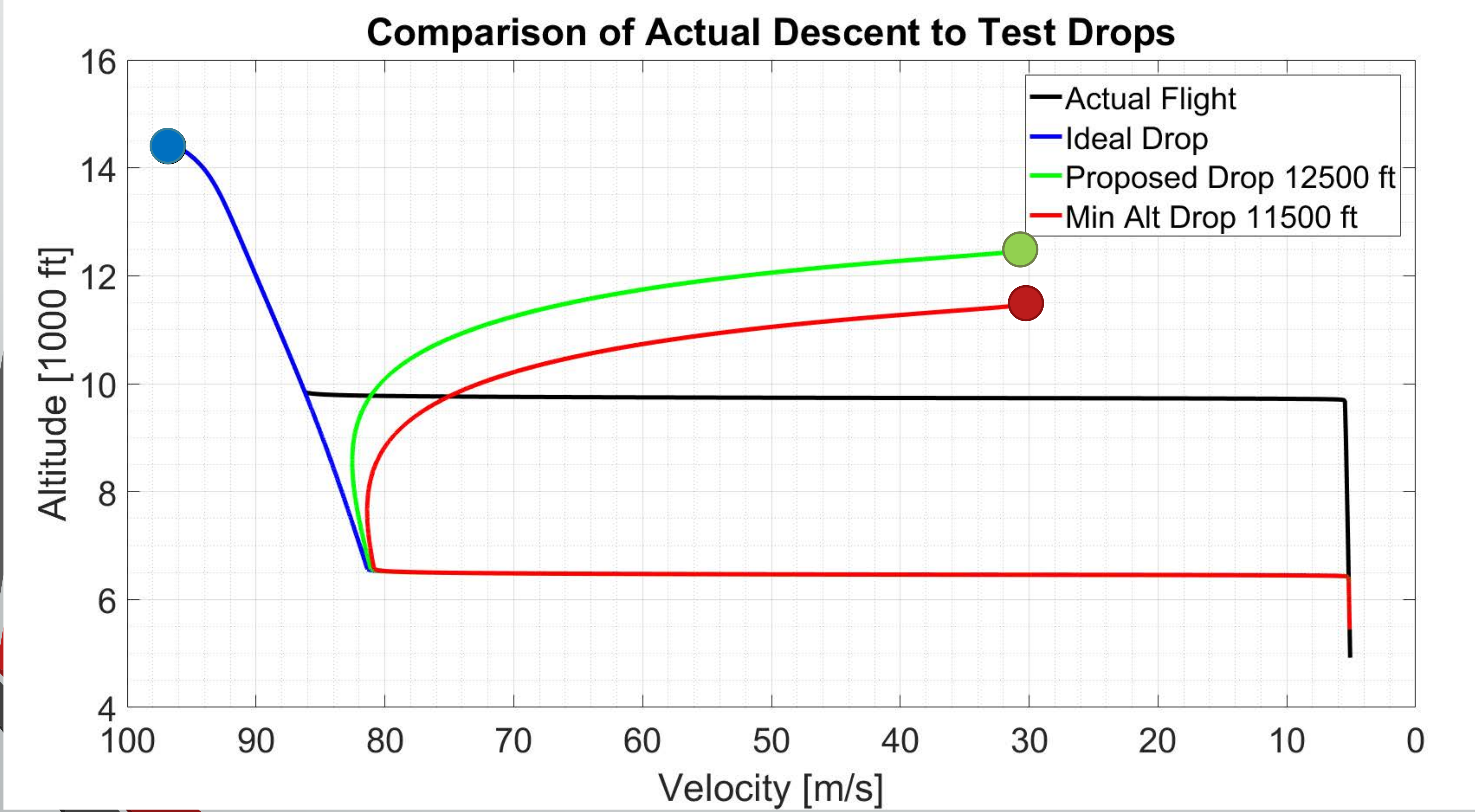
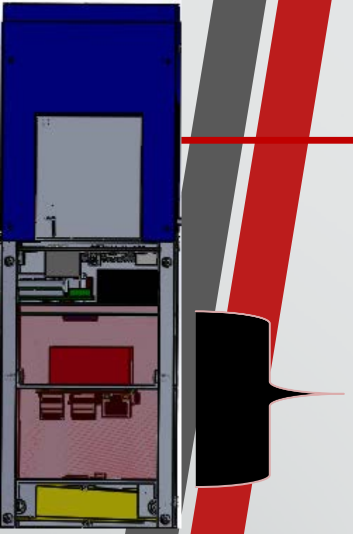


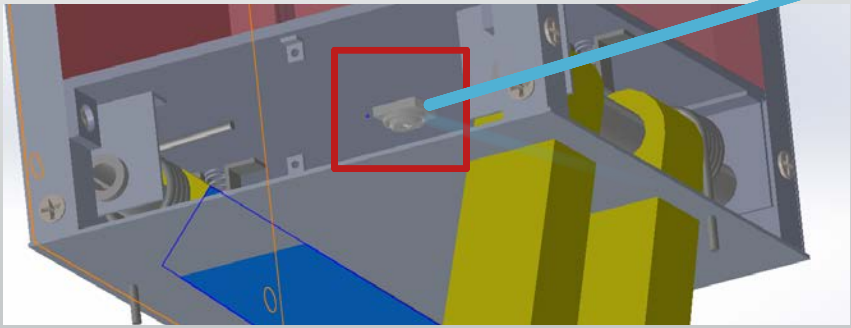
Drop Test Measurement Unit

REPTAR

Raytheon



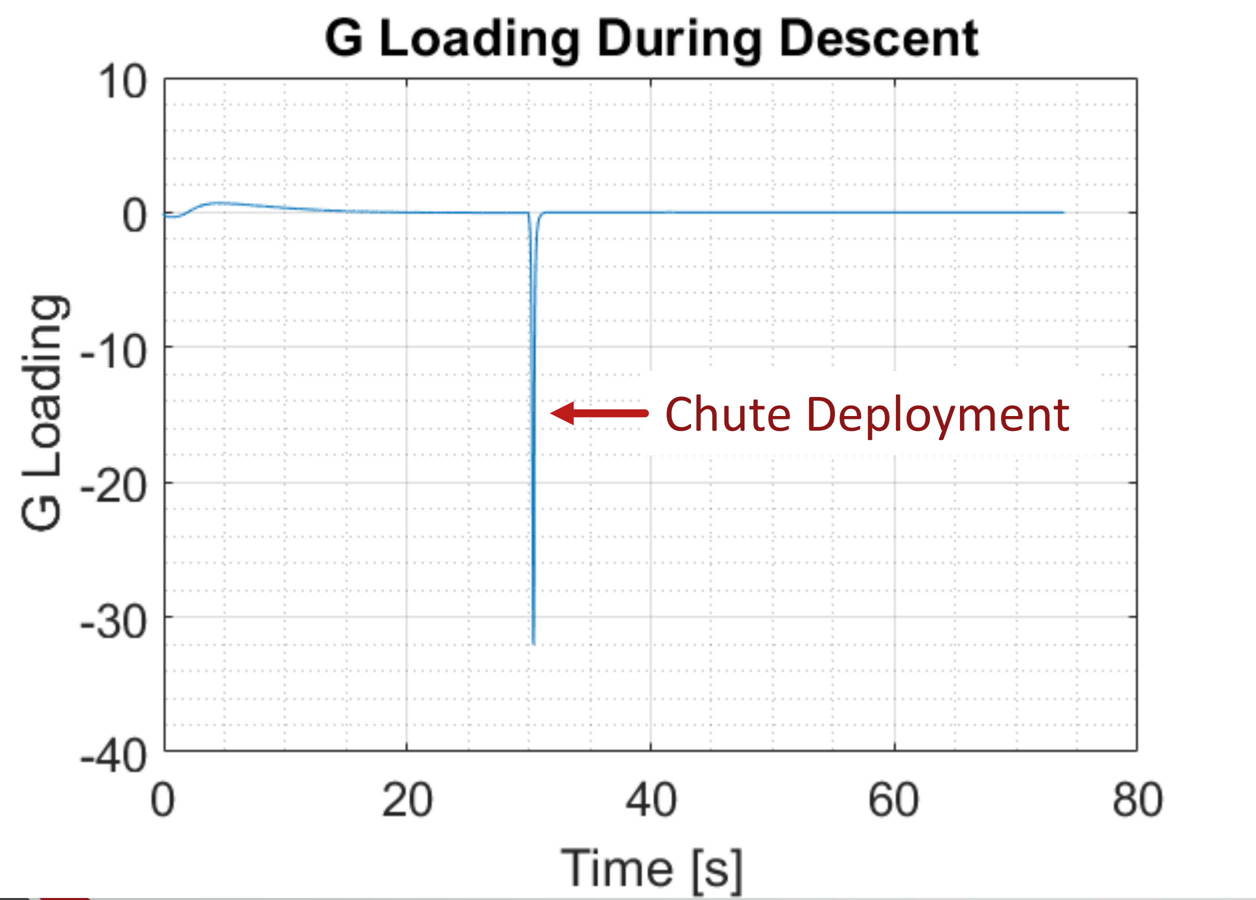
- Where?
  - Housed where Raytheon Payload would be stored in actual mission
- How?
  - Accelerometer (ADXL377, +/- 200G with an error of 1G)
  - Raspberry Pi Camera
- Quantities from the main avionics:
  - Altitude (Altimeter)
  - Location (GPS)
- Mass and Volume
  - Mass: 177 g of instruments + 1157 g of ballast
  - Volume: 1U
- <u>Additional Measurements will be taken from the plane</u>

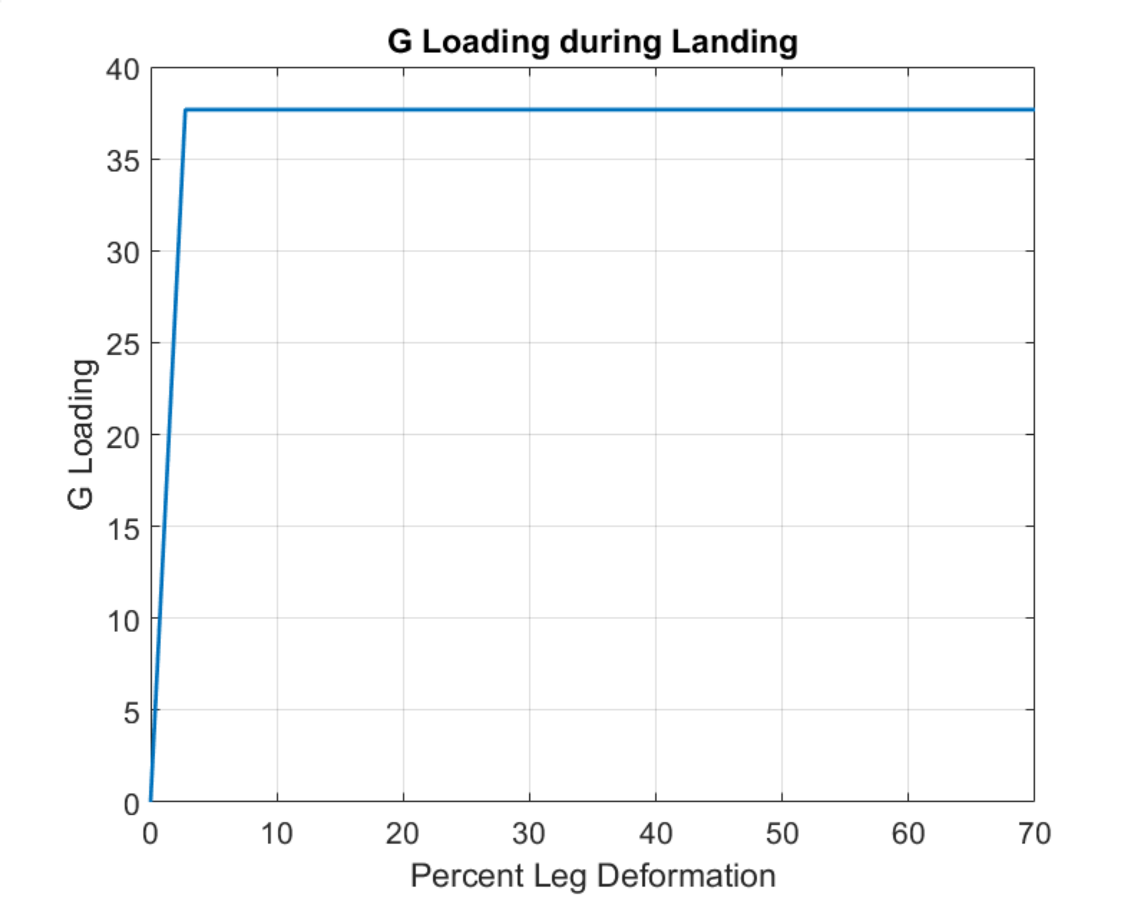


Expected G-Model

REPTAR

Raytheon

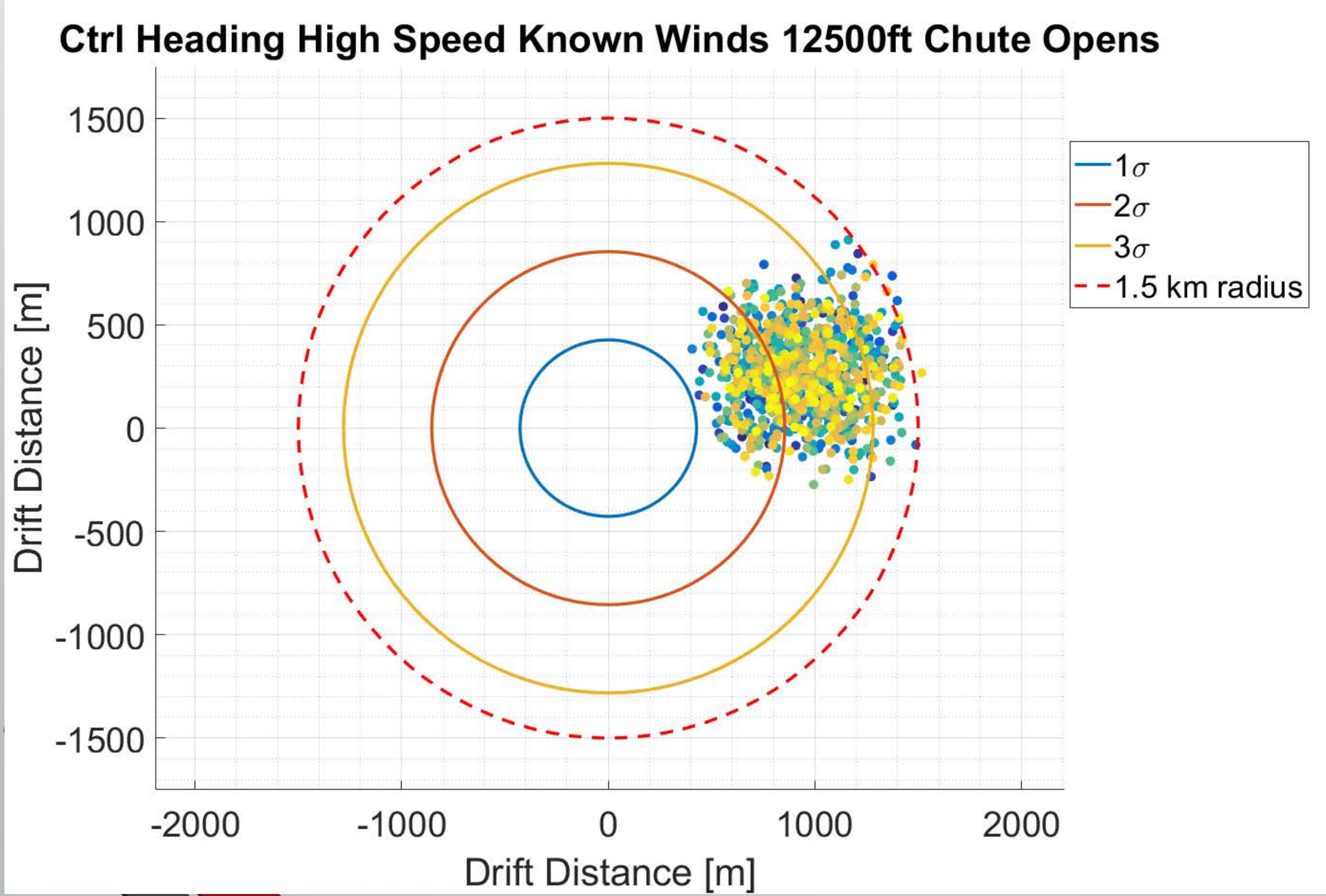




Drift Zone and Recovery

REPTAR

Raytheon



Monte Carlo Parameters

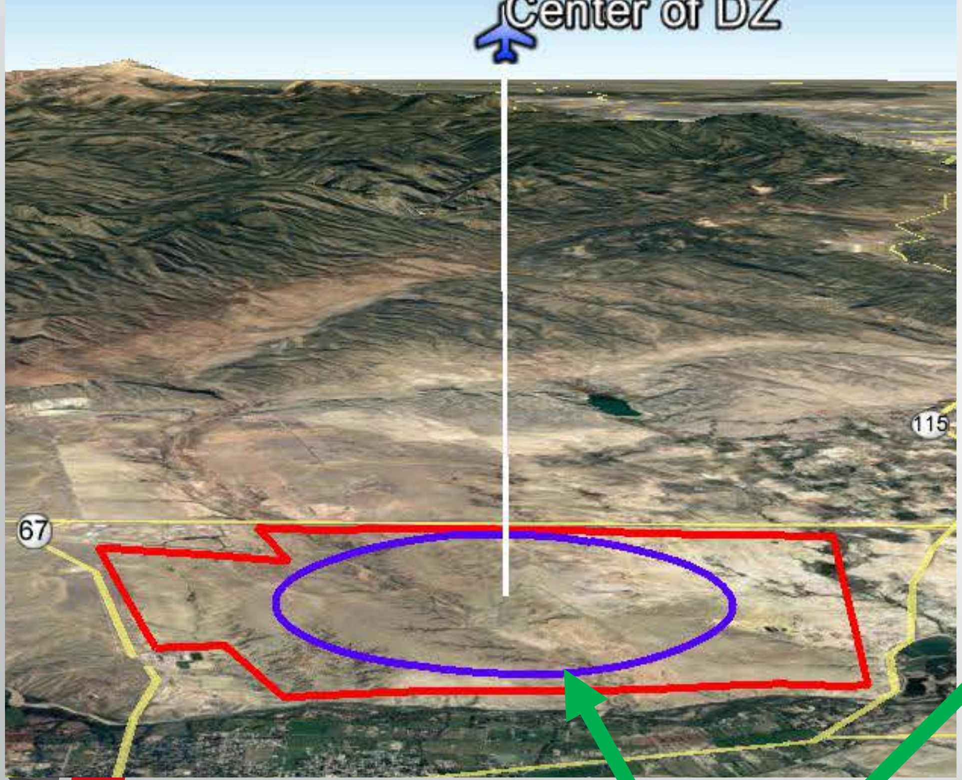
Initial Velocity = 32.0 [m/s]
Initial Velocity Variance = 5.0 [m/s]
Min Alt = 12500 [ft], Alt Variance = 200 [ft]
Heading Range = 20 [deg]
Pos. Variance (x) = 500 [m]
Pos. Variance (y) = 500 [m]
Pos. Shift (x) = -250 [m]
Pos. Shift (y) = -250 [m]
Wind Vel. min = 5 [kts]
Wind Vel. Variance = 5 [kts]
Wind Dir. min = 230 [deg]
Wind Dir. Variance = 40 [deg]
Chute Open Alt Min = 1900 [m]
Chute Open Variance = 200 [m]
Standard Deviation = 213.5 [m]
Known Winds 2520 2530 2540 2545

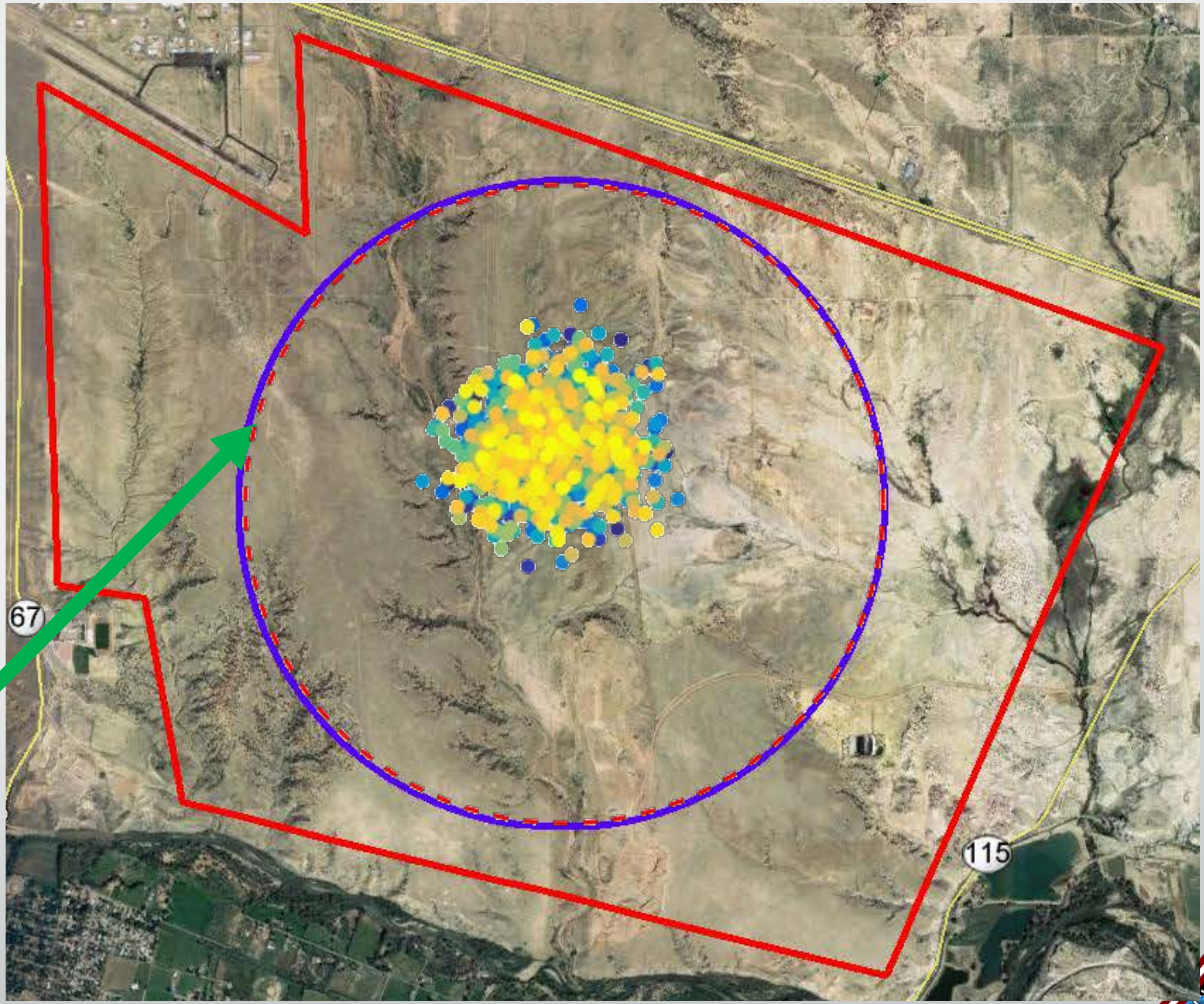
Drop Zone

REPTAR

Raytheon

Entire drop zone is
accessible for recovery





1.5km radius
Reference
Circle

Consequences Table

REPTAR

Quantities	All golden!	Location Transmission Fails	Landing Fails	Parachute Fails	All fail
G's experienced	37	37	52	840	840
Location Determined?	Yes	No	Likely	No	No
Time to Land (s)	~86 s	~86 s	~86 s	~32 s	~32 s
Data survived	Yes	Yes	Yes	Likely	Likely

Post Flight Analysis

REPTAR

Raytheon

Compare:

- G-loading experienced during flight
- Expected drift vs actual drift
- Expected time to land vs actual time to land

Review:

- Leg deployment footage

Summary of Confidence for Drop Test

REPTAR

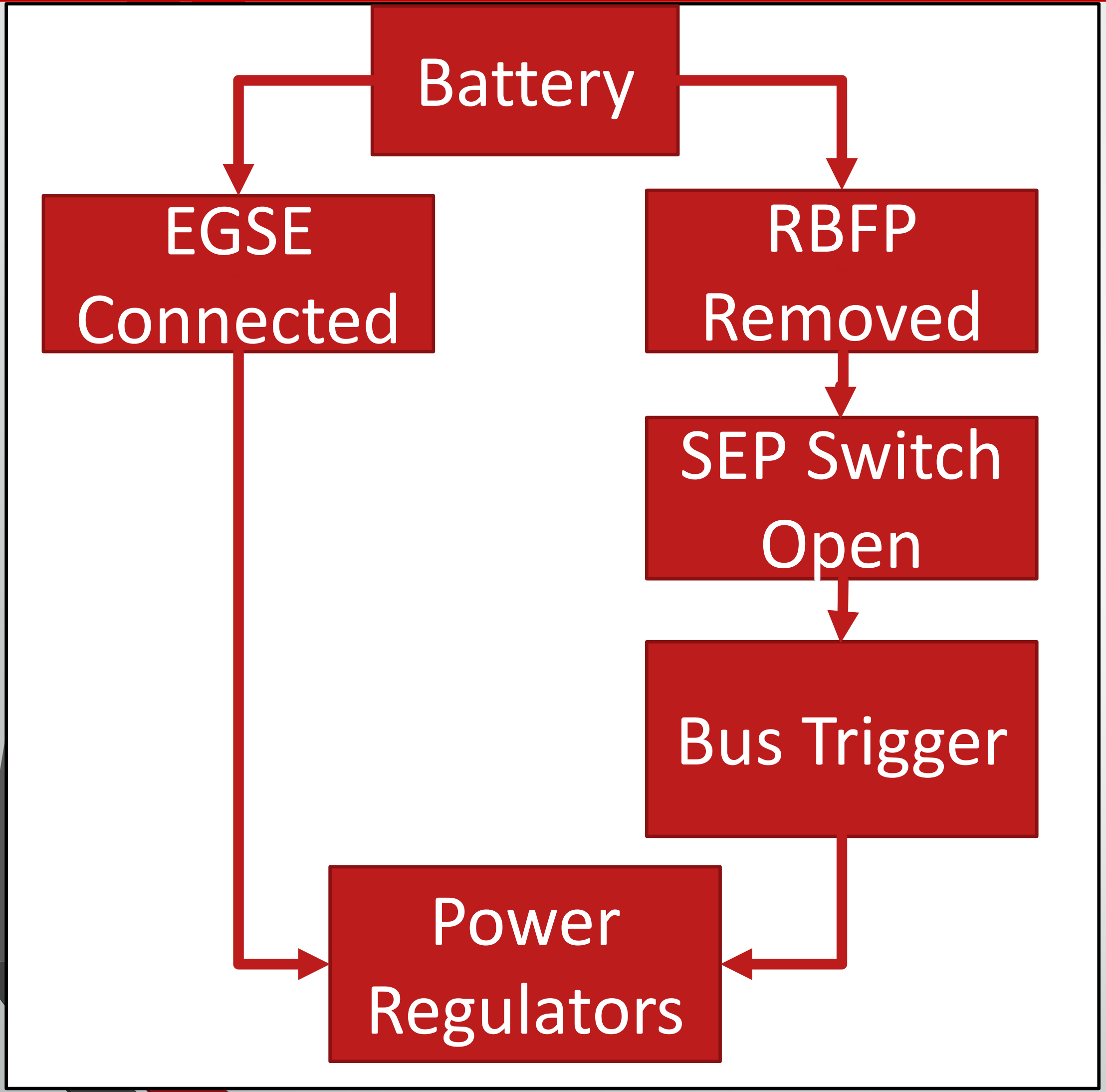
Raytheon

- Descent System:
  - 85% confidence of parachute deployment
- Landing System:
  - High confidence that legs and side panels will properly deploy
  - 95% confidence towards aluminum foam landing characteristics
  - Concerns towards uncontrollable landing environment
- Avionics System:
  - High confidence in avionics system as designed
  - Flight environment can introduce issues in communication
- Overall:
  - Current: 81% confidence that full system will perform successfully in drop test
  - Future: Further testing to reduce variance

Launch Inhibit Considerations

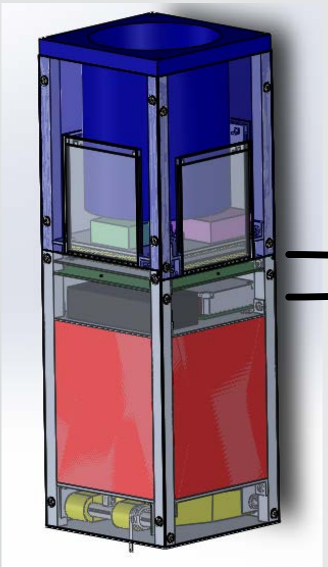
REPTAR

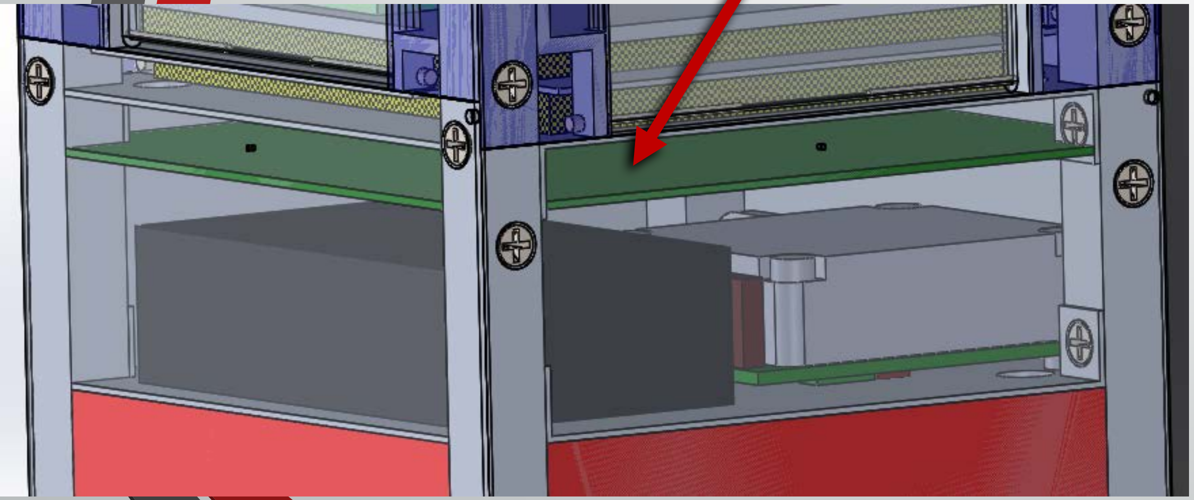
Raytheon



- **CPE**:
  - Interfacing to Deployment Mechanisms
- **Requirements**:
  - FR1: REPTAR shall survive launch and standby phase in space
  - FR2: REPTAR shall conform to industry CubeSat standards
- **Concerns:**
  - None at this time

Altimeter Considerations





- **CPE**:
  - Altimeter Accuracy
- **Requirements**:
  - DR 3.1: REPTAR shall survive an instantaneous G loading of 40 G's
- **Concerns**:
  - Errors – Inherent inaccuracies in CDH subsystem
  - Delays – CDH tasks that take time, during which REPTAR has traveled some distance

CDH Error Stackup

Delay Source	Description	Altitude [m]
Update Delay	Distance traveled between measurement samples	0.8
Transmission Delay	Distance traveled during the transmission from Altimeter to Microcontroller	order of millimeters
Calculation Delay	Distance traveled during a computation cycle of the flight code	0.9
Equilibrium Delay	Distance traveled during the time taken to equilibrate the ambient and internal pressures	1.3
Parachute Delay	Distance traveled during the parachute deployment	1.0
Total		**4.0**

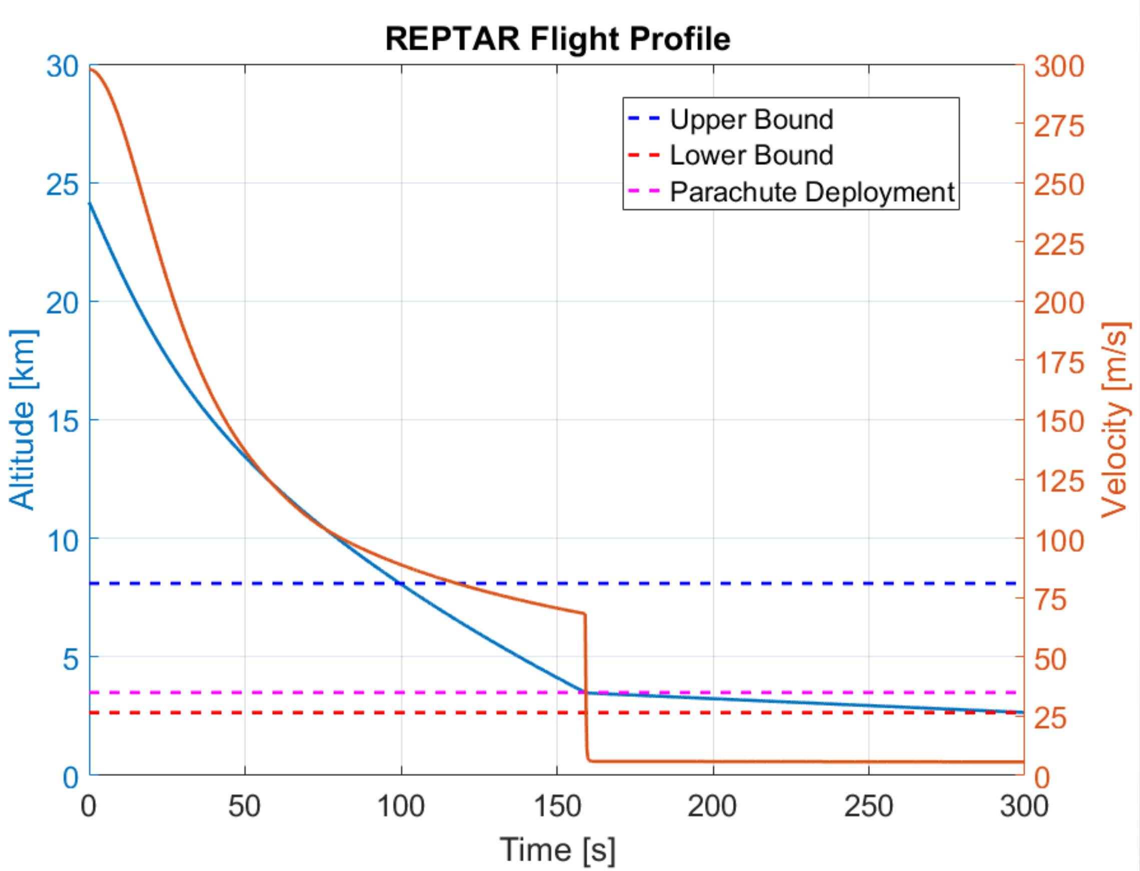
Error Source	Description	Altitude [m]
Altimeter Error	Smallest altitude reading resolved by the altimeter	0.7
Calculation Error	Interpolation error in standard atmosphere lookup tables	5.0
Total		**5.7**

$$h_{margin} = 2\sum h_{delay} + \sum h_{error} = \boxed{\mathbf{13.7\ m}}$$

Key Altitudes

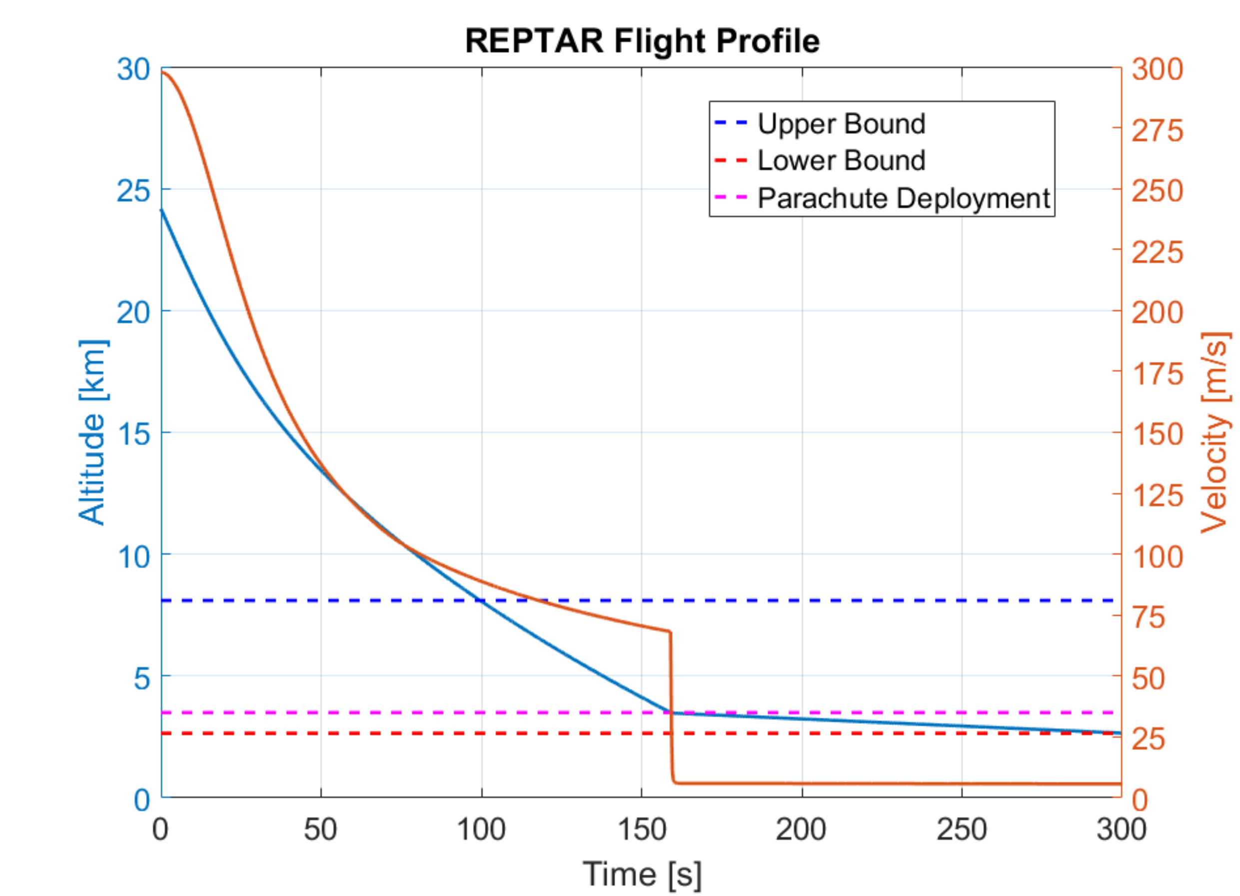
REPTAR

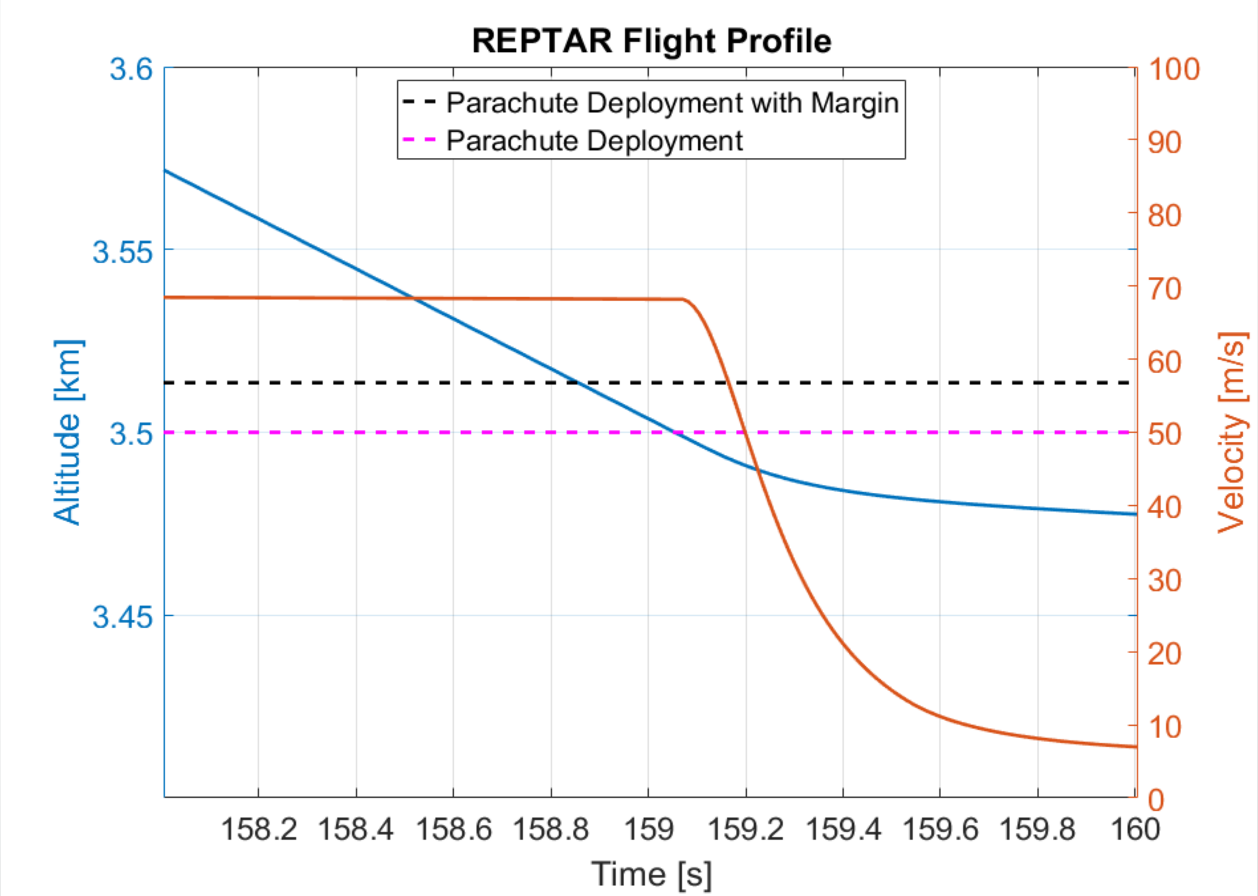
Raytheon



Altitude [m]	Description	Driver
TPS Jettison	Begin altitude sensing	REPTAR terminal velocity becomes subsonic
5900	Upper Bound for parachute deployment	Parachute deployment at higher altitudes induces greater than 40 G's
3513.7	CDH target for parachute deployment	Builds in margin from CDH error stackup
3500	Target for parachute deployment	Factor of safety for deceleration and deployments
3050	Lower Bound for parachute deployment	Not enough time for deceleration or deployments

Key Altitudes



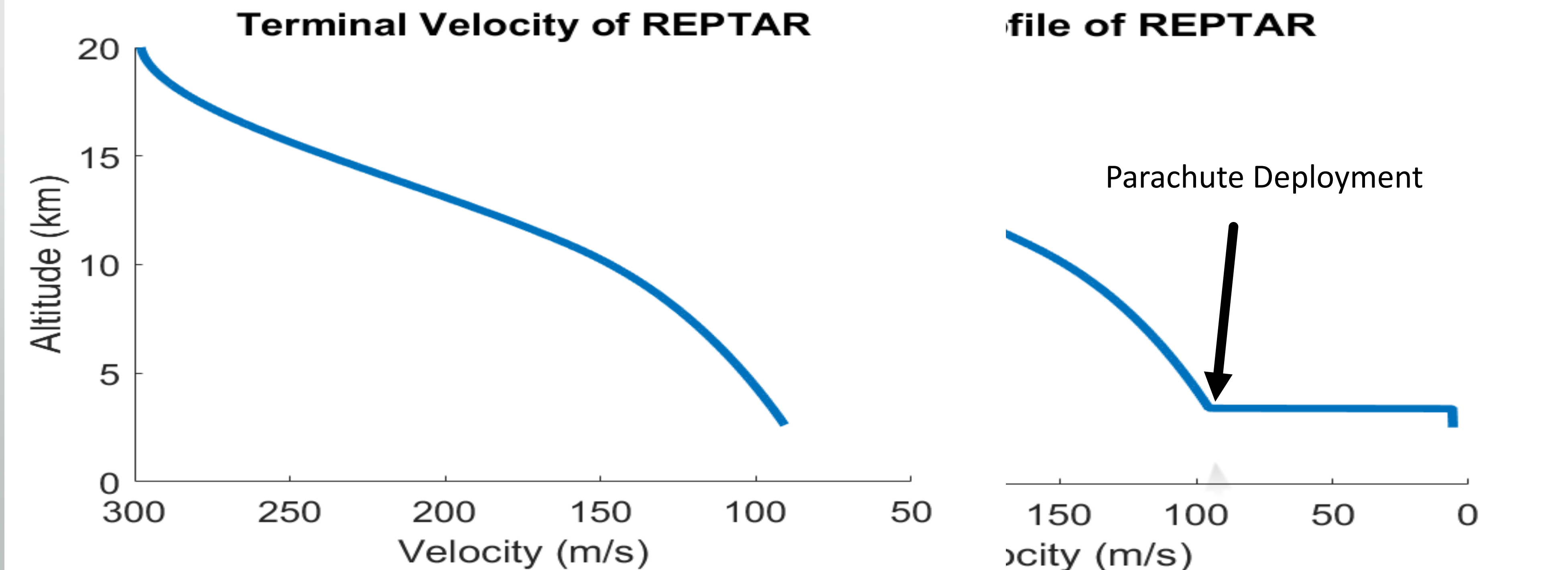


Descent Stage Design

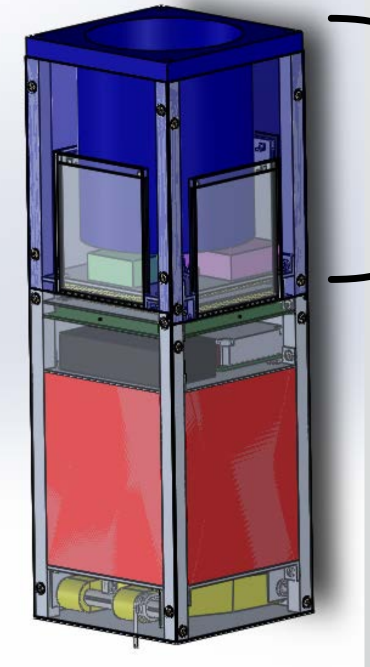
REPTAR

Raytheon

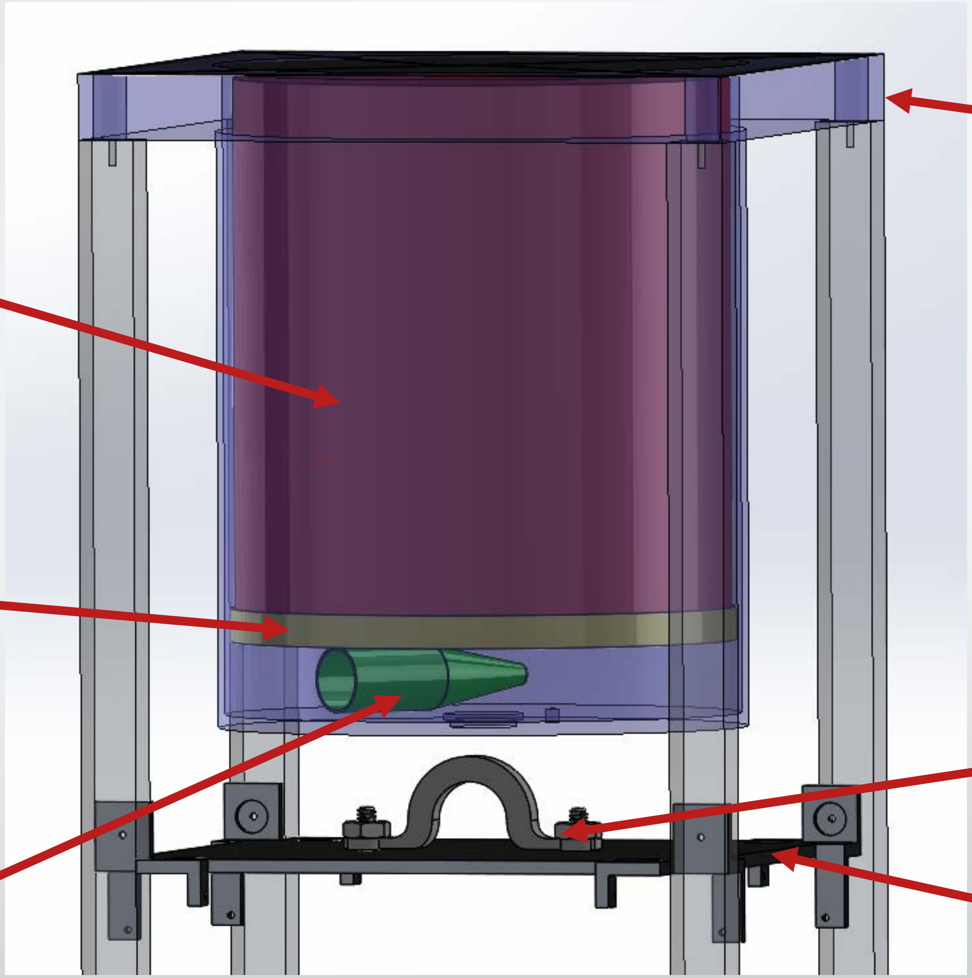
- Without Deceleration: 91 m/s & 840 Gs
- Selected Parachute
  - 48” Diameter
  - Cd = 2.2
- With Deceleration: 5.7 m/s & 53 Gs



Descent Subsystem Design



Descent



Parachute

Thermal Wadding

Ejection Canister

Fiberglass Housing

12.3 cm

U-Bolt

Bottom Plate

Chute Exit Velocity Model Development

REPTAR

Raytheon

e = specific energy of black powder [3MJ/kg]
L= energy losses for pressure, thermal, friction, etc
m_{BP} = mass of black powder
m_c = mass of parachute = 0.122kg
V_c = velocity of parachute
$E = e \cdot m_{BP}$ Total Energy in Control System

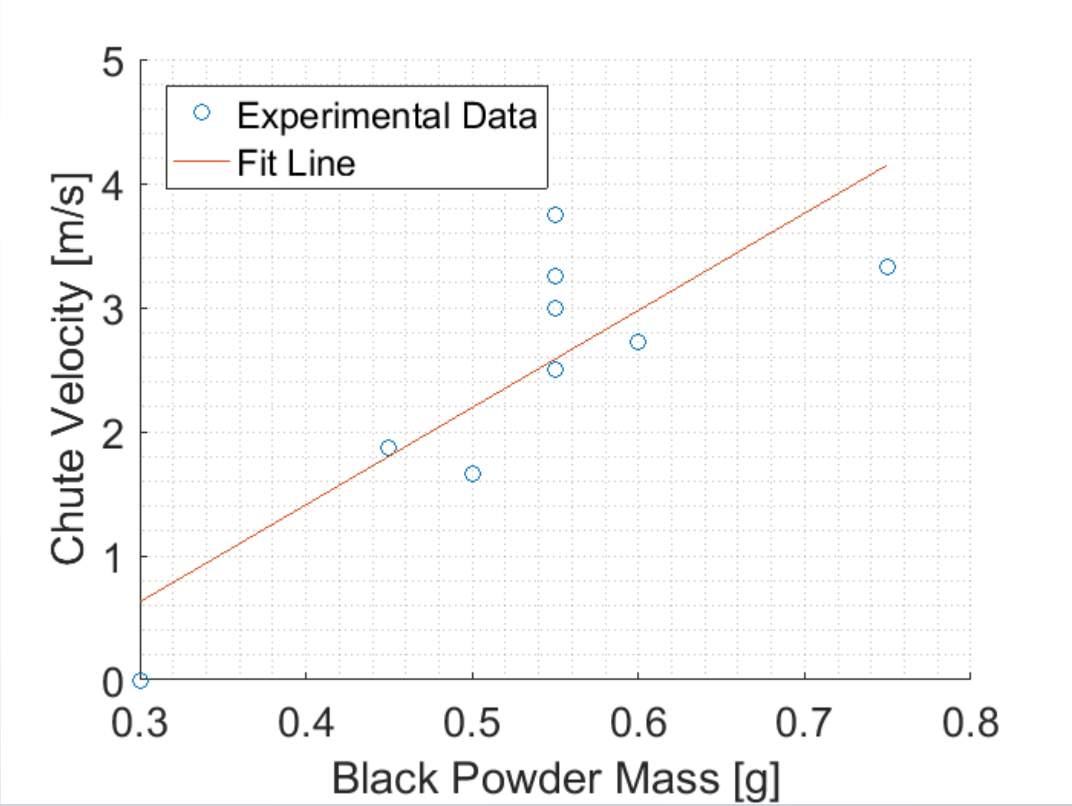
$$e \cdot m_{BP} - L = \frac{1}{2} m_c V_c^2 \qquad V_C = \sqrt{\frac{2(e \cdot m_{BP} - L)}{m_c}}$$

From the regression:

$$V_C = 7831 m_{BP} - 1.7218$$

Setting the velocity equations equal to each other and solving for L

$$L = e \cdot m_{BP} - \frac{m_c}{2}[7831 m_{BP} - 1.7218]^2$$

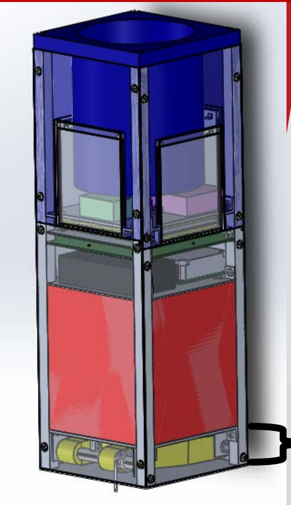


Landing Legs Design

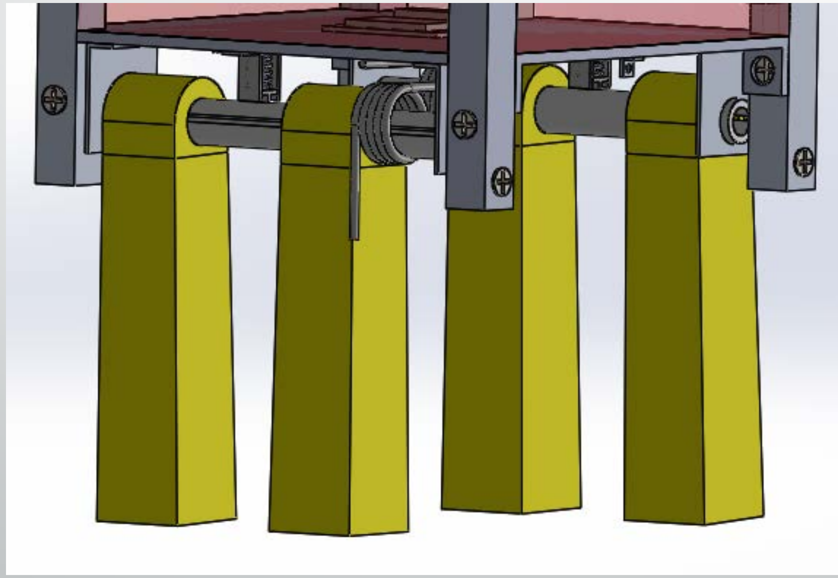
REPTAR

Raytheon

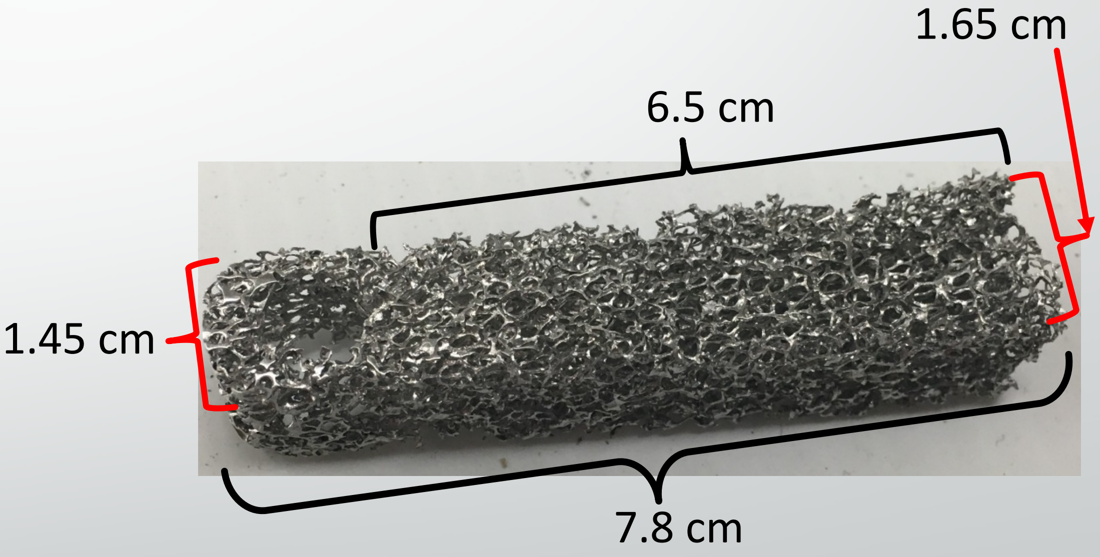
- 4 Legs designed to absorb remaining energy of vertical velocity
- Made of highly compressible aluminum foam
- Deploy and lock using torsional spring system utilizing Kanthal coil



Landing



Deployed System

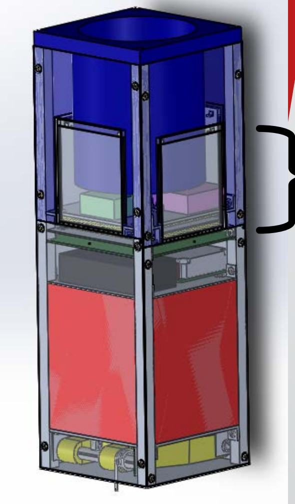


Leg Design

Side Panel Design

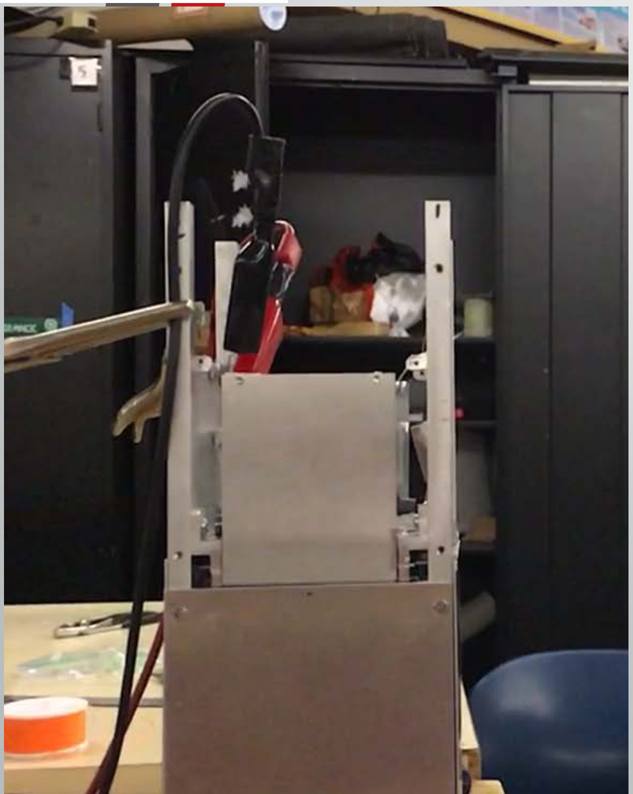
REPTAR

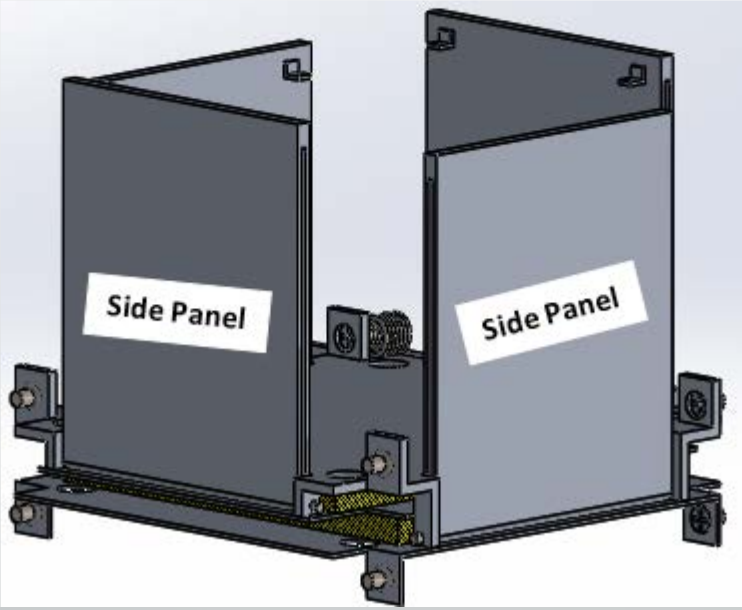
Raytheon



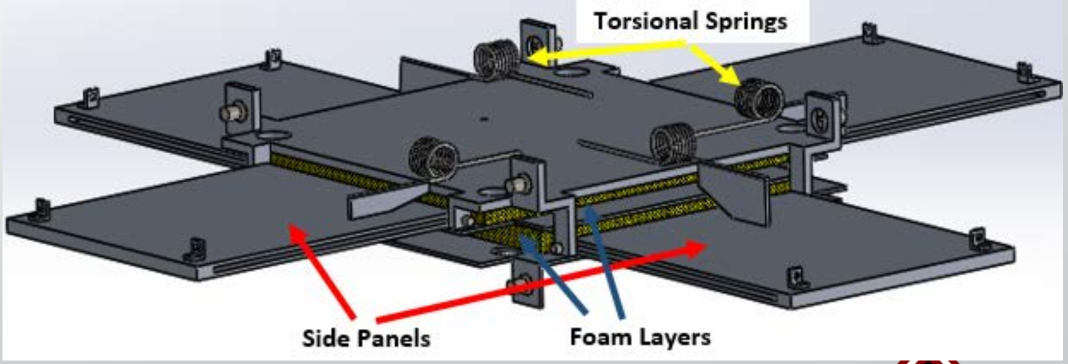
Landing

- Needed to absorb energy due to horizontal velocity on impact due to wind during descent
- Designed to compress aluminum foam stored internally
- Deploy via torsional spring system utilizing Kanthal coil





Undeployed Side Panels



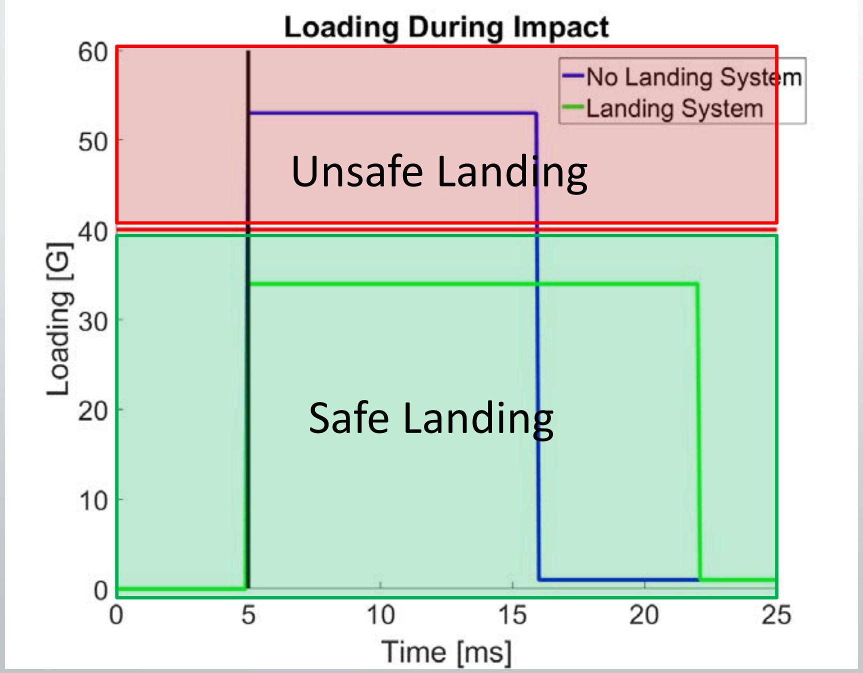
Deployed Side Panels

Landing Stage Design

REPTAR

Raytheon

- Landing subsystem is meant to keep system under 40 G upon impact
- Nominal landing speed of 5.7 m/s from descent subsystem
  - Need to account for high wind speed as well
- Crushable leg structure designed to limit G-Loading during impact
  - Done in both horizontal and vertical directions

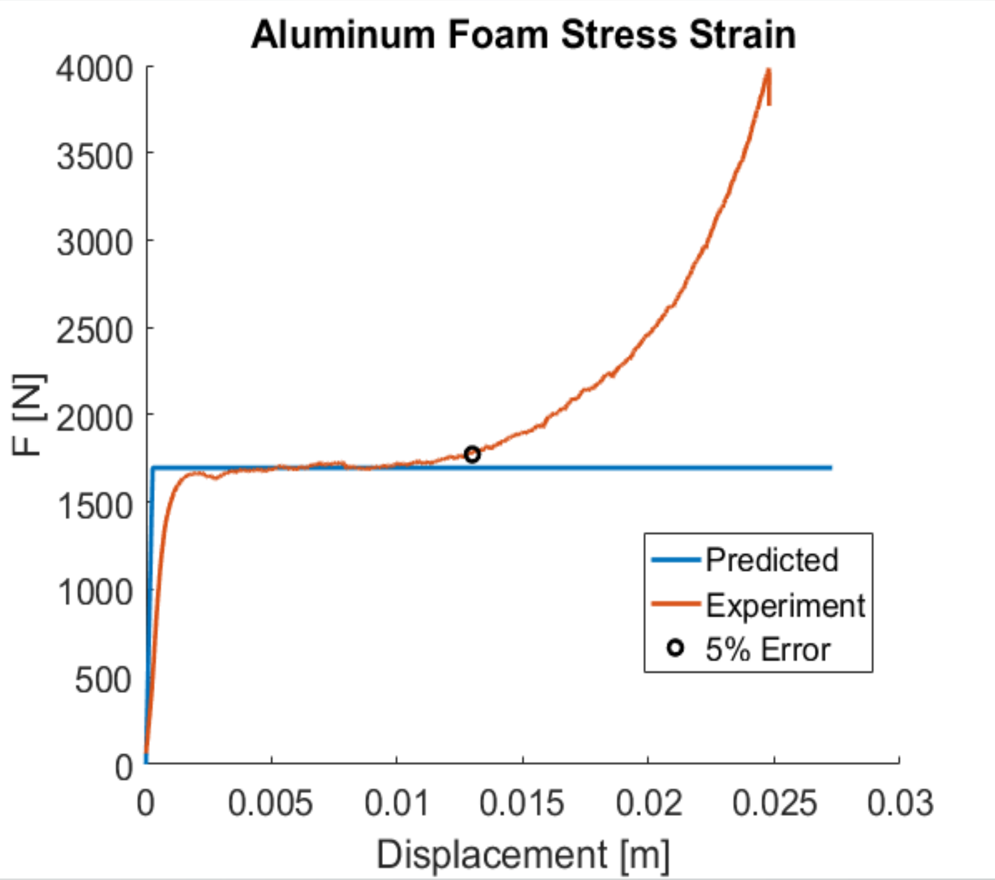


Landing Testing

REPTAR

Raytheon

- Both deployments underwent static deployments without Kanthal coils in no-wind and 6 m/s wind scenarios
- Aluminum foam performed as expected, but initial design susceptible to buckling causing a tapered redesign



Aluminum Foam Material Testing

REPTAR

Raytheon

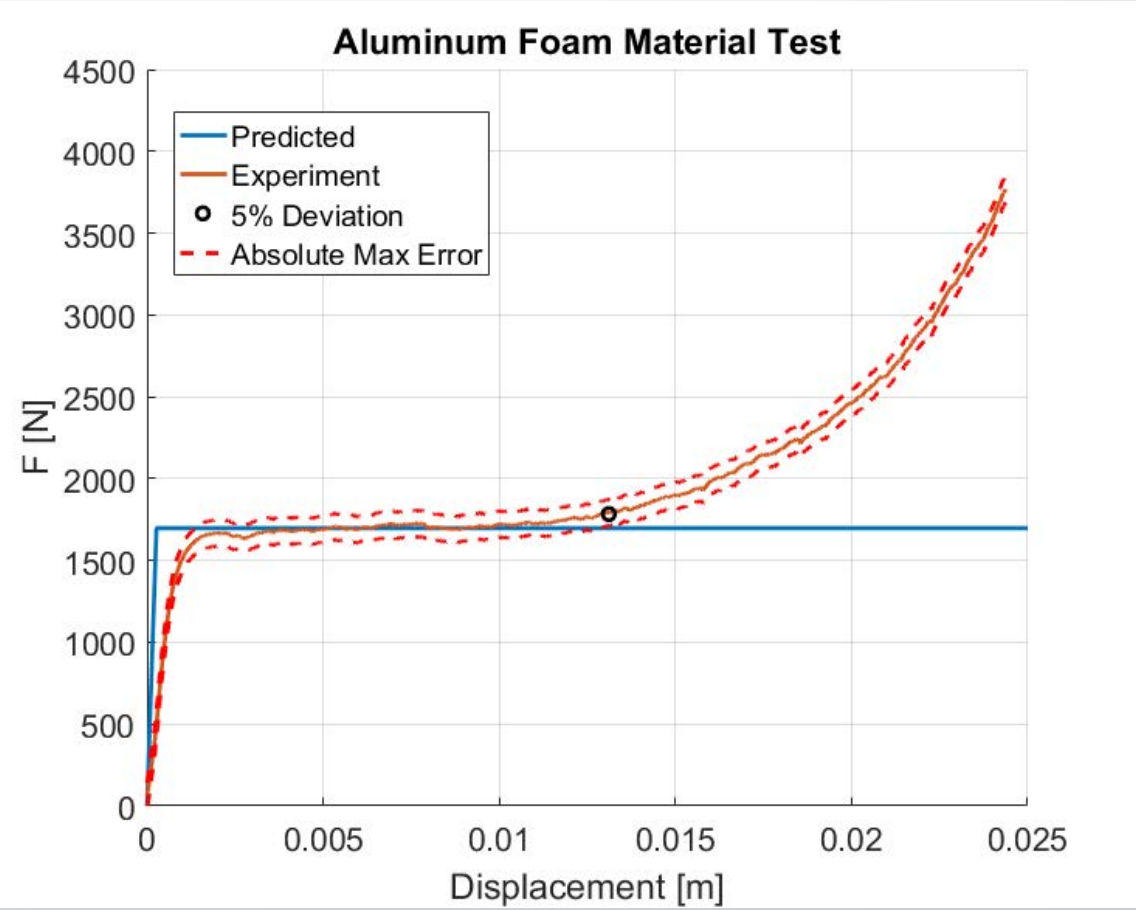
- Test Energy Absorbing Properties of Aluminum Foam
  - Tested in ITLL Instron Materials Testing Laboratory
- DR 3.1
  - Survive 40 G
- Purpose
  - Validate compression strength of foam
  - Validate possible compression of foam
- Model
  - $W = F \bullet d$
  - $\sigma_{crush,f} = 0.58 TS_s \rho^{3/2}$

Test Results

REPTAR

Raytheon

- Load Cell
  - Range from 496-49800 N
  - Maximum Error of 0.16 %, 79.97 N
- Tested to 64% Compression
  - Deviates from model at 46% compression
  - Design assumed with 60% compression



Torsion Spring Calculations

- Torque required to deploy the base legs and the side panels is calculated using the Drag Force from the descent through the atmosphere
- Force of Drag, $F_d = \frac{1}{2}\rho V^2 A C_d$
- Moment, $M = F_d \times l$ where l is the length dimension of the legs (7.3 cm)
- $c_d = 2.02$, used as a worst case scenario for a flat plat straight into the wind
- $A_{Base\ Leg} = 7.8\ cm \times 1.65\ cm \times 2\ legs$for undeployed legs into direct velocity
- $\rho = 0.8191, 0.8543, 1.0065, 1.112\ kg/m^3$ for altitudes of 4000, 3600, 2000, and 1000 m, respectively
- $V = 100, 90, 6\ (with\ chute)\ m/s$ for various terminal velocities at altitudes as well as expected landing speeds reached following chute deployment

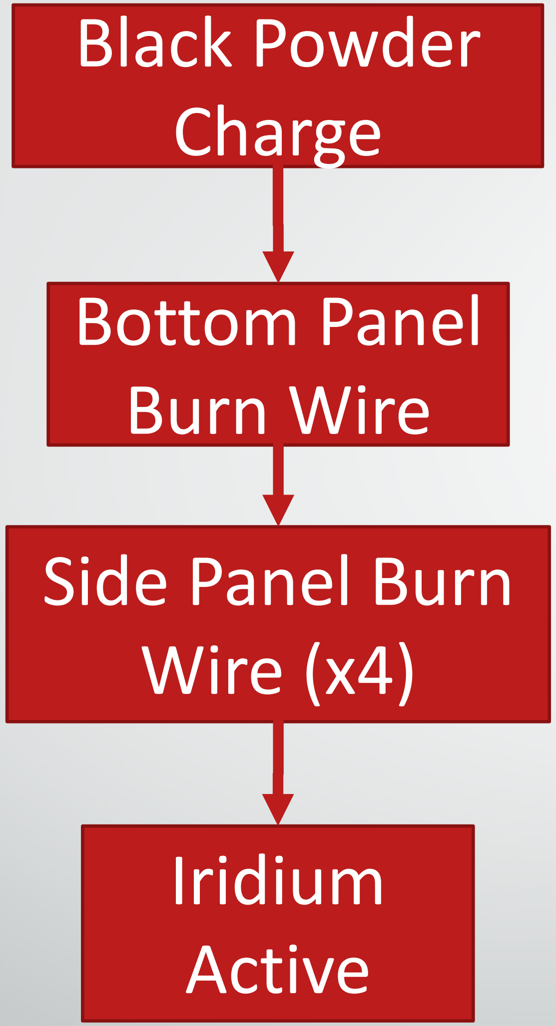
Torsion Spring Calculations (cont'd)

REPTAR

Raytheon

- From Drag Force calculations:
  - Moment required for base legs to deploy:
    - $M(4000\,m) = 1.661\;N\,m = 14.70\;in\;lbs$
    - $M(3600\,m) = 1.403\;N\,m = 12.42\;in\;lbs$
    - $M(2000\,m)_{\frac{w}{o}chute} = 1.653\;N\,m = 14.63\;in\;lbs$
    - $M(2000\,m)_{w/chute} = 0.0073\;N\,m = 0.065\;in\;lbs$

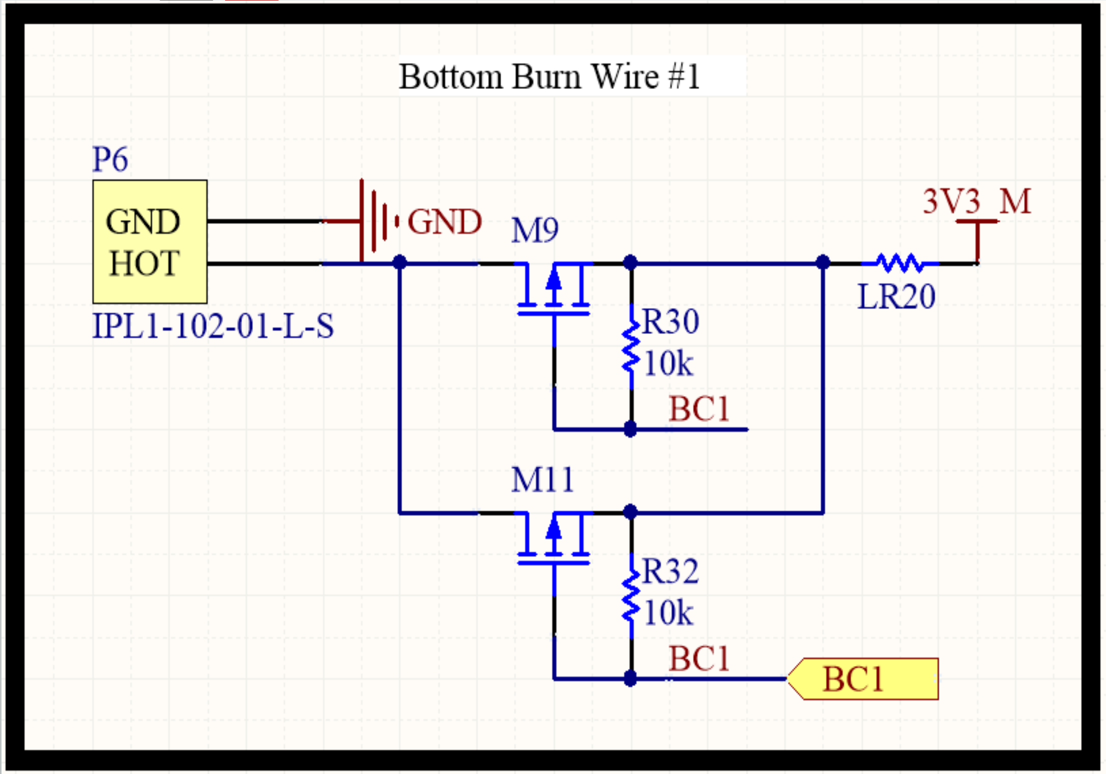
Avionics Deployment Considerations

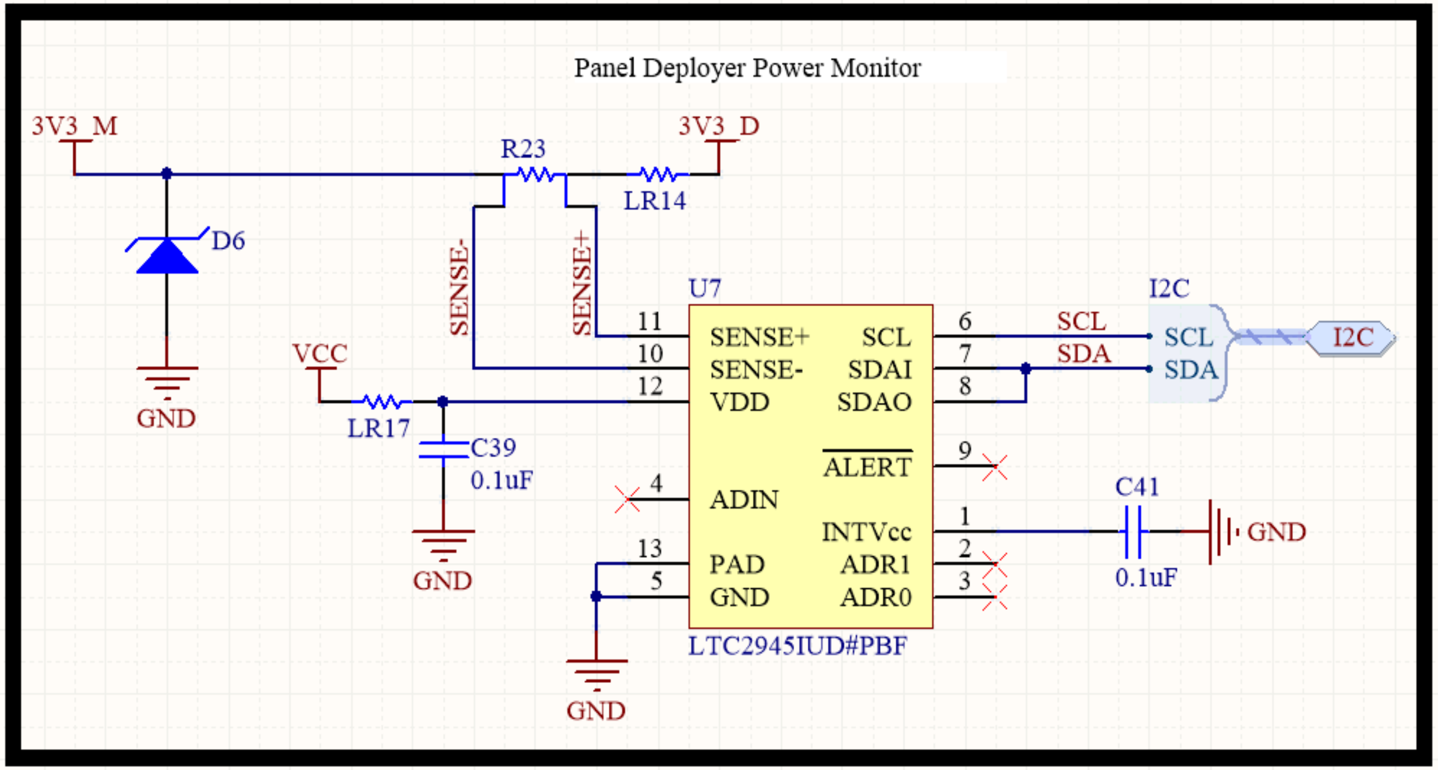


- **Critical Element:**
  - Avionics Interface
- **Requirements:**
  - REPTAR shall survive an instantaneous G-Loading of 40 G
  - REPTAR shall communicate its location over a radius greater than or equal to 45 miles
- **Concerns:**
  - Physical Interface and Sensors
  - Power Budget
  - Avionics Thermal Budget

Deployment Triggering and Monitoring

REPTAR
Raytheon

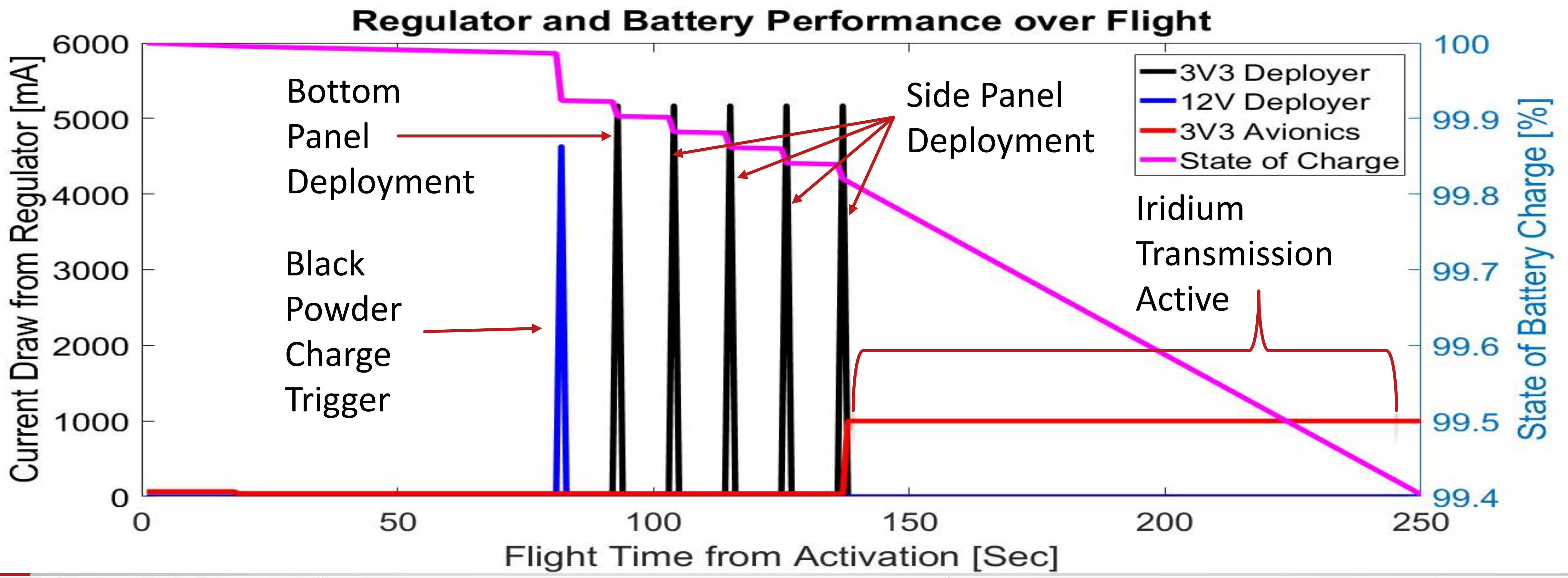




- FET Controlled Burn Wire Interface Connector to AWG 14 Wire (29 Amp. Max)
- Power Monitor capable of "snapshotting" 1 second periods and determining power transfer.

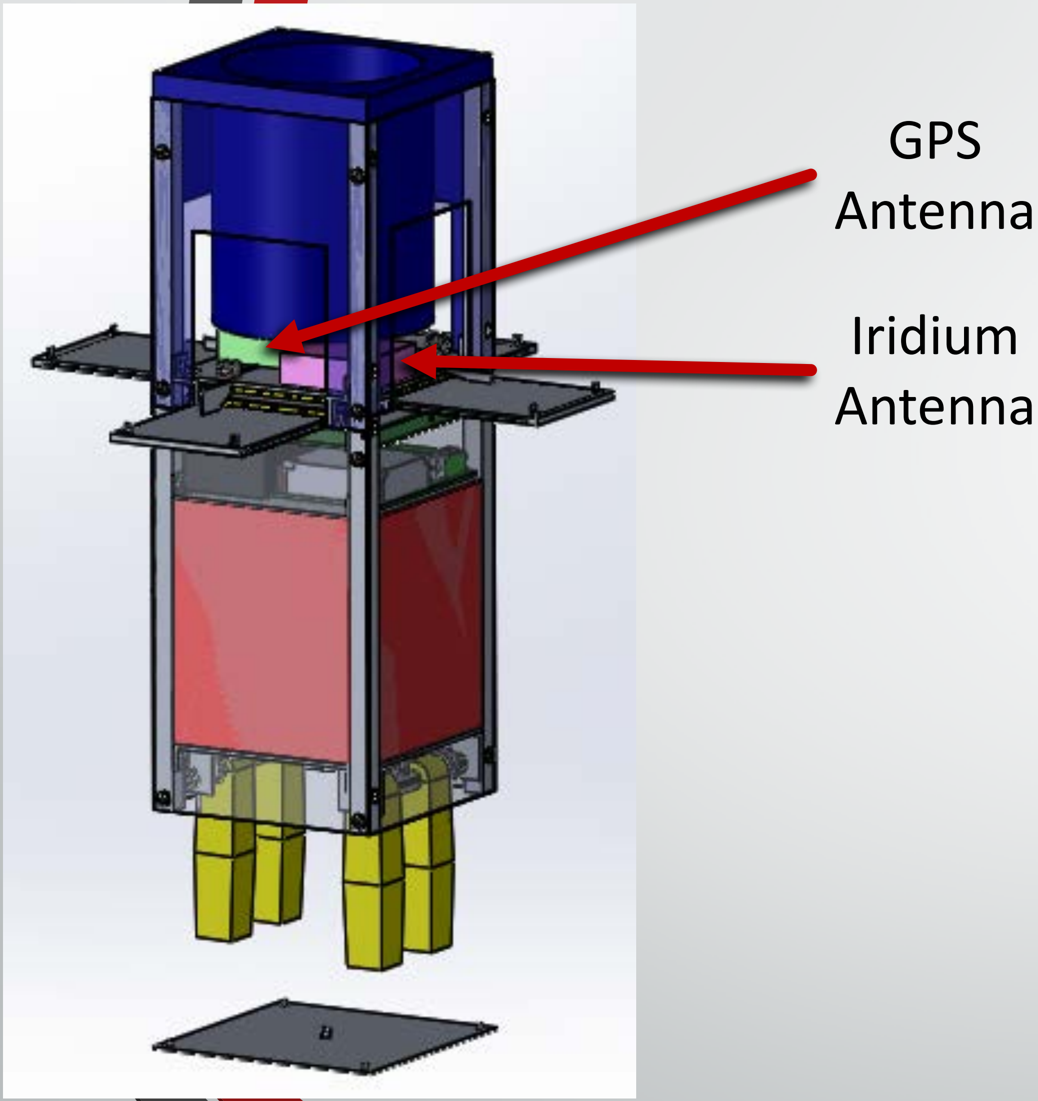
Battery and Regulator Performance

REPTAR



Regulator	Max Rated Current Draw [mA]	Max Modelled Current Draw [mA]
3V3 Avionics	1,200	920
3V3 Burn Wire	8,000	5,560
12V Black Powder	10,000	4,670

Antenna Considerations

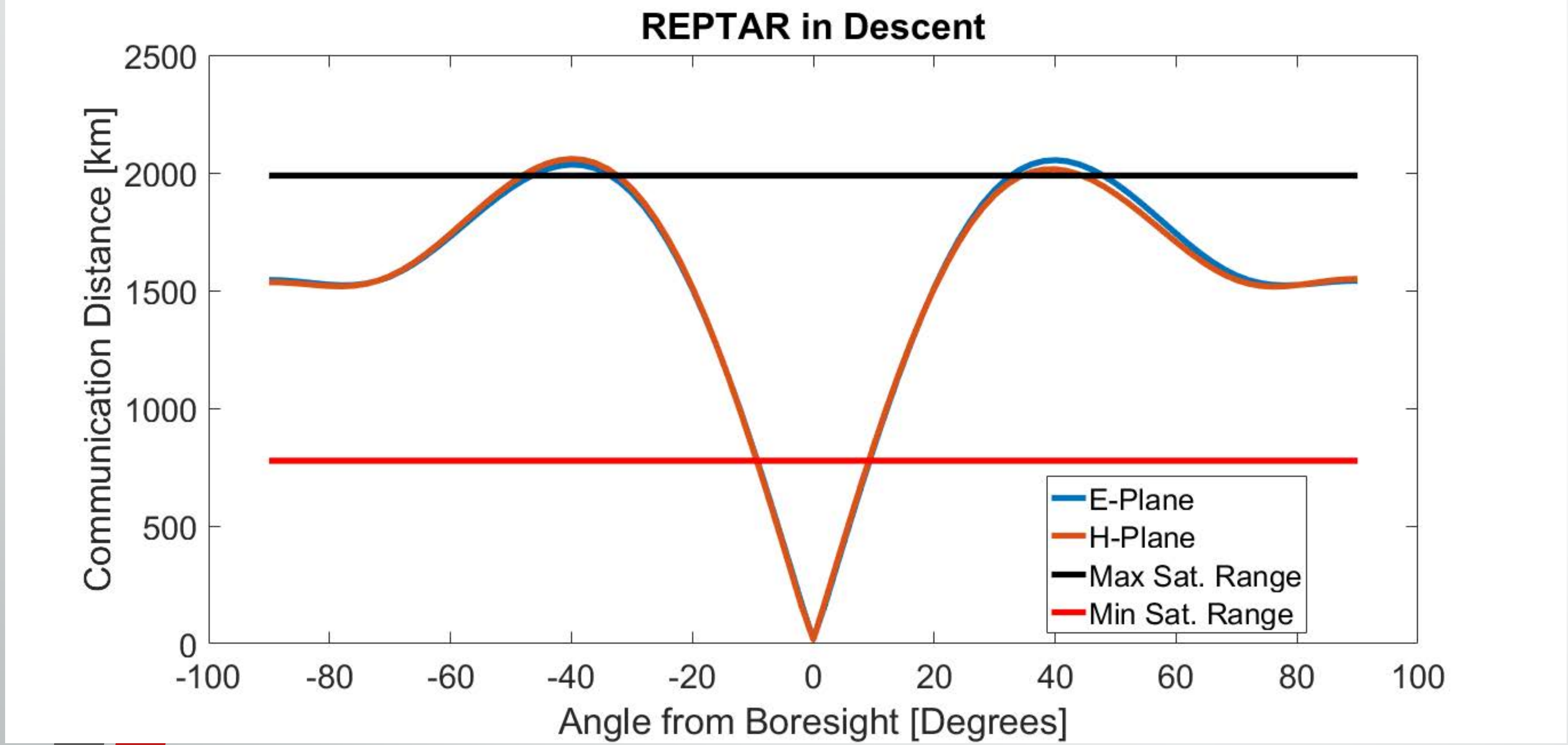


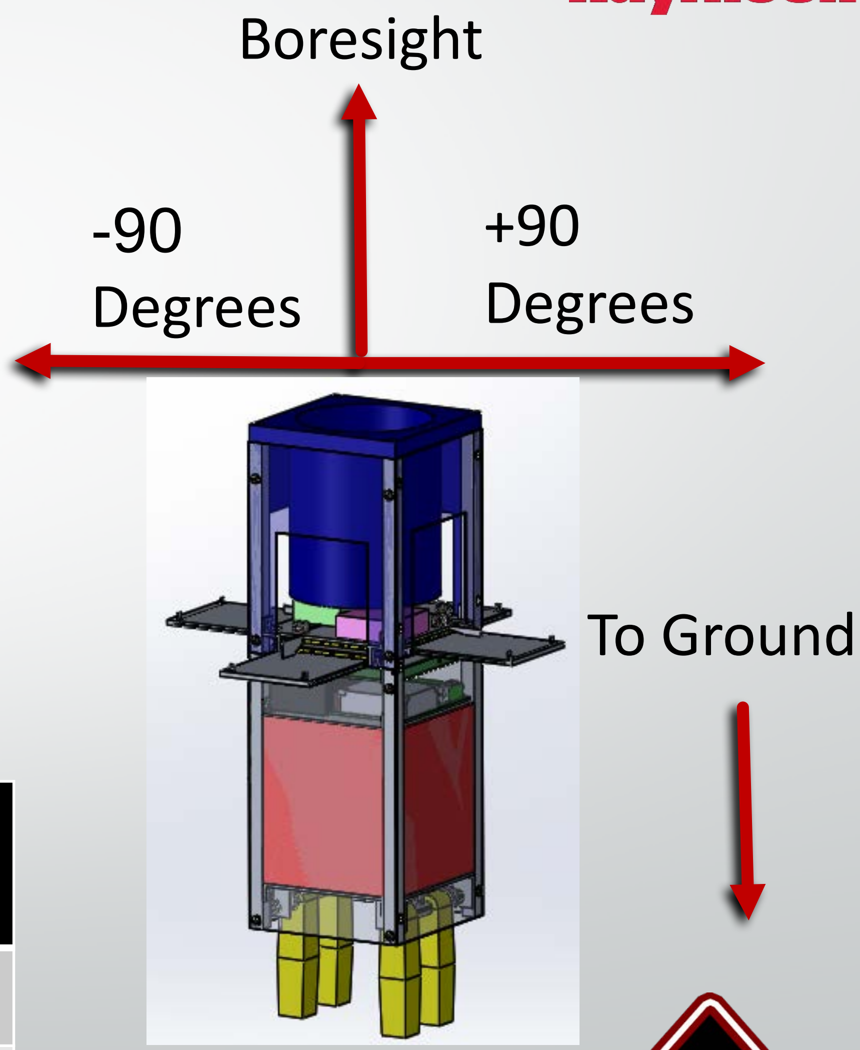
- **Critical Element:**
  - Antenna Performance
- **Requirements:**
  - REPTAR shall communicate its location over a radius greater than or equal to 45 miles
- **Concerns:**
  - Antenna Pattern inside REPTAR Structure
  - Location of Iridium Communication Satellites relative to REPTAR

Descent Iridium Antenna Pattern Performance

REPTAR

Raytheon



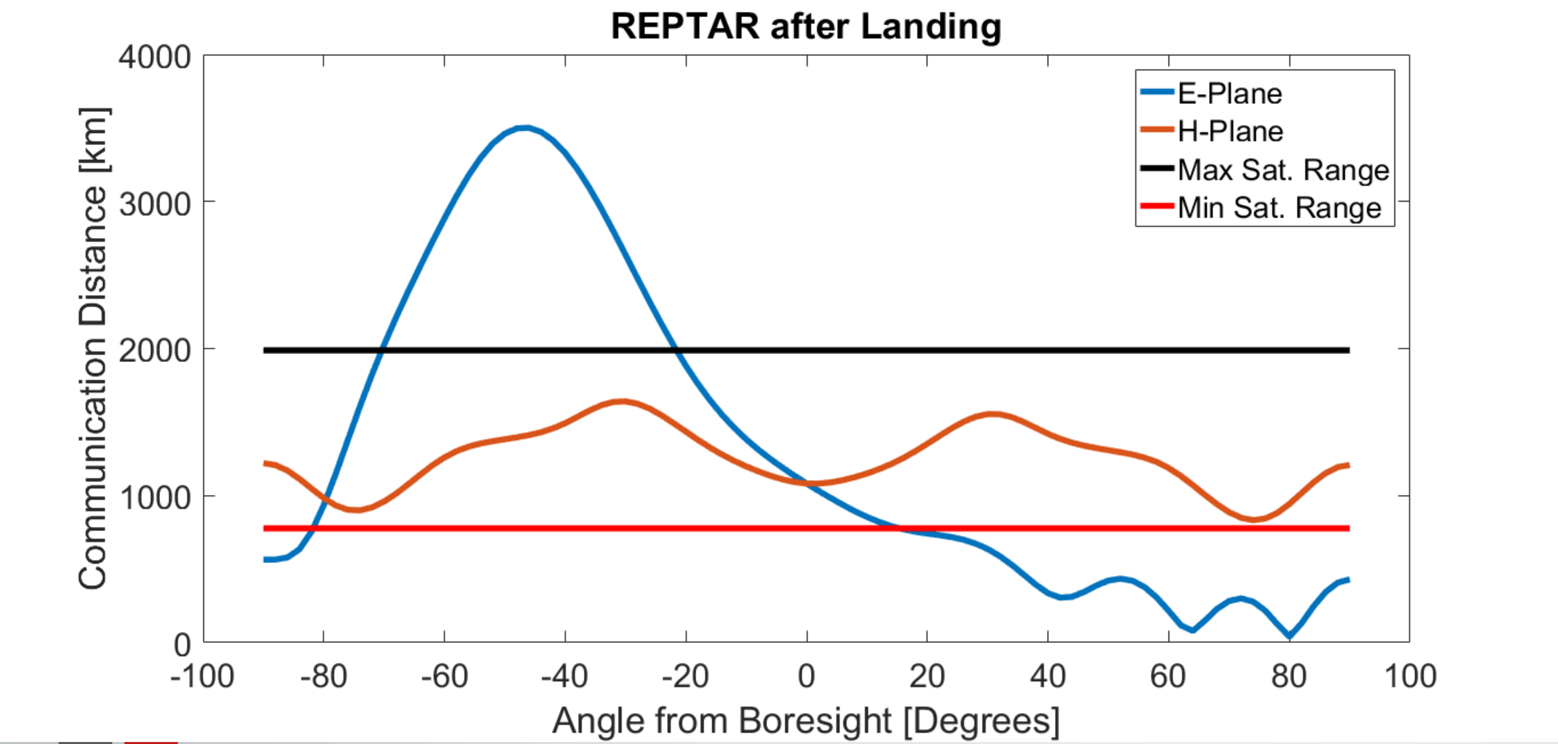


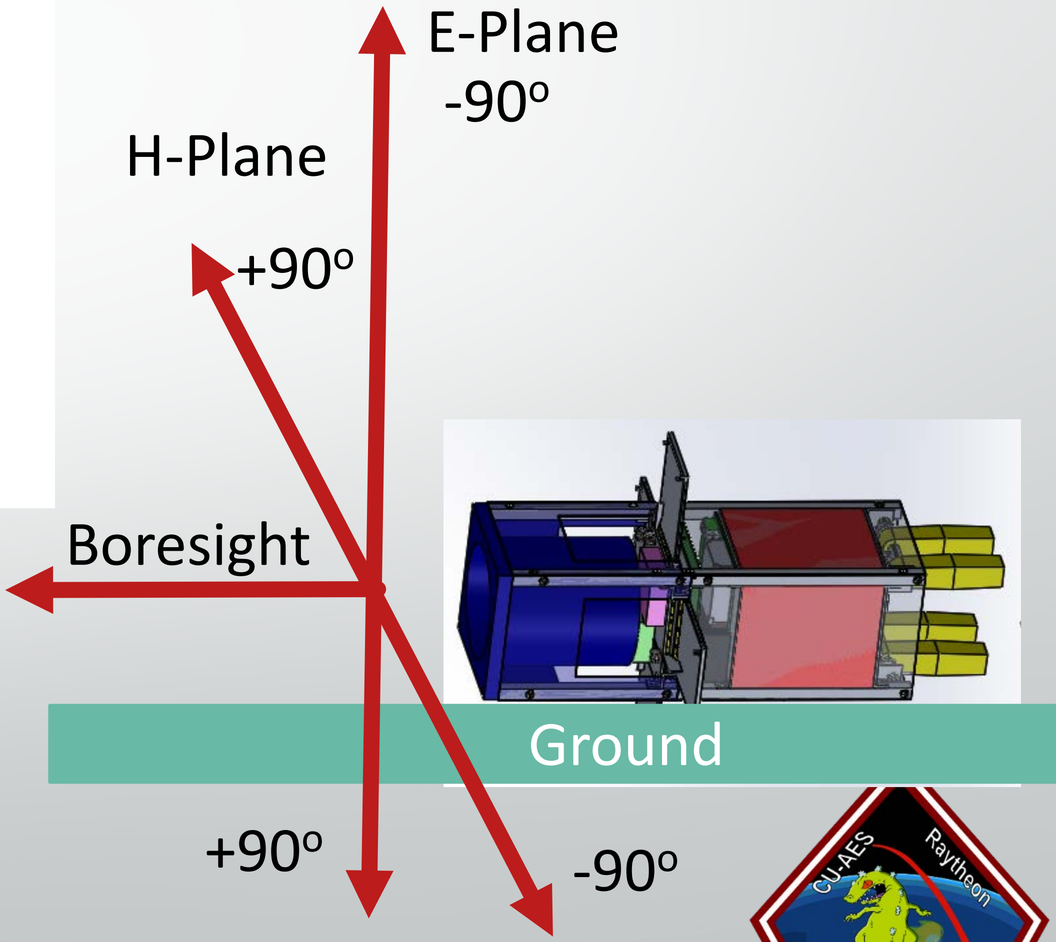
Iridium Parameter	Power [dBm]
Transmitted Power	32.0
Minimum Receive Sensitivity	-127.6

Landed Iridium Antenna Pattern Performance

REPTAR

Raytheon





Iridium Parameter	Power [dBm]
Transmitted Power	32.0
Minimum Receive Sensitivity	-127.6

Iridium Orbit Path

REPTAR

Raytheon

STK Descent Model (1km Elevation)
4 Hour Period

- Iridium Orbit:
  - 100 Hour Orbital Period
  - 86 Active Satellites
  - 100% Earth Antenna Coverage
- STK Model in Descent:
  - 100% Coverage
- STK Model after Landing
  - Worst Case: 75% Coverage (90/120 minutes)