REPTAR

REcoverable ProTection After Reentry

Preliminary Design Review

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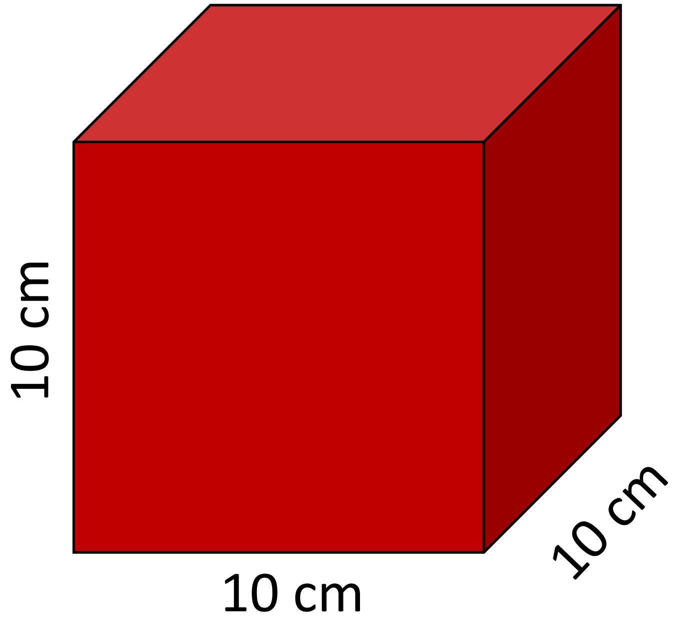
Customer: Steve Thilker, Collin Baukol, Cody Humbargar, Jason Latimer (Raytheon)

Project Statement

REPTAR shall assist in the recovery of a de-orbited Raytheon 1U 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.



Motivation

Raytheon

- Recovery of payload enables:
  - Lower mission costs by re-using the payload
  - Get samples collected by payload on-board.
  - Reduce the amount of space debris

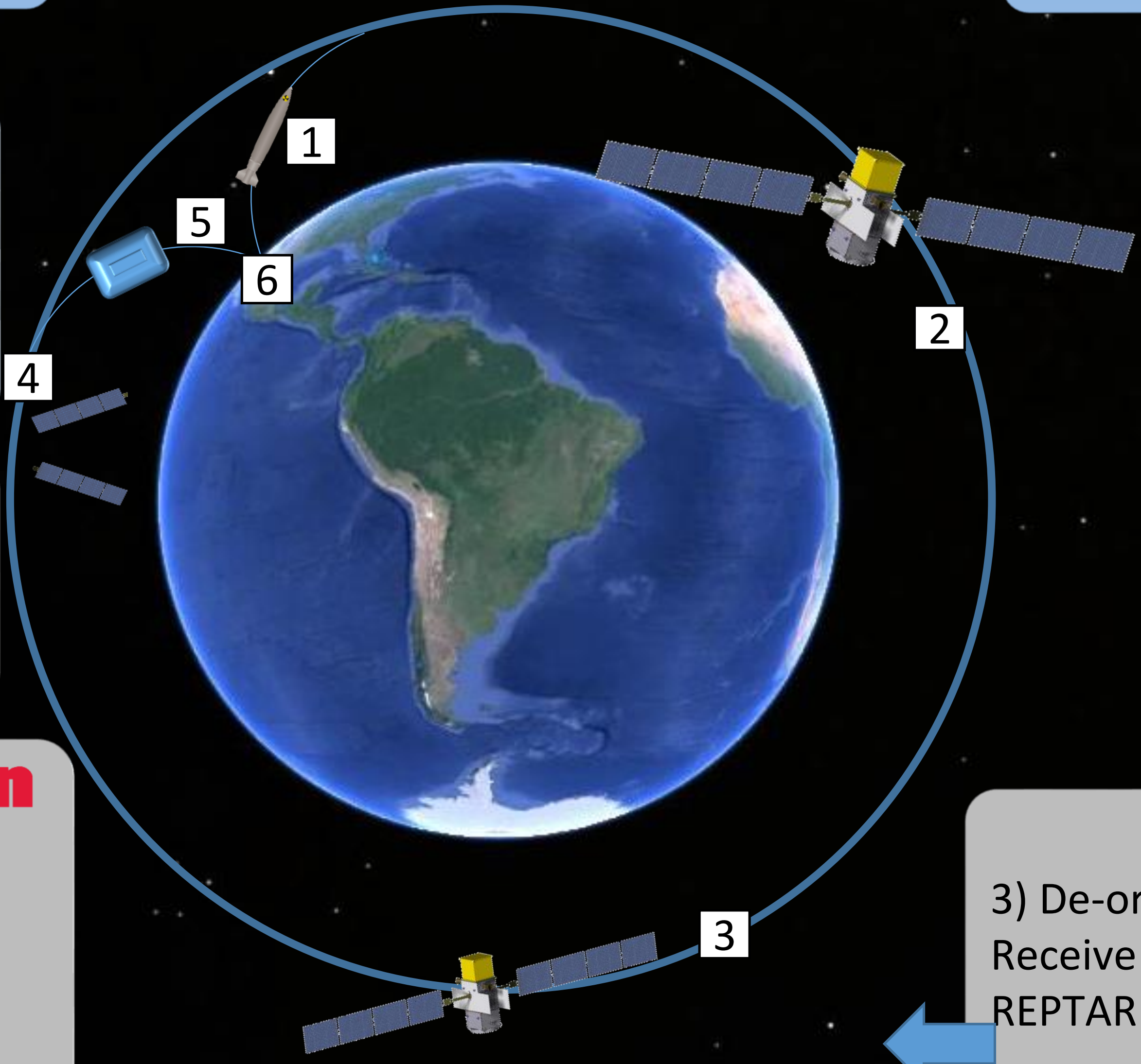
Functional Requirements

- FR.1 – REPTAR shall survive launch and a standby period in space
- FR.2 – REPTAR shall conform to industry CubeSat standards
- FR.3 – REPTAR shall keep the payload safe during descent and landing phases
- FR.4 – REPTAR shall be locatable after landing phase

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.



Raytheon

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

Raytheon

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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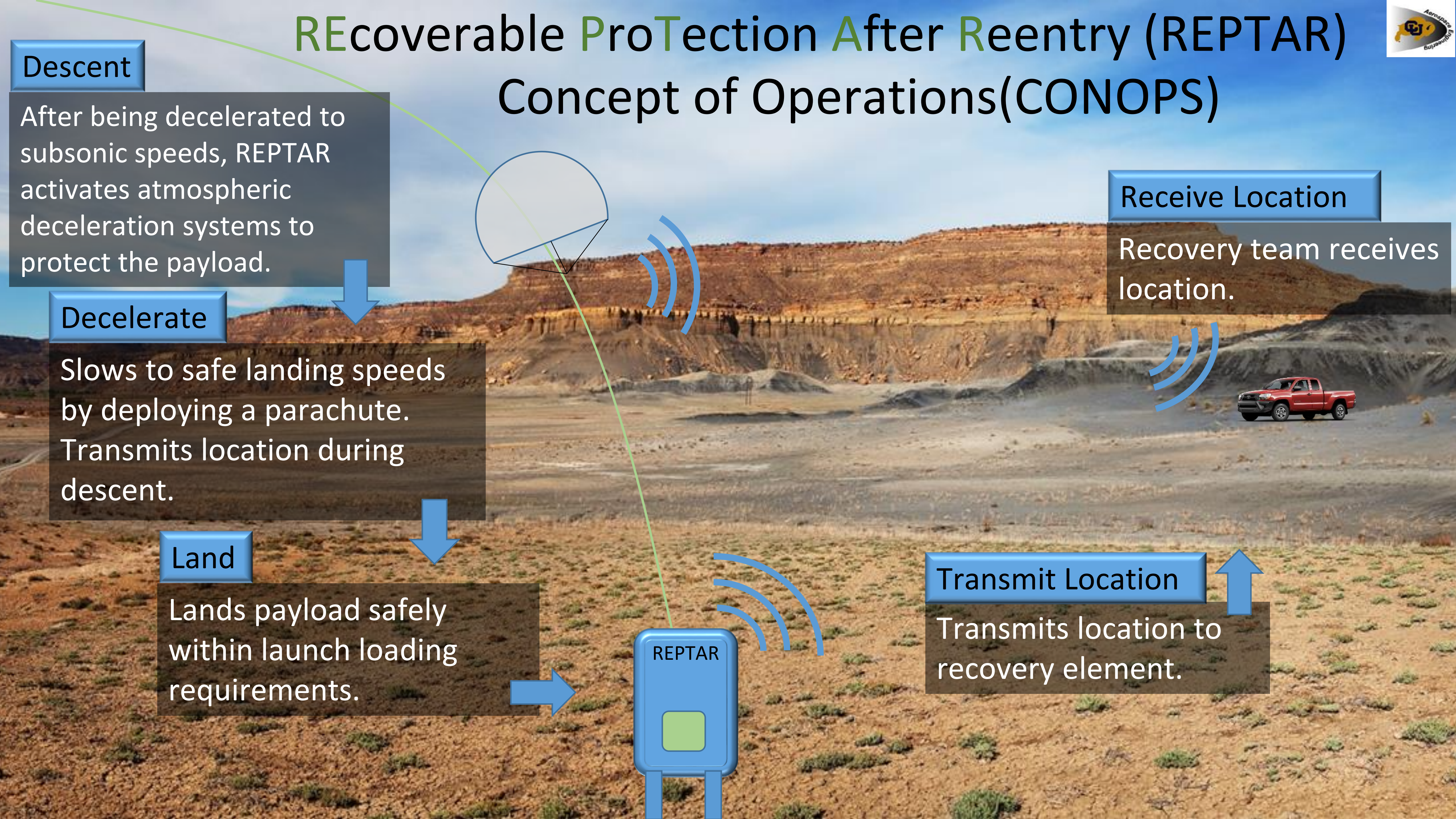
5) Deceleration
Decelerate to subsonic speeds.

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

Legend

- REPTAR Solution
- Raytheon Solution

REcoverable ProTection After Reentry (REPTAR) Concept of Operations(CONOPS)



Subsystems

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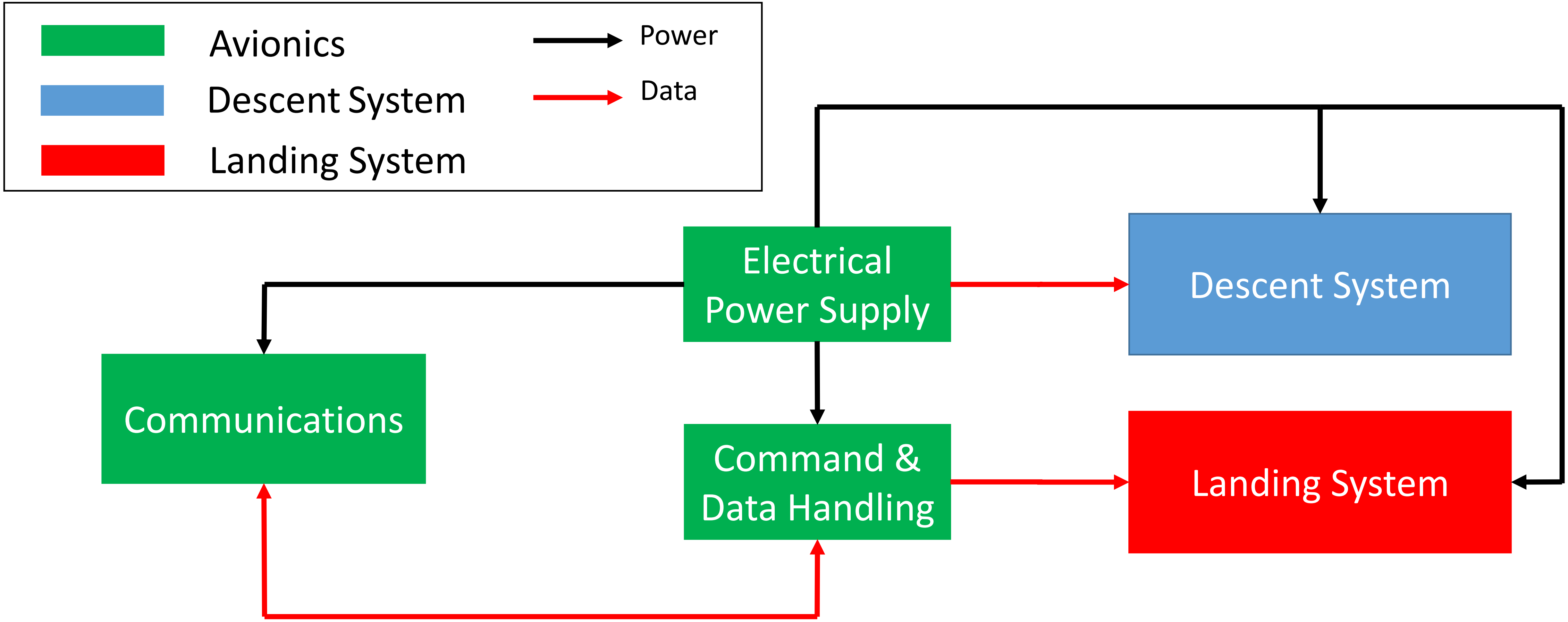
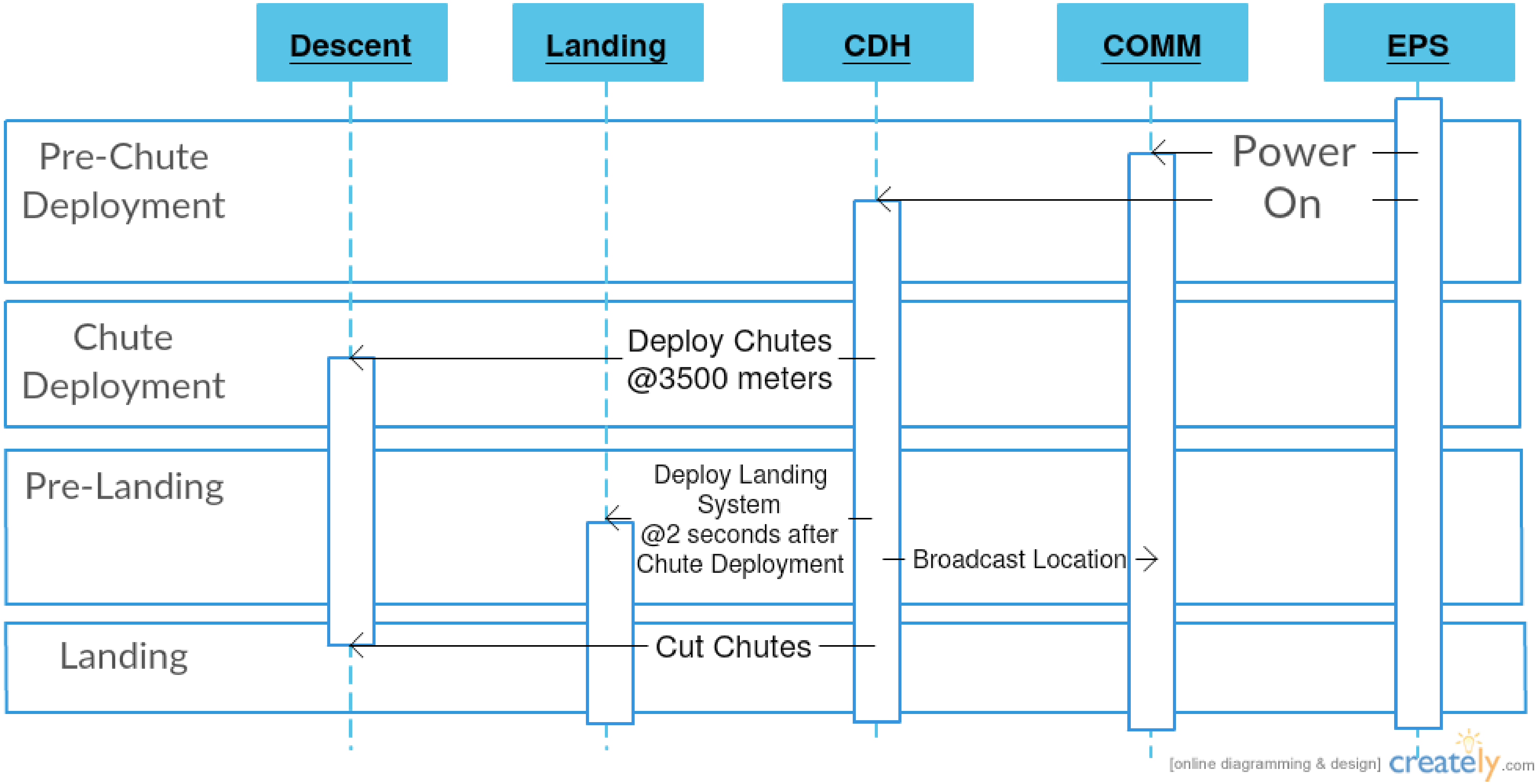


Events Timeline

Raytheon



Baseline Design

Descent Baseline Design

Earlier: Drogue and Parachute

- Issue: Volume constraints

Now: Parachute

- Issues Earlier: High velocity during main chute deployment
- Solution: Maximum Instant G Loading increased

Baseline Design

Raytheon

<u>Landing</u>

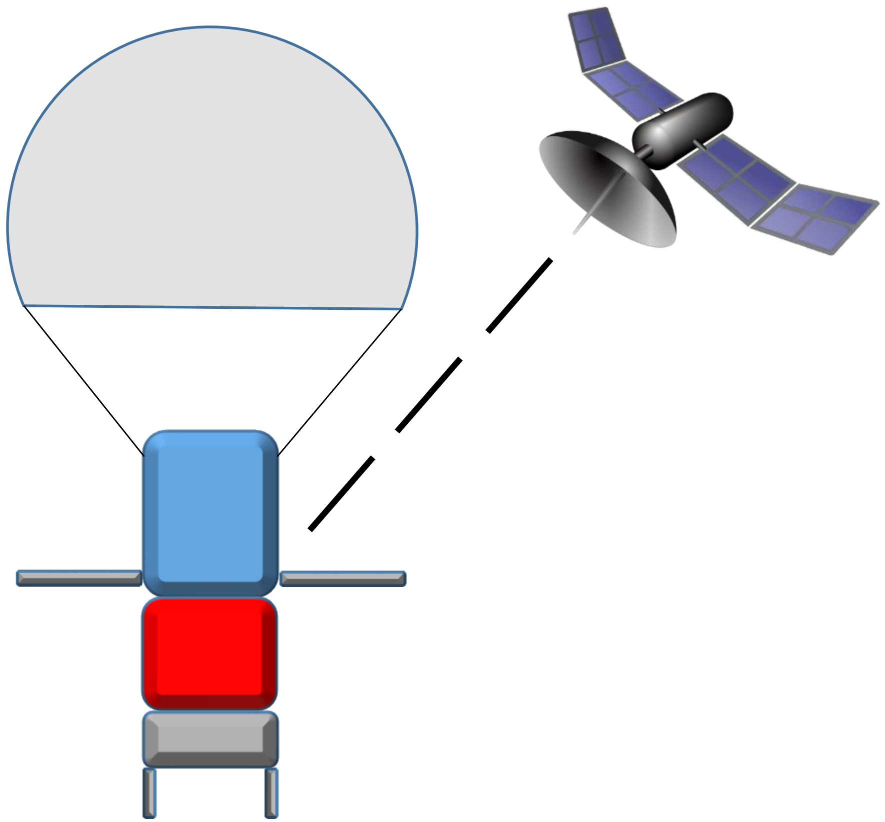
A deployable structure with energy absorption

Cost efficient and medium complexity

<u>Location Determination</u>

Global Positioning System (GPS)

Reliable, cost efficient, accurate



Location Transmission Baseline Design

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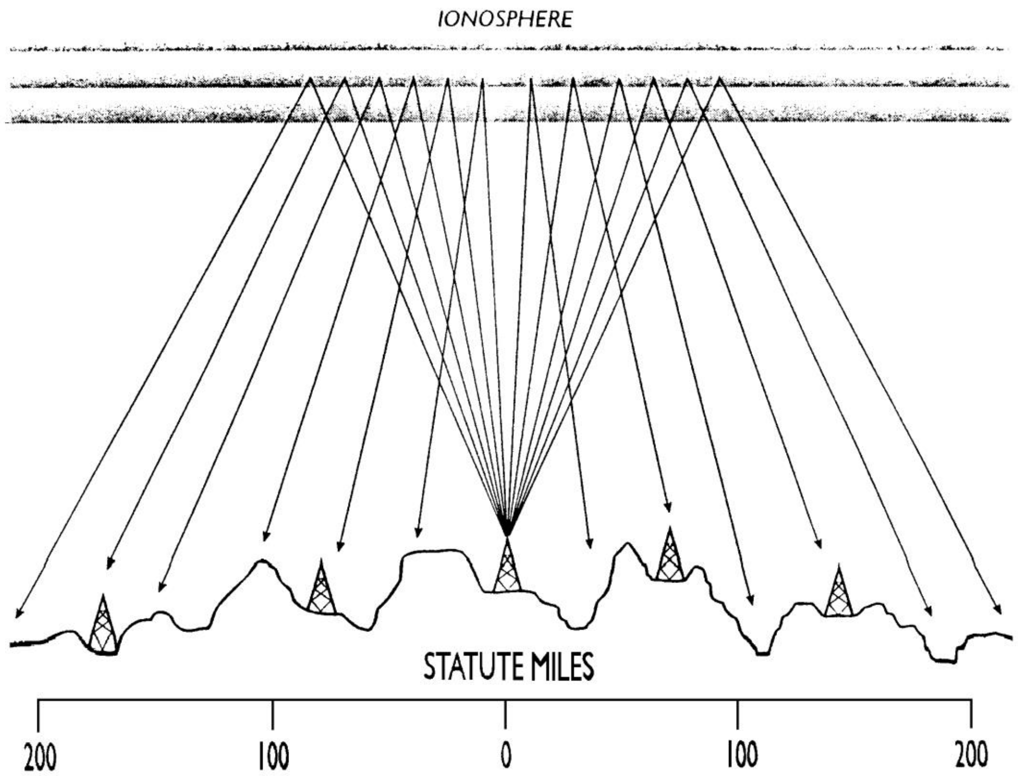
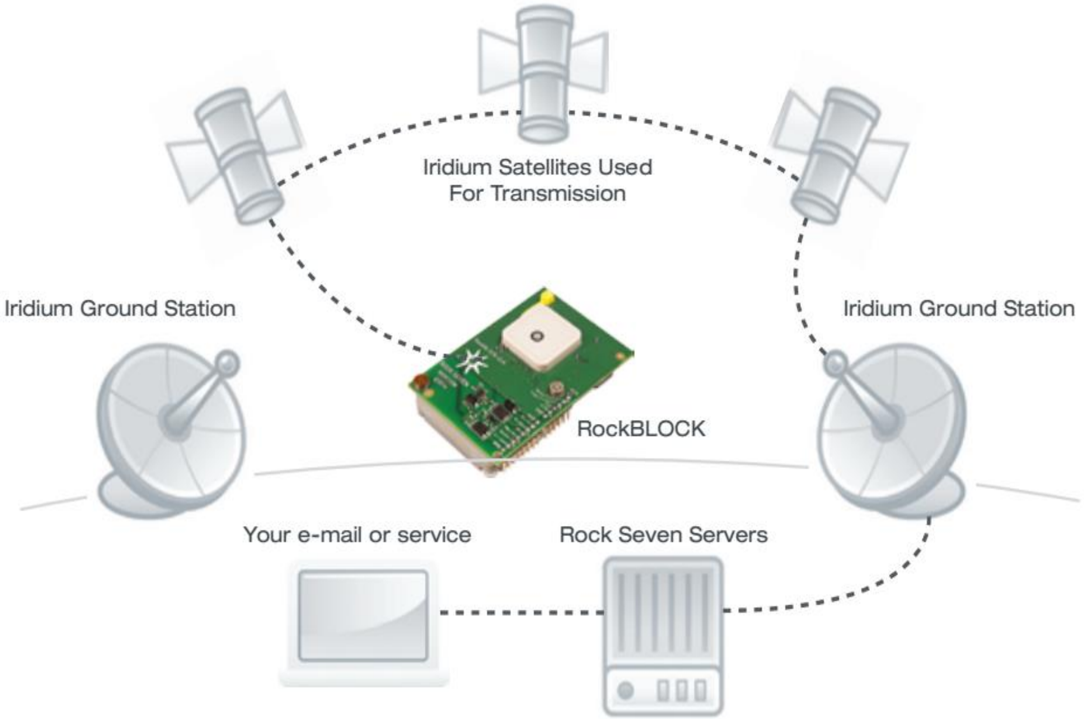
Earlier: Near Vertical Incidence Skywave (NVIS)

- Issue: Complexity



Now: Iridium

- Issues Earlier: Affordability
- Solution: now affordable, easy to integrate and test

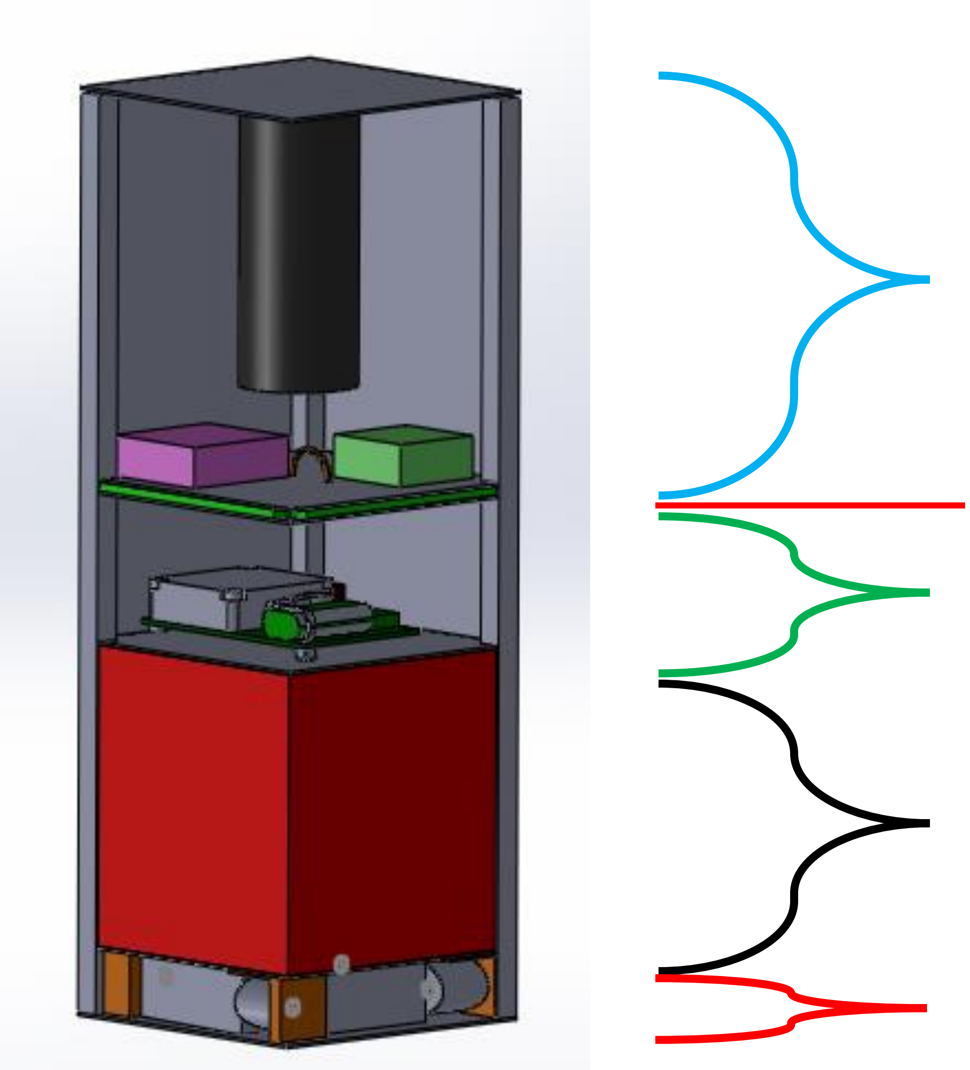


Overview | Descent | Landing | Avionics | Summary | Backup Slides

SolidWorks Model

Raytheon

FR.2



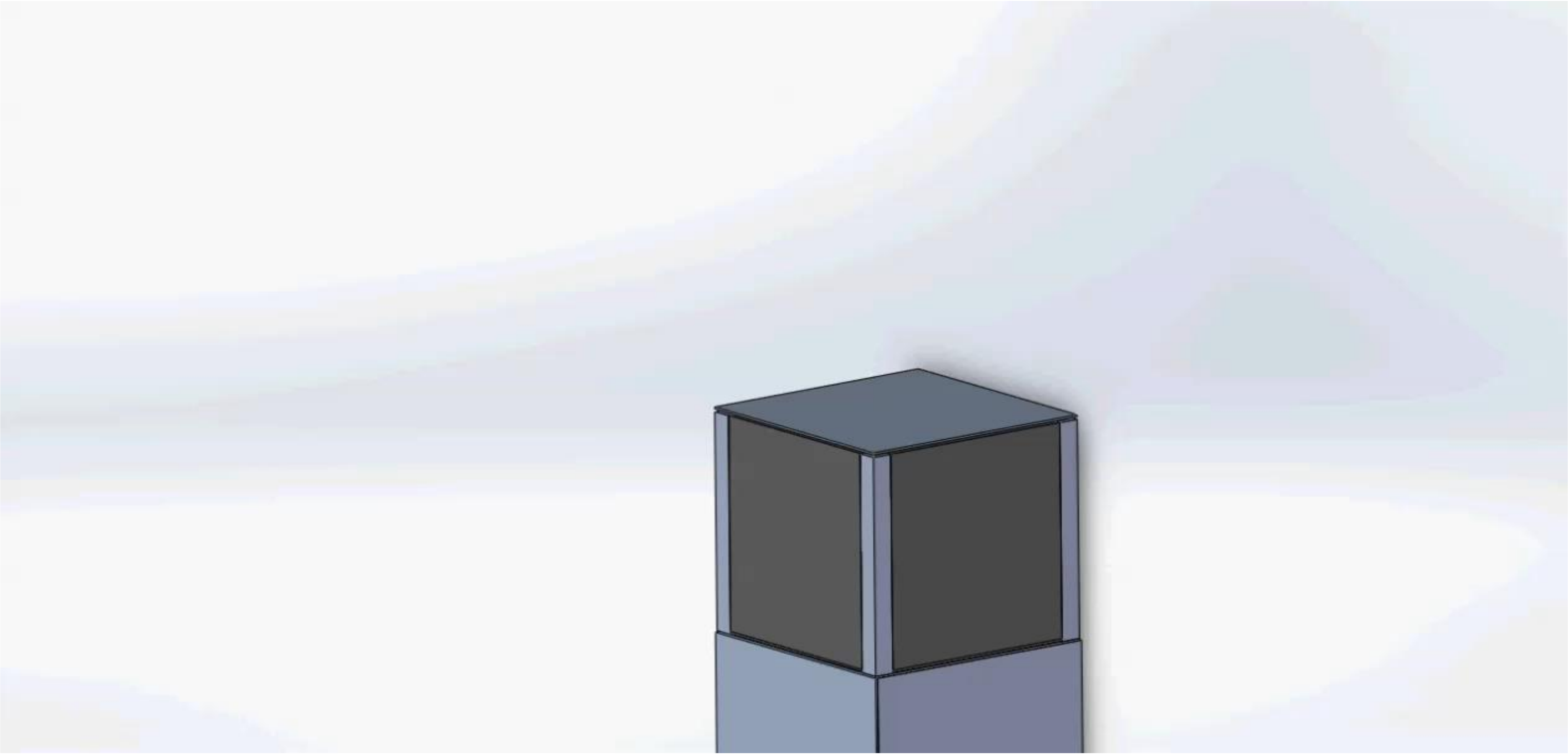
Descent Subsystem (1.25U, 41.6%)

Landing Subsystem (0.09U, 3%)

Avionics Subsystem (0.5U, 16.7%)

Raytheon Payload (1U, 33.3%)

Landing Subsystem (0.12U, 4%)



Critical Project Elements

Systems	Critical Elements
Descent	• Top side deployment
Landing	• Horizontal velocity • Side and legs deployment
Avionics	• Frangibolt and Pinpuller interfaces • Internal skills development
Full System	• Mass and volume constraints • Manufacturability • Testing

Descent Feasibility Analysis

Requirements

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- The instantaneous loading experienced by the vehicle shall not exceed 40G's as defined by MIL-STD-810G (DR 1.3)
- The sustained loading experienced by the vehicle shall not exceed 6.5G's (DR 1.2)
- Descent mechanism shall meet mass and volume requirements (FR.2)
- Descent deployment mechanisms shall have an interface with the CDH system
- Chute must be released after landing

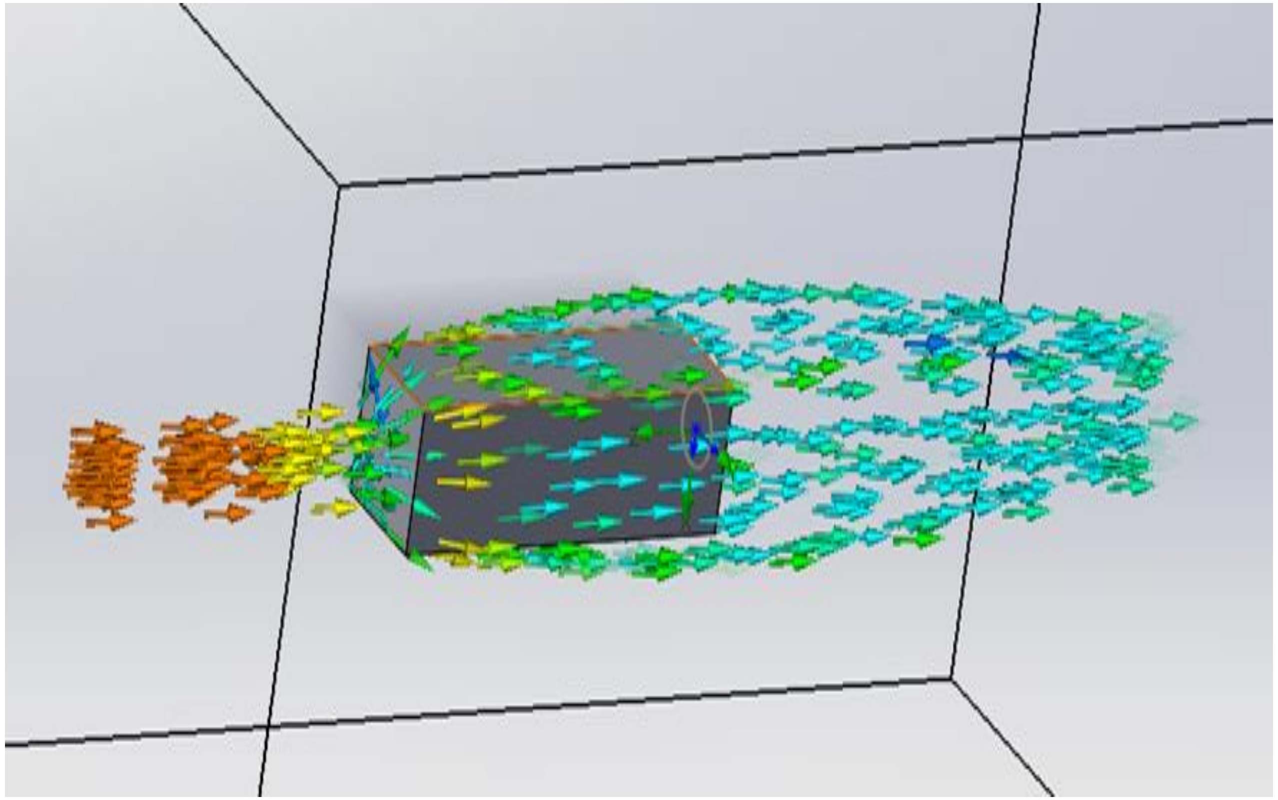
Mission Assumptions

Raytheon

- Aimed for center of Utah Test & Training Range (UTTR)
- Protected during re-entry by Thermal Protection System (TPS)
- System Dimensions: 3U
- Total System Mass: 4 kg
- Terminal velocity at altitude greater than 3600 meters MSL

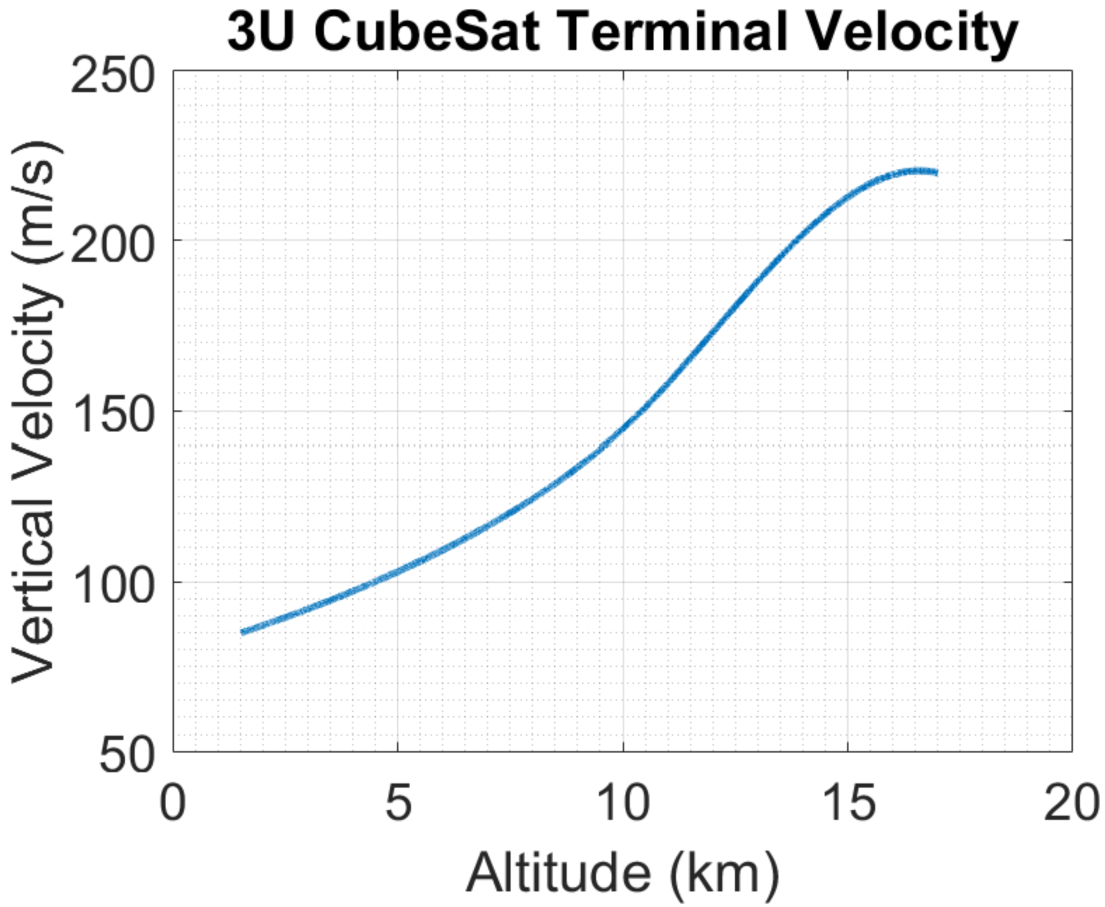
Assumptions

Raytheon



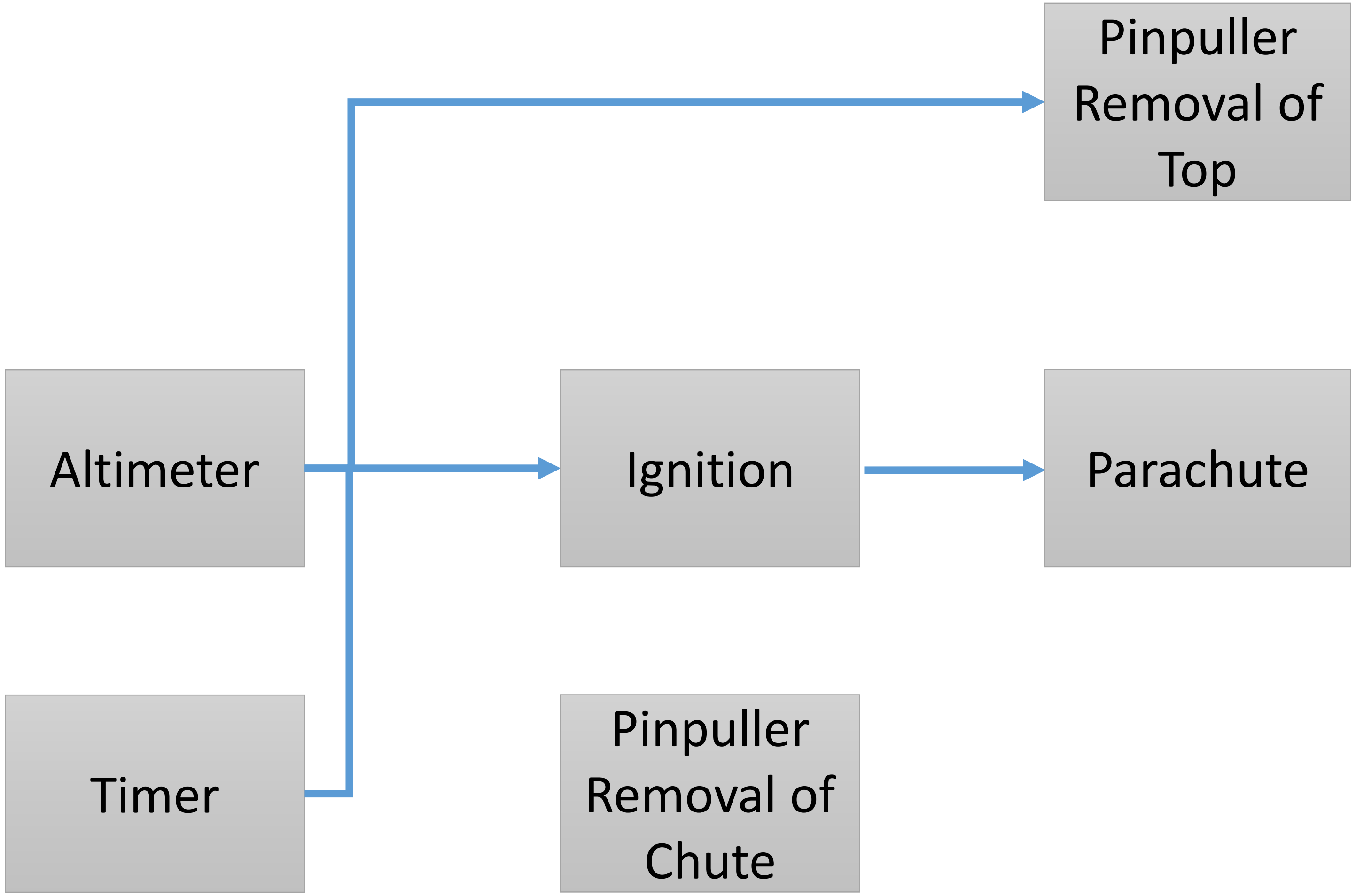
Flow Simulation

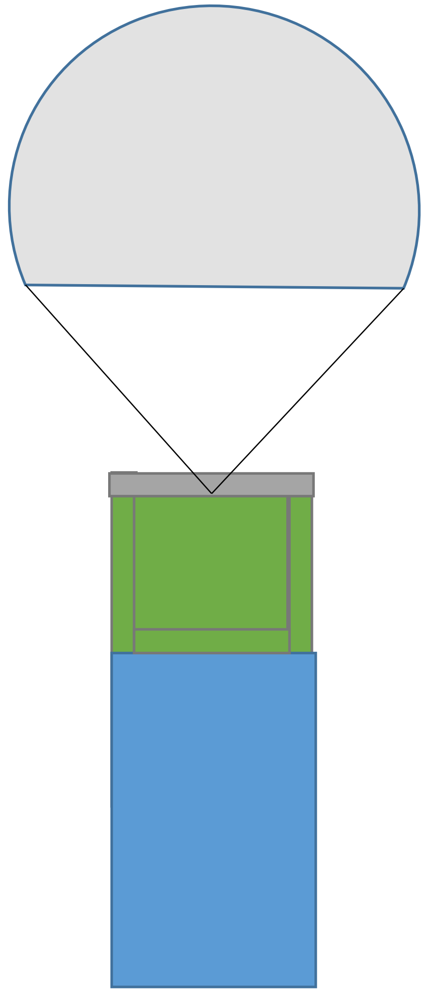
$C_D = 1.07$



Descent Functional Block Diagram

Raytheon





Descent Functional Block Diagram

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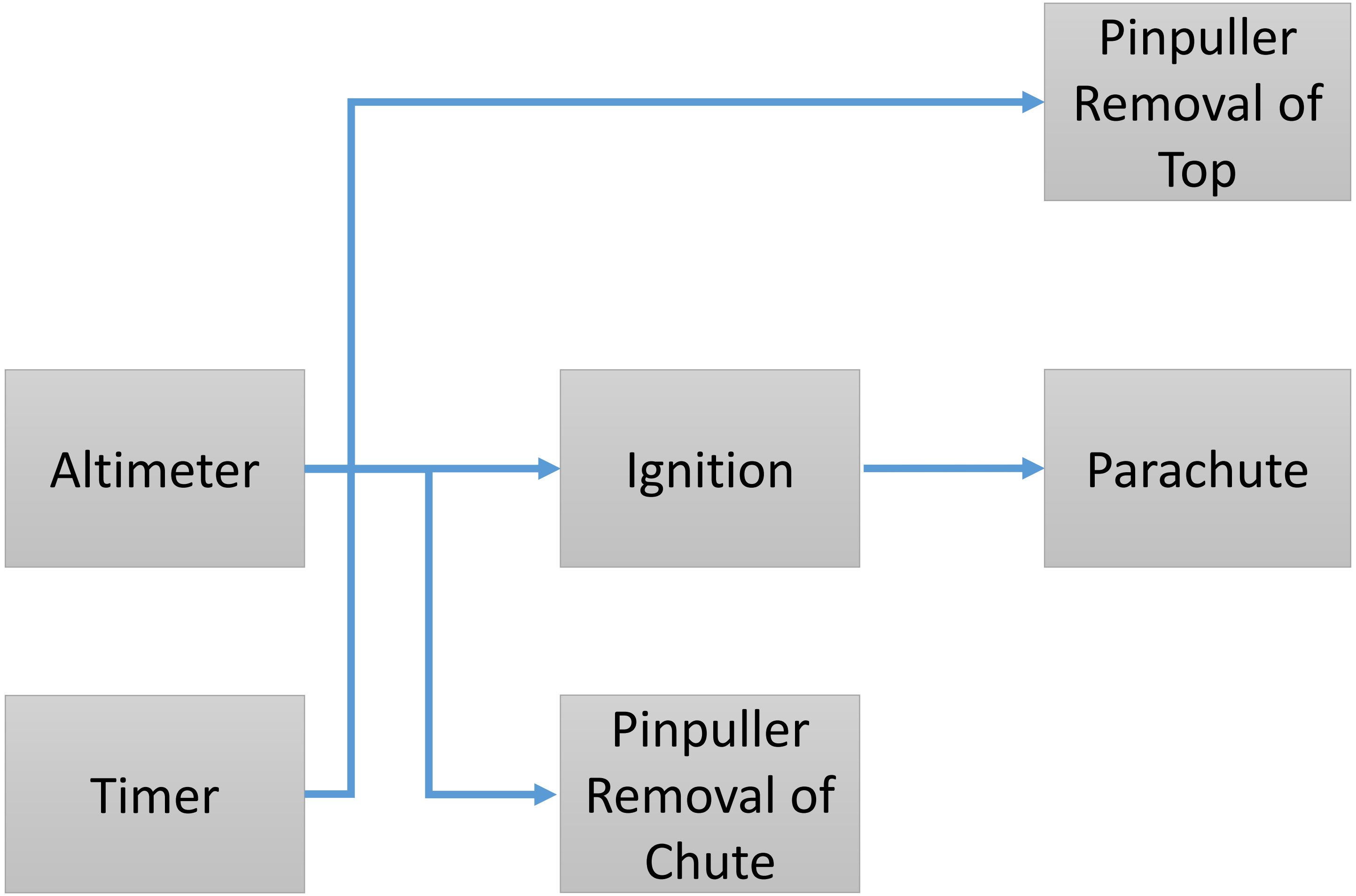
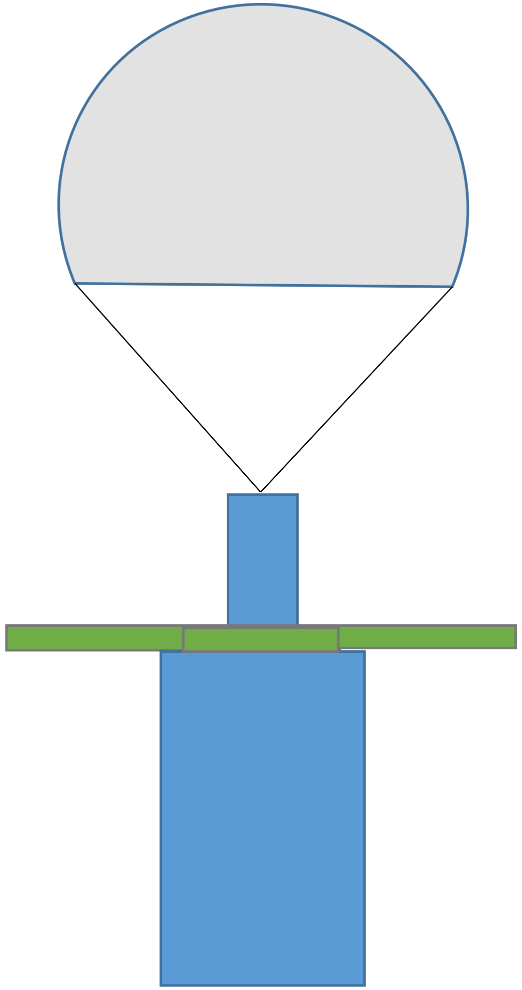
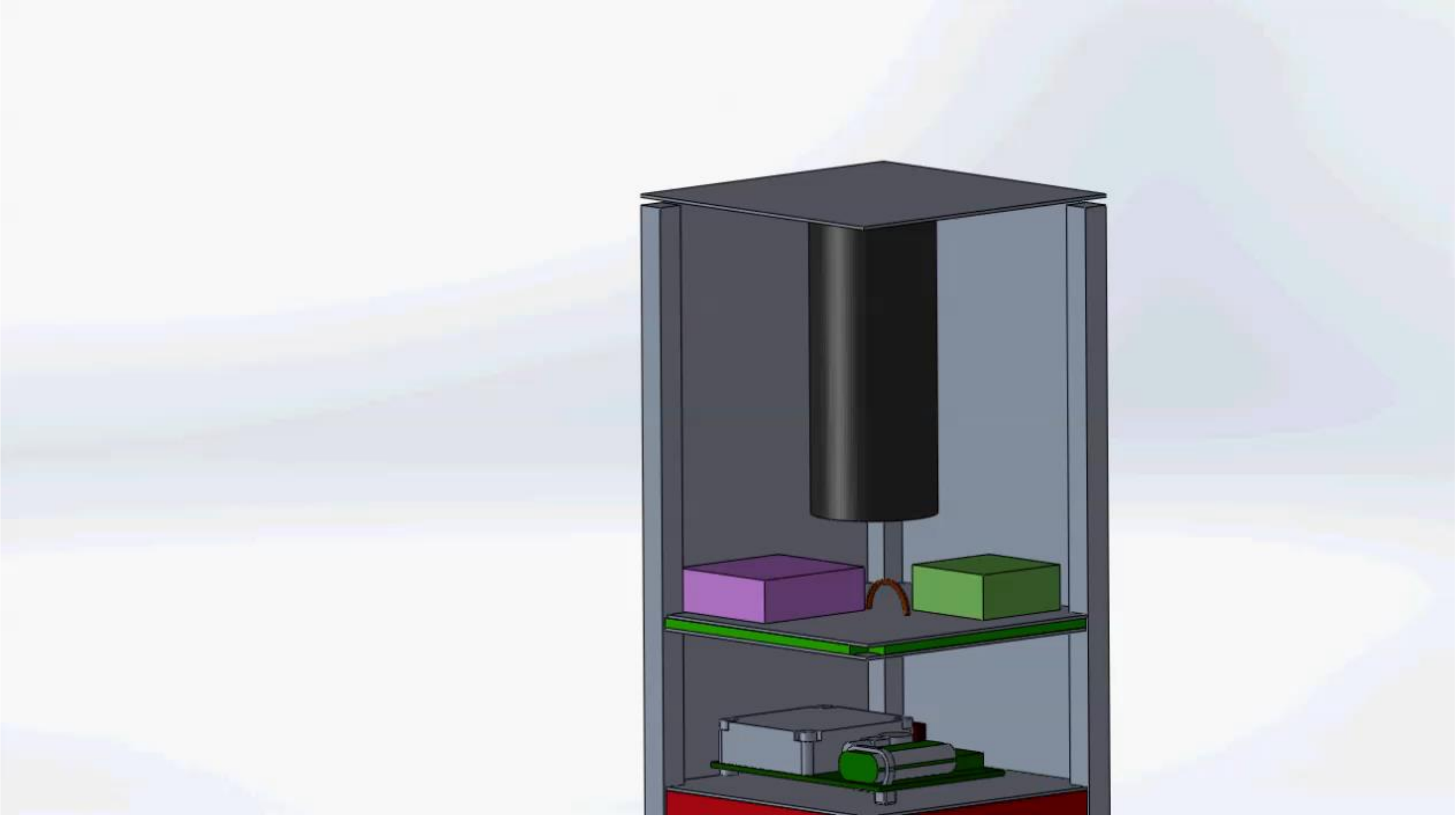




Design (SolidWorks)

Raytheon



TiNi Aerospace
Standard PinPuller P5

Manufactured
Deployment Cylinder

Fruity Chutes 48” Diameter
Iris Ultra Compact Parachute

Ejection Canister

Bass Pro Shops GOEX FFFFg
Black Powder

Recovery Wadding

TiNi Aerospace
Standard PinPuller P5

Deployment Systems

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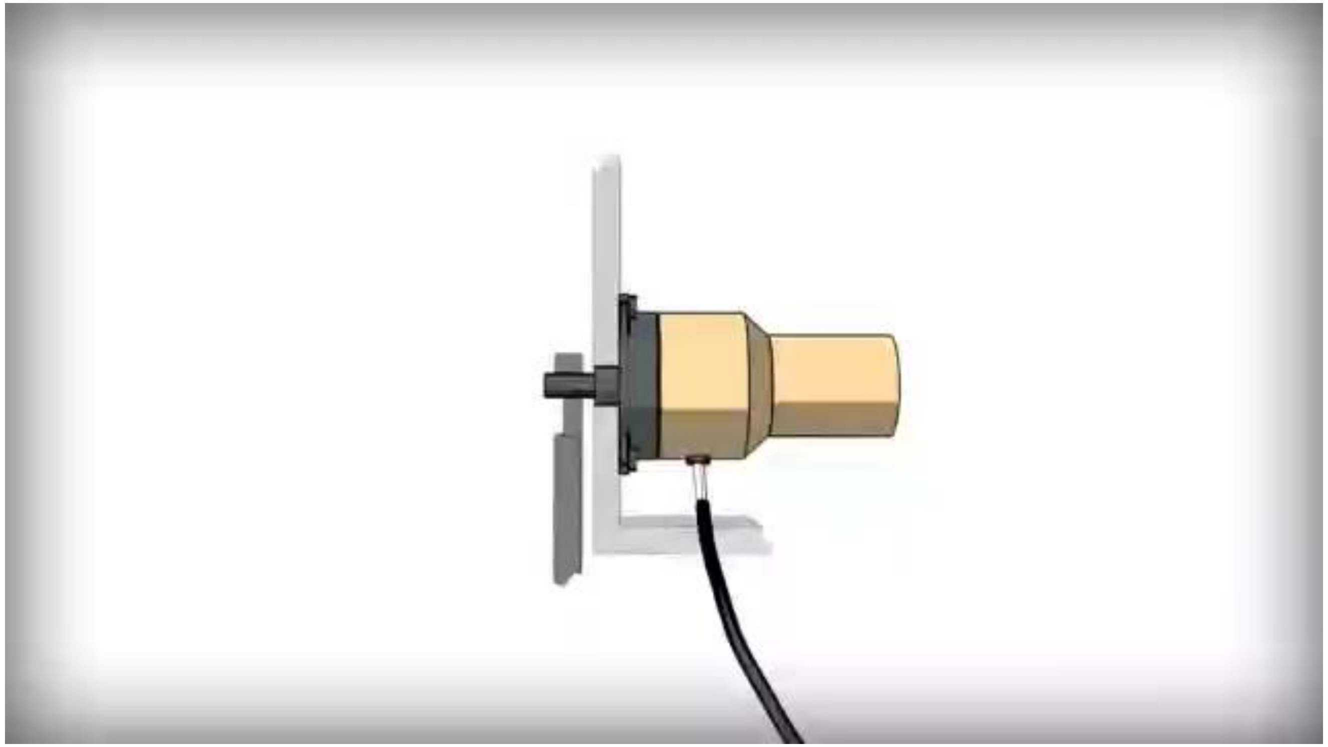
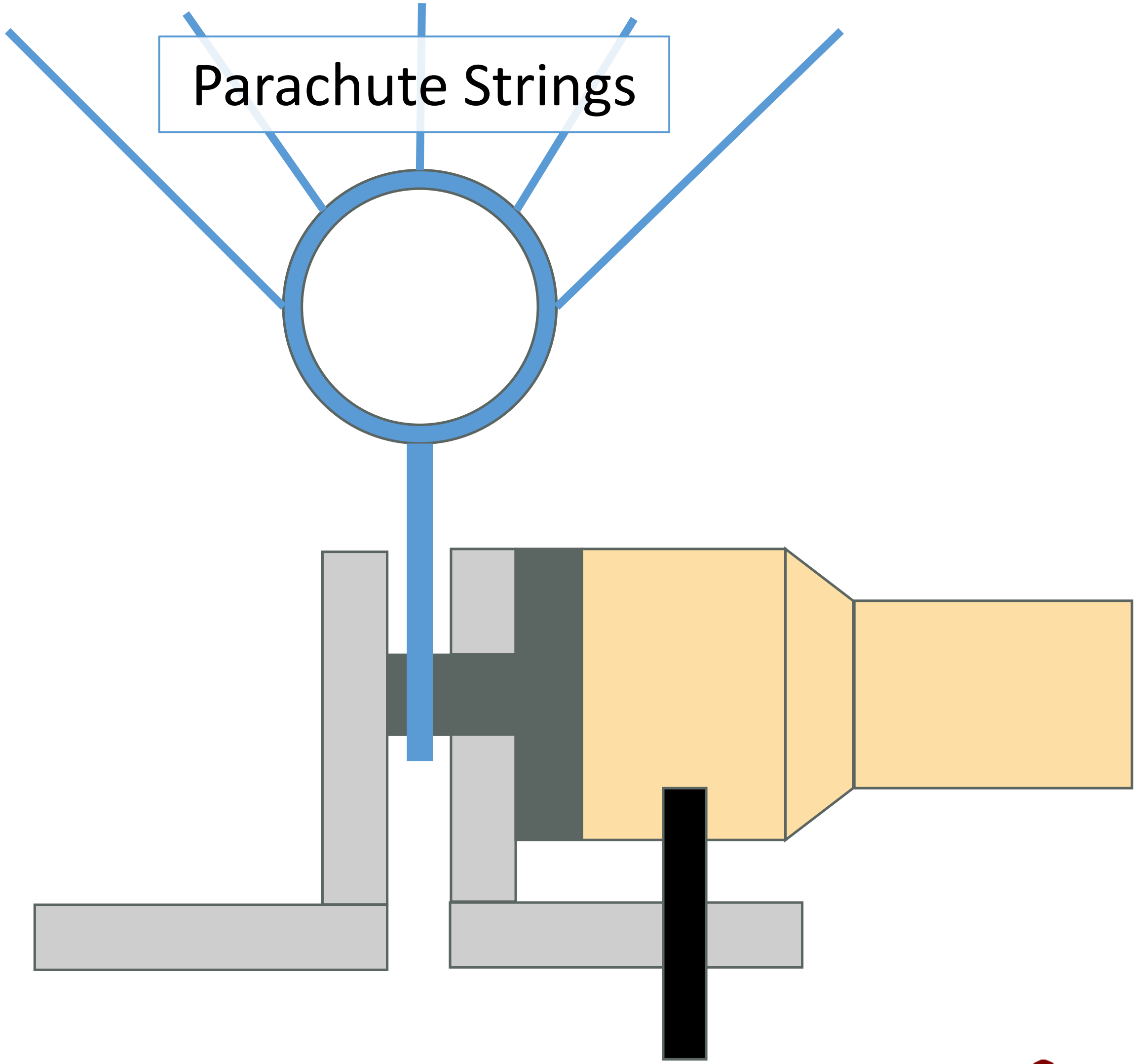
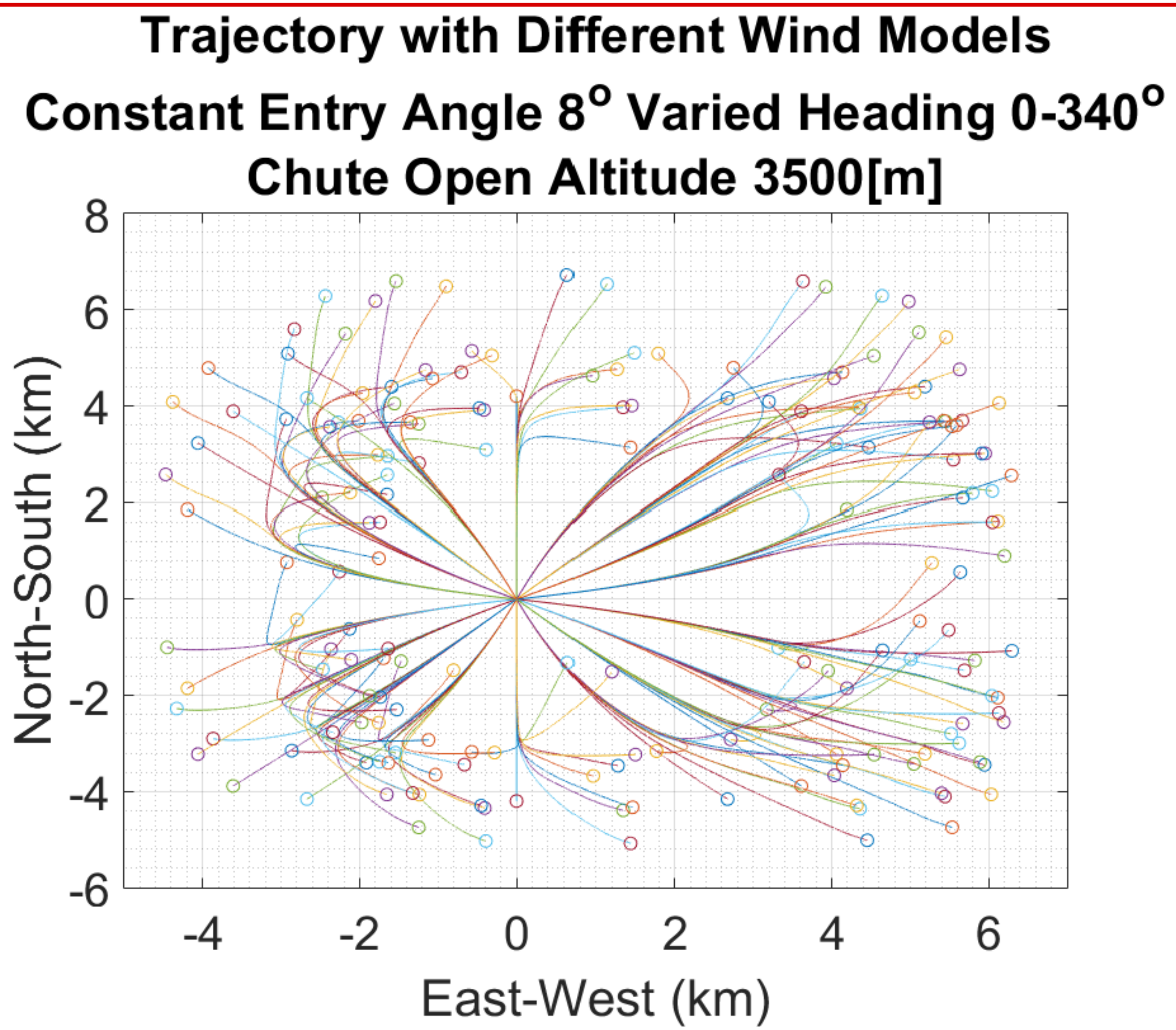


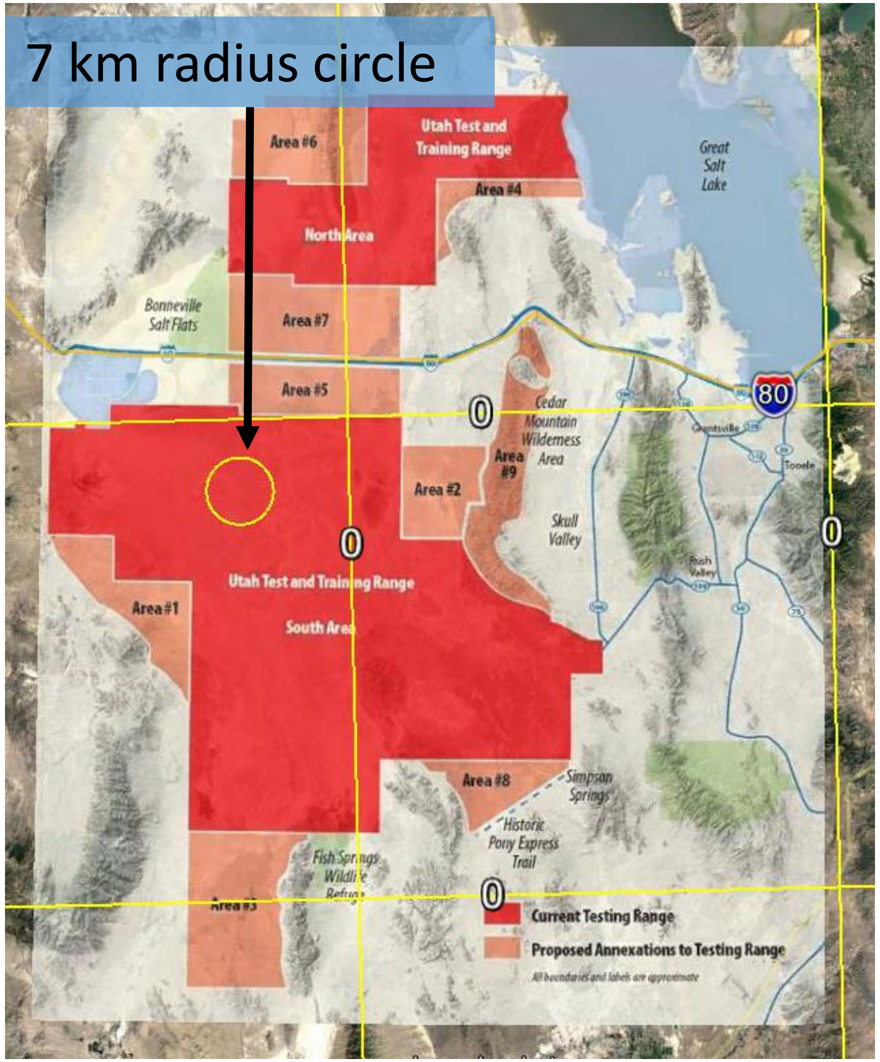
TiNi Aerospace
Standard PinPuller P5



Wind Influence on Trajectory

Raytheon

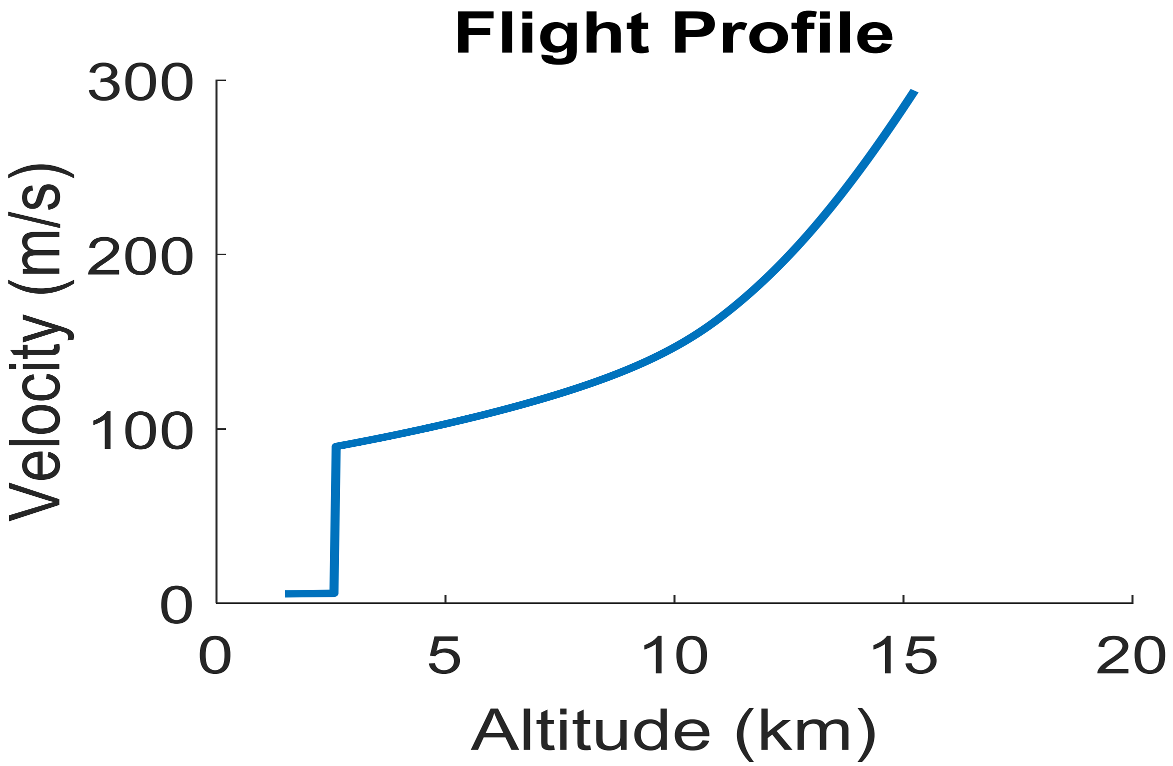




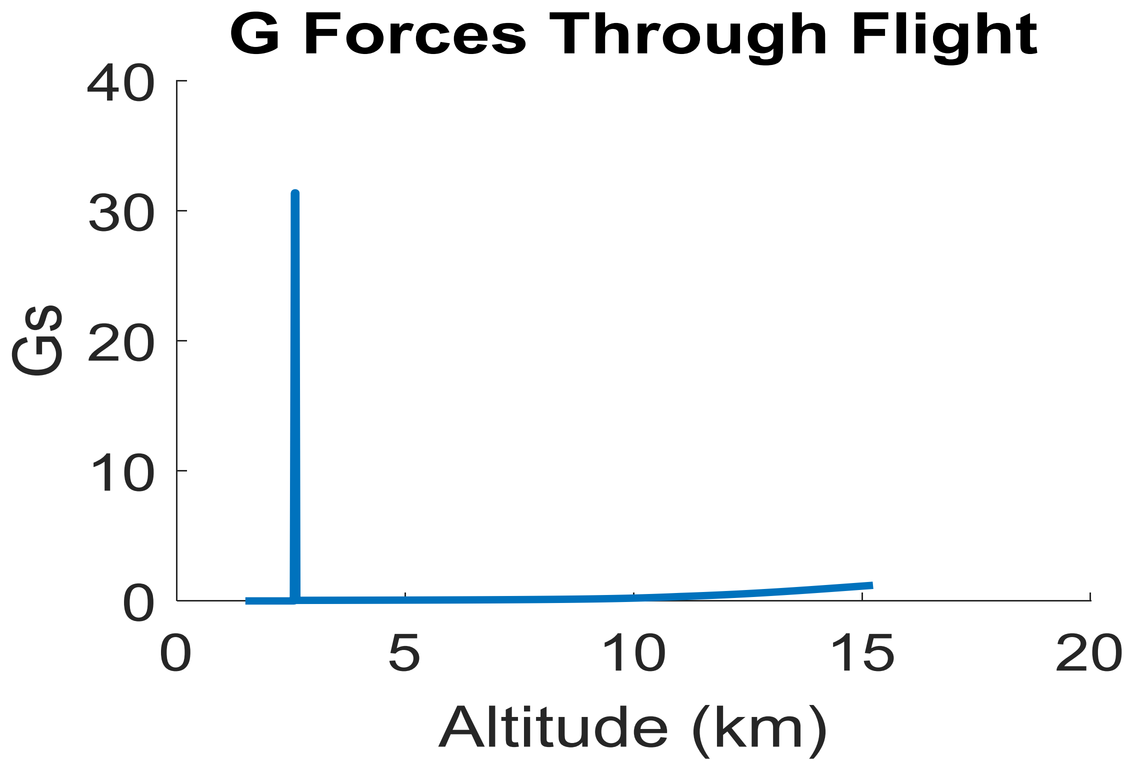
Overview | Descent | Landing | Avionics | Summary | Backup Slides

Design Feasibility

Raytheon



- Minimum height required: 43 m
  - Landing Velocity = 5.4 m/s
- UTTR Ranges 1500-2000 m MSL
  - Deploying at 3500 m MSL



- Minimum time required: 0.46 sec
  - G Load of 33.8 G's (DR 1.3)
- Sustained < 1.2 G's (DR 1.2)

Design Feasibility

Requirement	40 G Max Instantaneous Loading (DR 1.3)	6.5 Sustained G Loading (DR 1.2)	6.3 m/s Landing Speed
Design	33.8 G's	1.2 G's Max	5.4 m/s
Feasibility	✓	✓	✓

Cost	Mass	Volume
$650	1.04 kg	1.25 U

Landing Feasibility Analysis

Landing Requirements & Assumptions

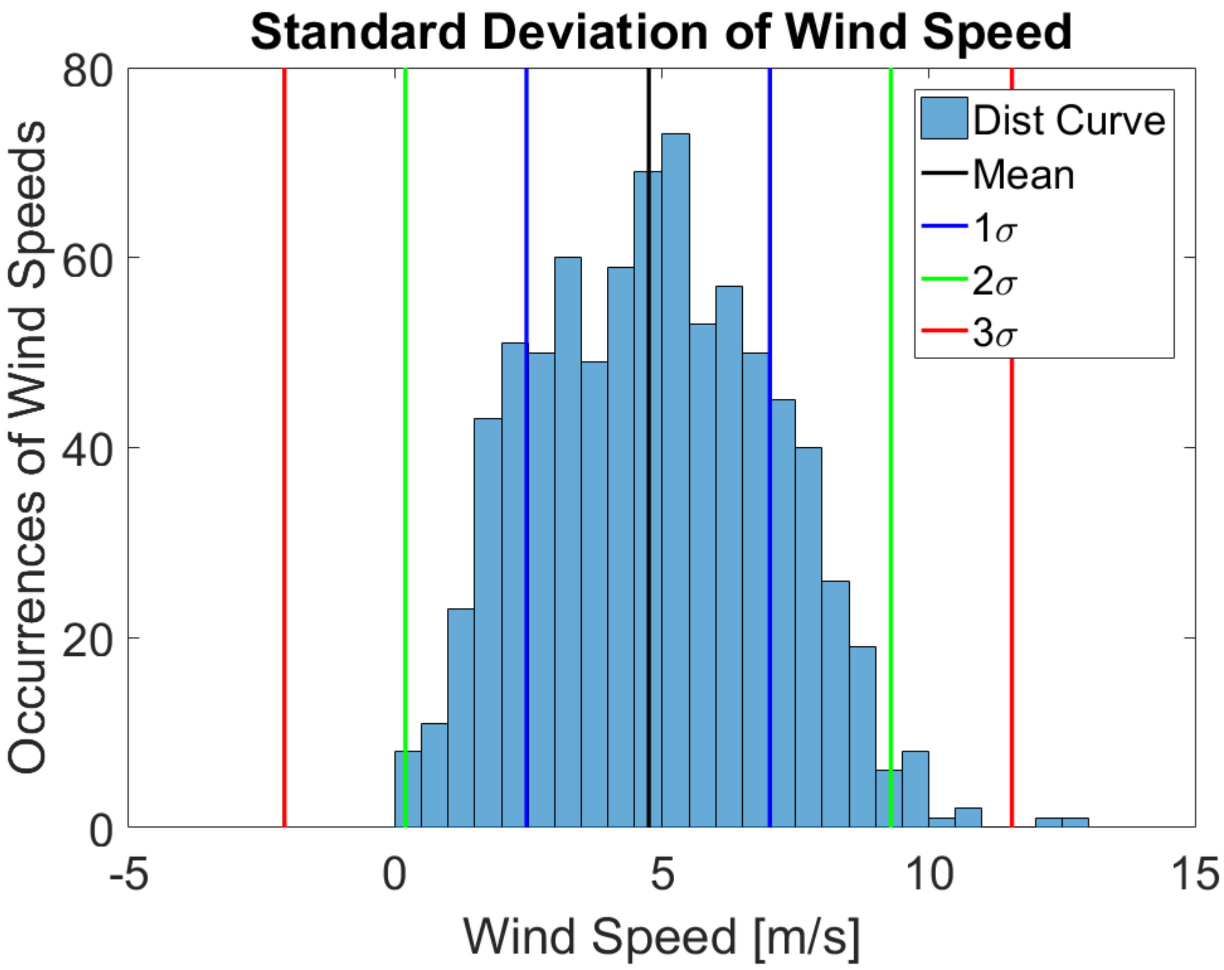
Raytheon

Requirements

- The instantaneous loading experienced during landing shall not exceed 40G's (DR 1.3)
- Landing mechanisms shall meet mass and volume requirement (FR.2)
- Landing deployment mechanisms shall have an interface with the CDH system

Assumptions

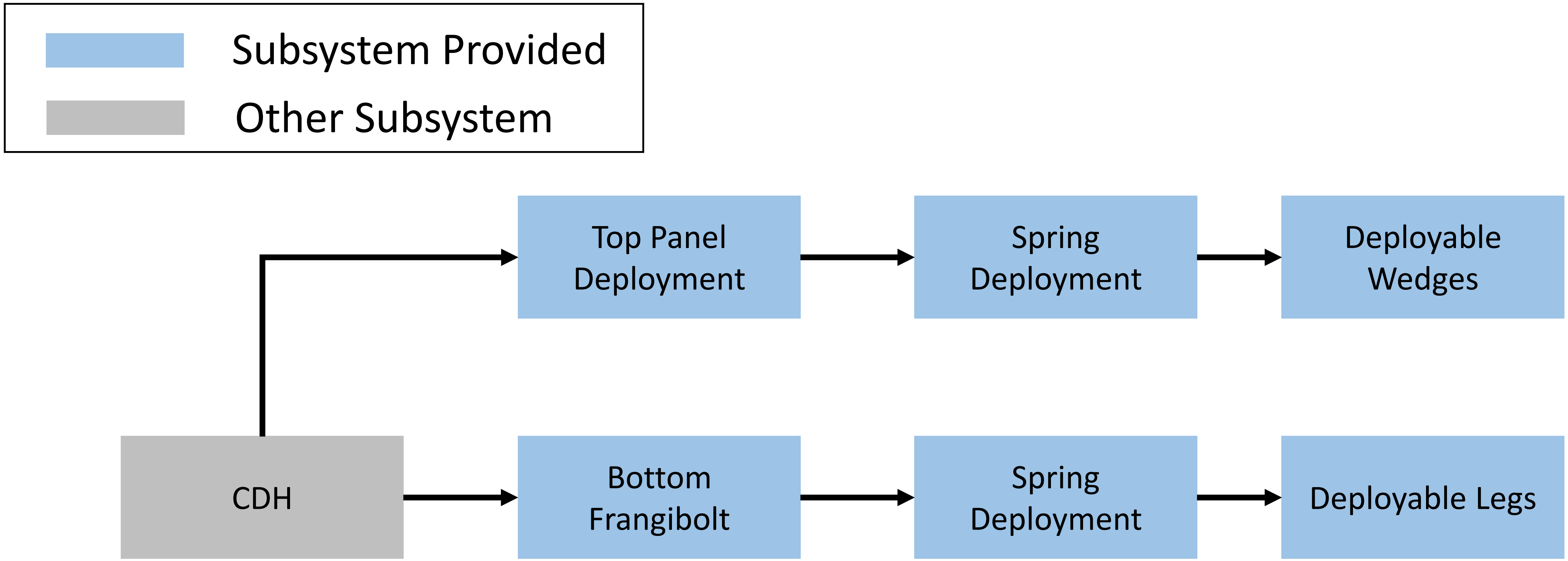
- Maximum vertical velocity : 6.3 m/s
- Mass: 4 kg
- Average Wind speed : 4.74 m/s
  - Standard deviation: 2.27 m/s



Overview | Descent | Landing | Avionics | Summary | Backup Slides

Landing Functional Block Diagram

Raytheon



Base Leg Design

Leg Design

Dimensions: 7.3 cm x 1.2 cm x 1.2 cm

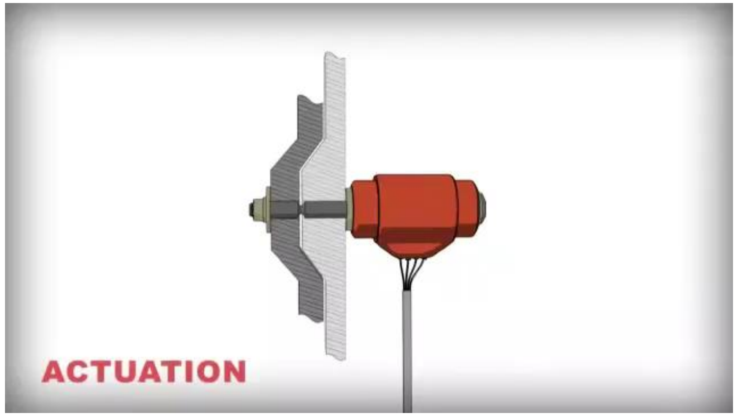
Effective Impact Area: 6.2 cm^2

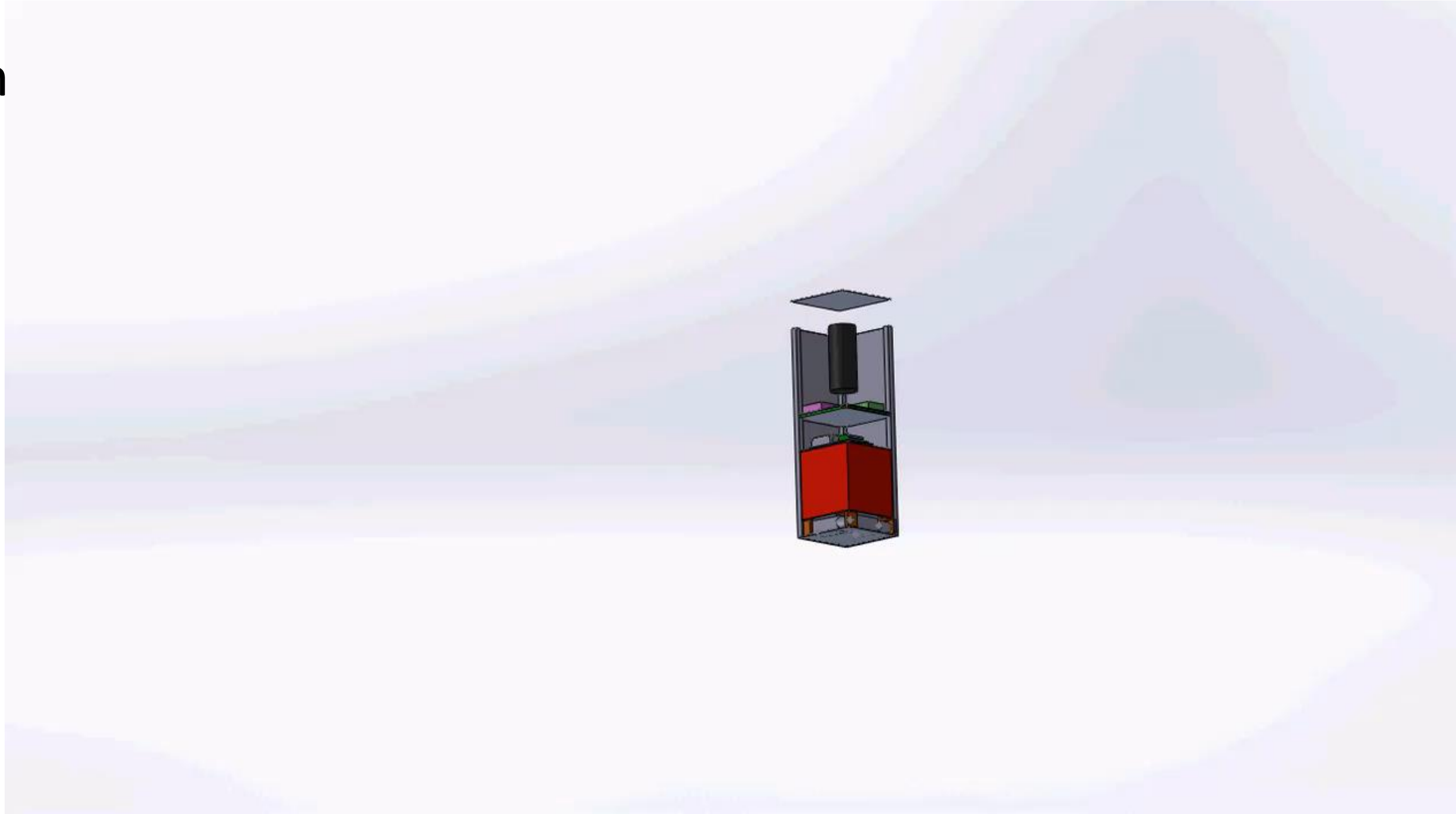
Duocel Aluminum Foam

Density: 3-12% of Aluminum

Compression Strength: 2.53 MPa

Max Compression: 70%

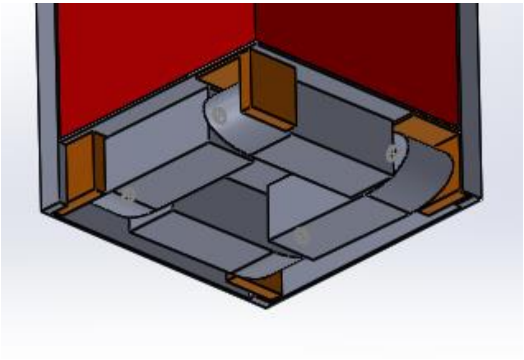


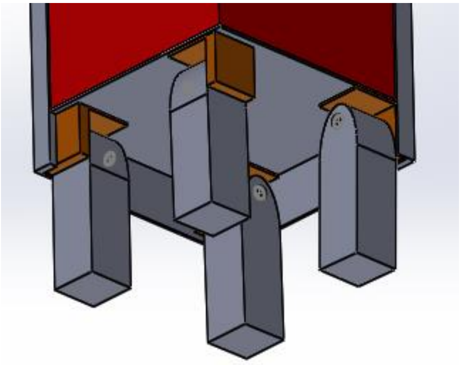


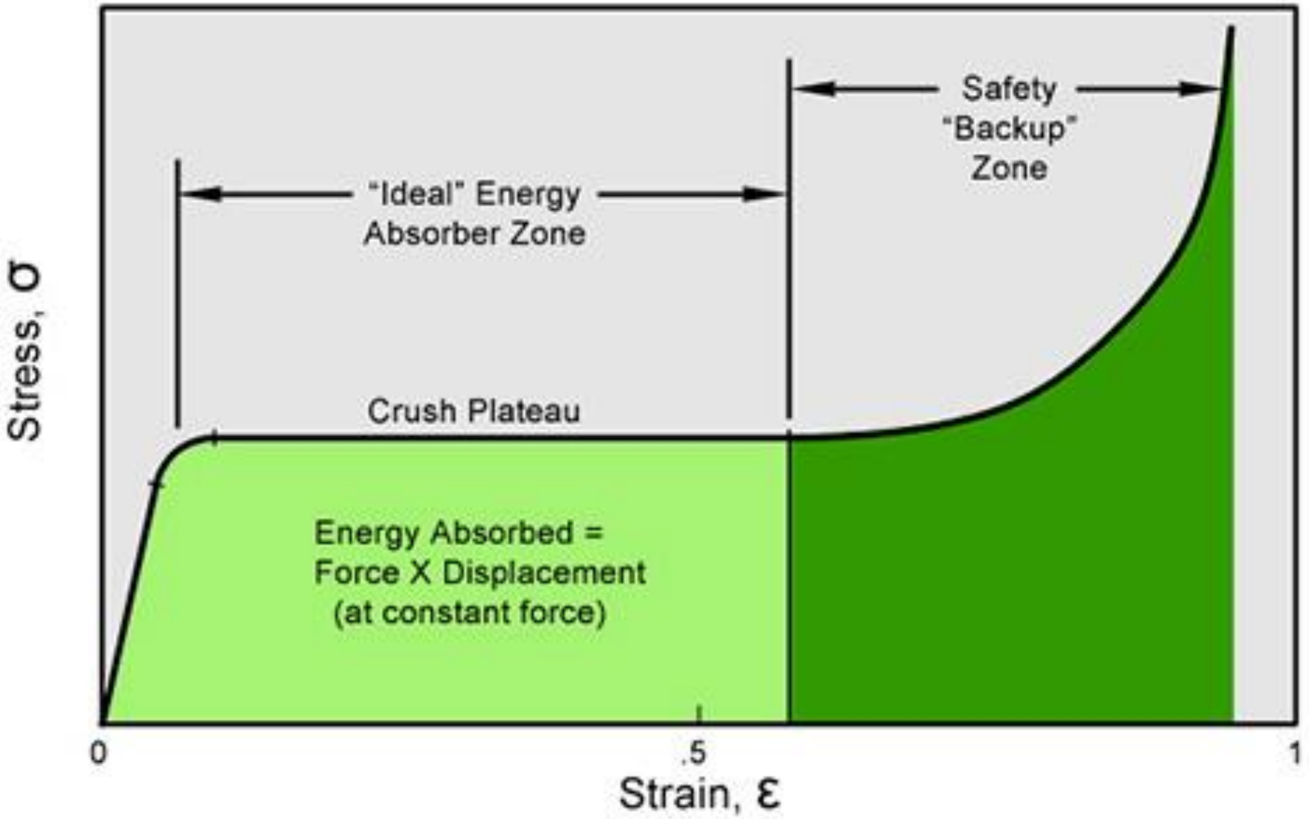
Leg Energy Absorption

Raytheon

Property	Value
Effective Impact Area	6.2 cm^2
Compression Strength	2.53 MPa
Max-Allowable Landing Speed	6.3 m/s
Max-Possible Deformation	5.1 cm
Expected Landing Speed	5.3 m/s
Expected Deformation	4.8 cm







Collapsible Mechanisms for Sides

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Aluminum Side Panels

Dimensions: 9 cm x 10 cm x 0.7 cm

Effective Impact Area: 6.2 cm^2

Center Foam Structure

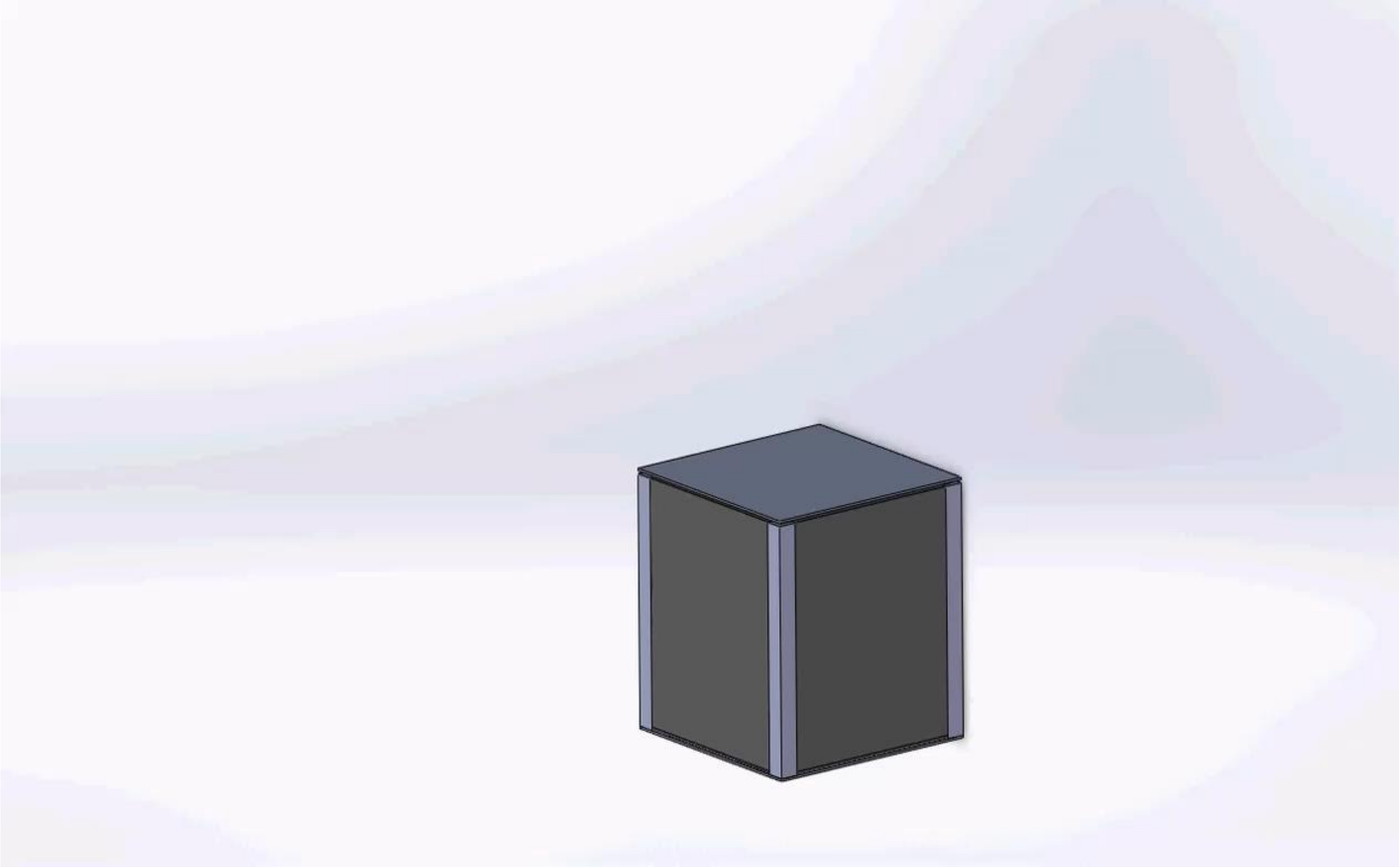
Dimensions: 9 cm x 9 cm x 0.9 cm

Duocel Aluminum Foam

Density: 3-12% of Aluminum

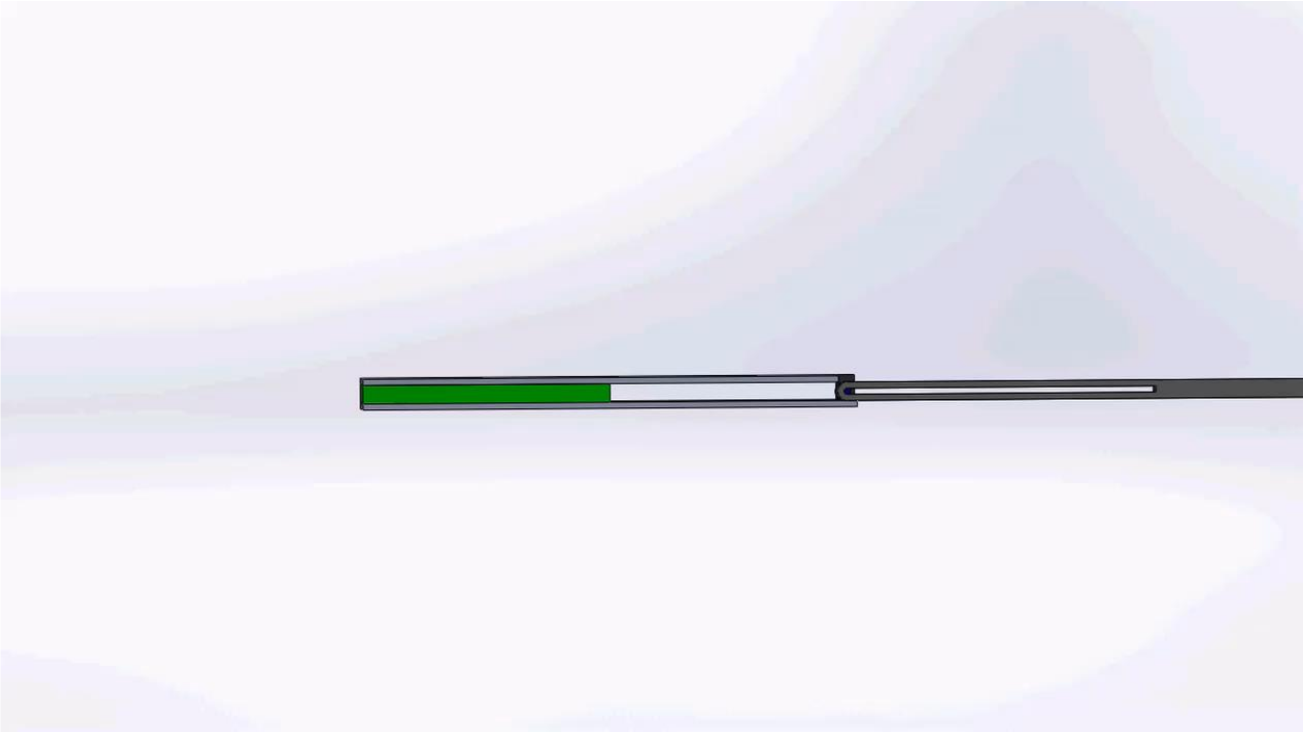
Compression Strength: 2.53 MPa

Max Compression: 70%



Collapsible Side Walls

Property	Value
Effective Impact Area	6.2 cm^2
Compression Strength	2.53 MPa
3σ Wind Speed	11.55 m/s
3σ Rotation Speed	32.08 rad/s
3σ Deformation	5.7 cm
Max-Possible Deformation	6.3 cm



Feasibility Summary

Requirement	40 G Max Instantaneous Loading (DR 1.3)	5.4 m/s Landing Speed	3σ Horizontal Speed of 11.55 m/s
Design	40 G Limit	6.3 m/s Allowable	12.06 m/s Allowable
Feasibility	✓	✓	✓

Cost	Mass	Volume
$650	0.78 kg	0.25 U

Avionics Feasibility Analysis

Requirements & Assumptions

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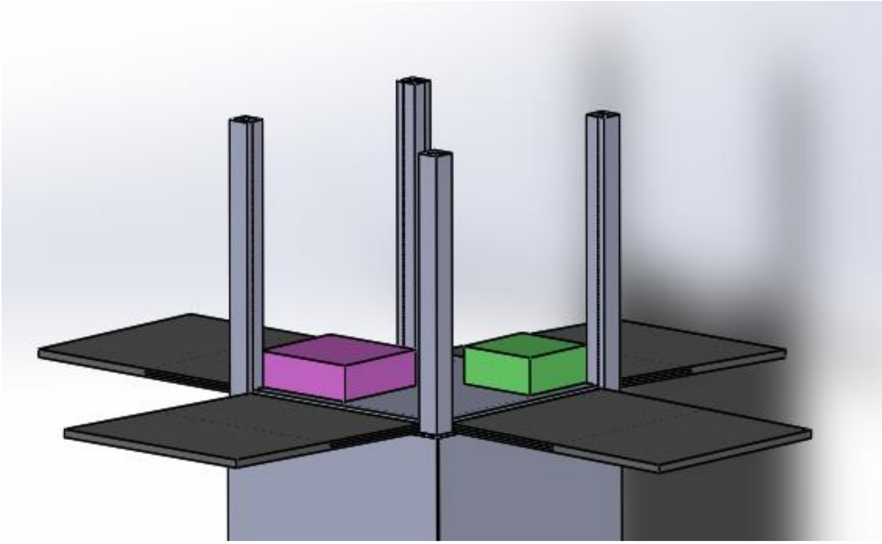
Requirements

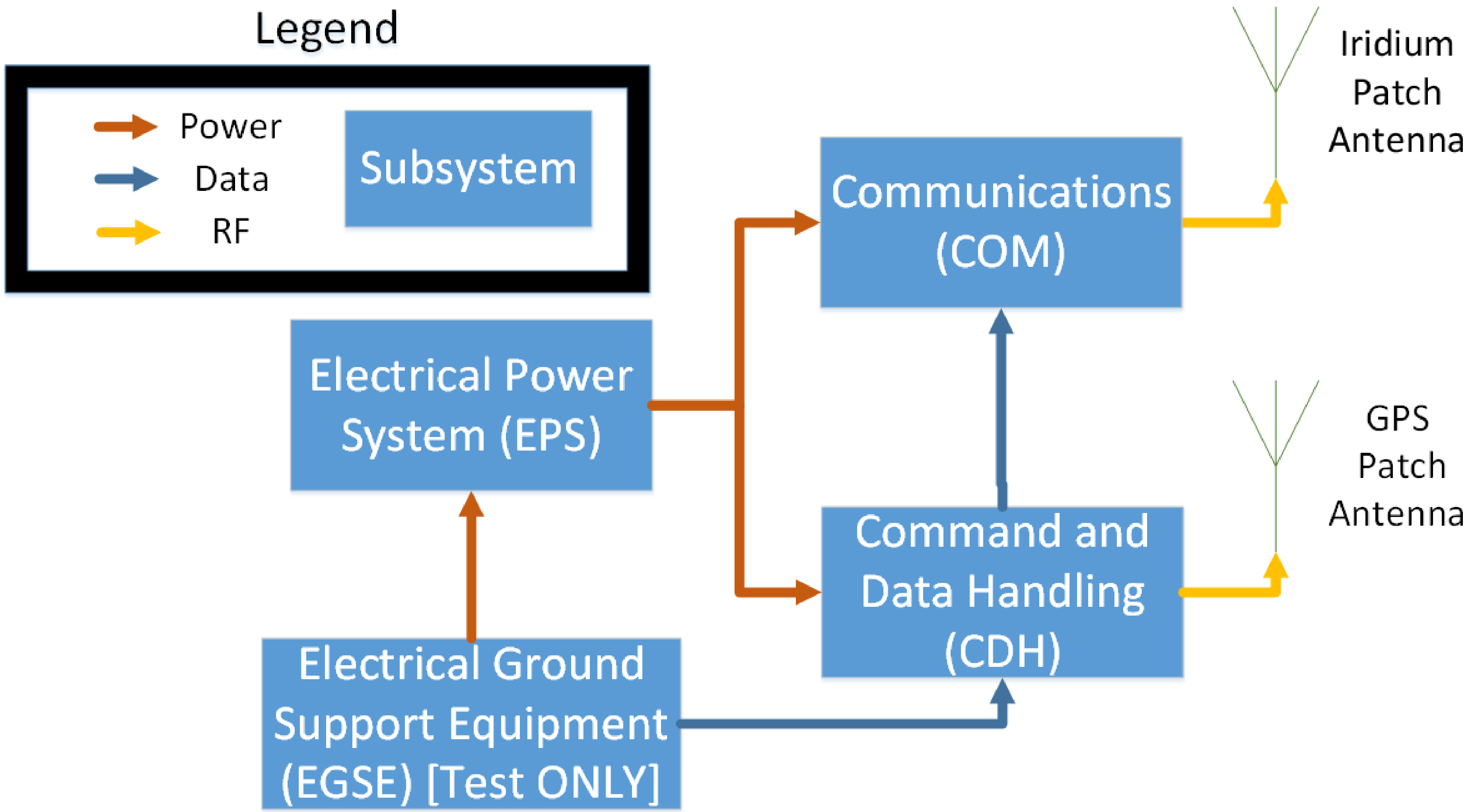
- Vehicle location must be determined (FR.4)
- Vehicle must transmit its location to search party (DR 4.1)
- Logical decisions need to be made based on sensor input
- Electronic components must be supplied adequate power
- Avionics shall meet mass and volume requirements (FR.2)



Assumptions

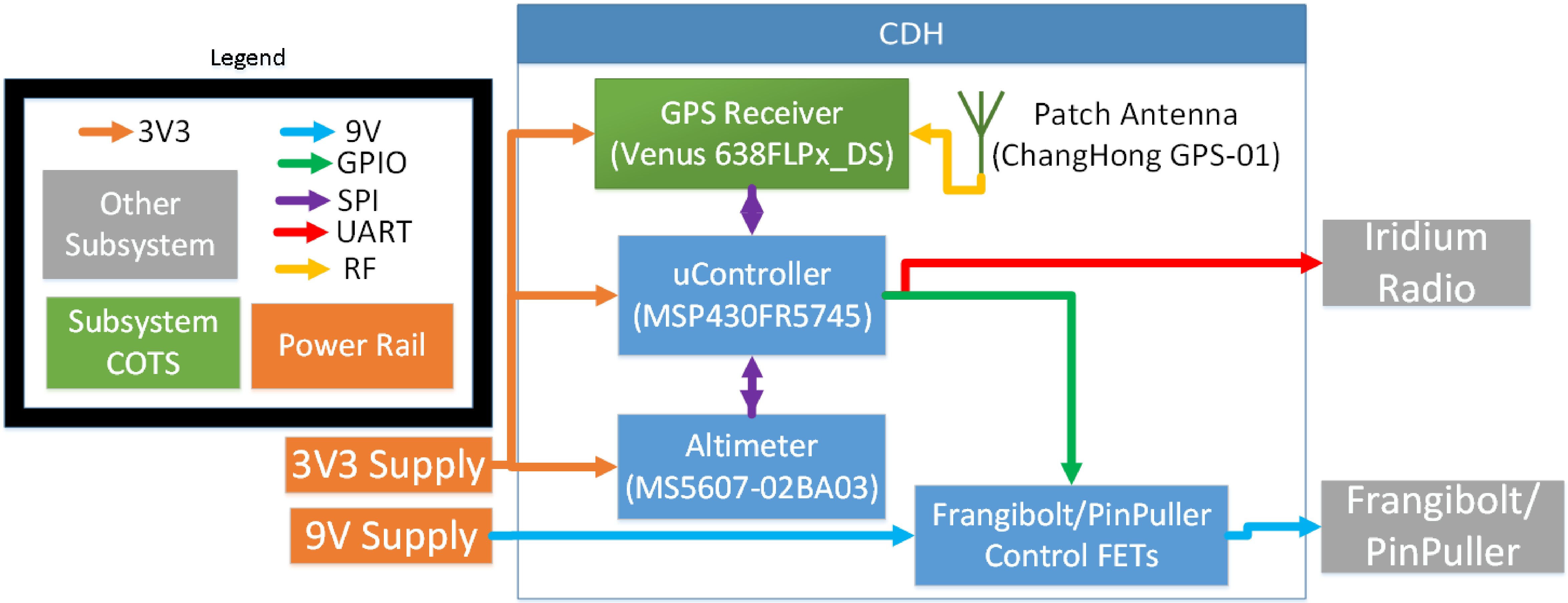
- Patch antennae have at least a 120 degree view of open sky
- An operating Iridium satellite is overhead

Avionics System Layout



Command Data & Handling(CDH)

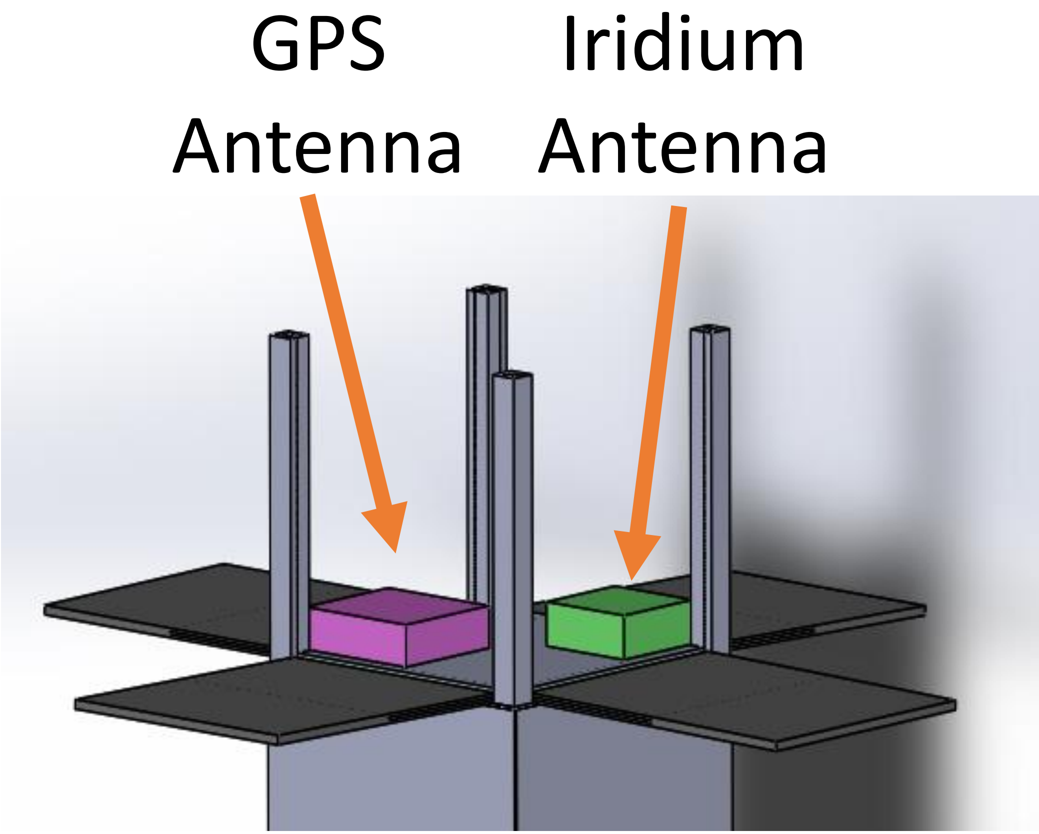
Raytheon



GPS Link Budget

Raytheon

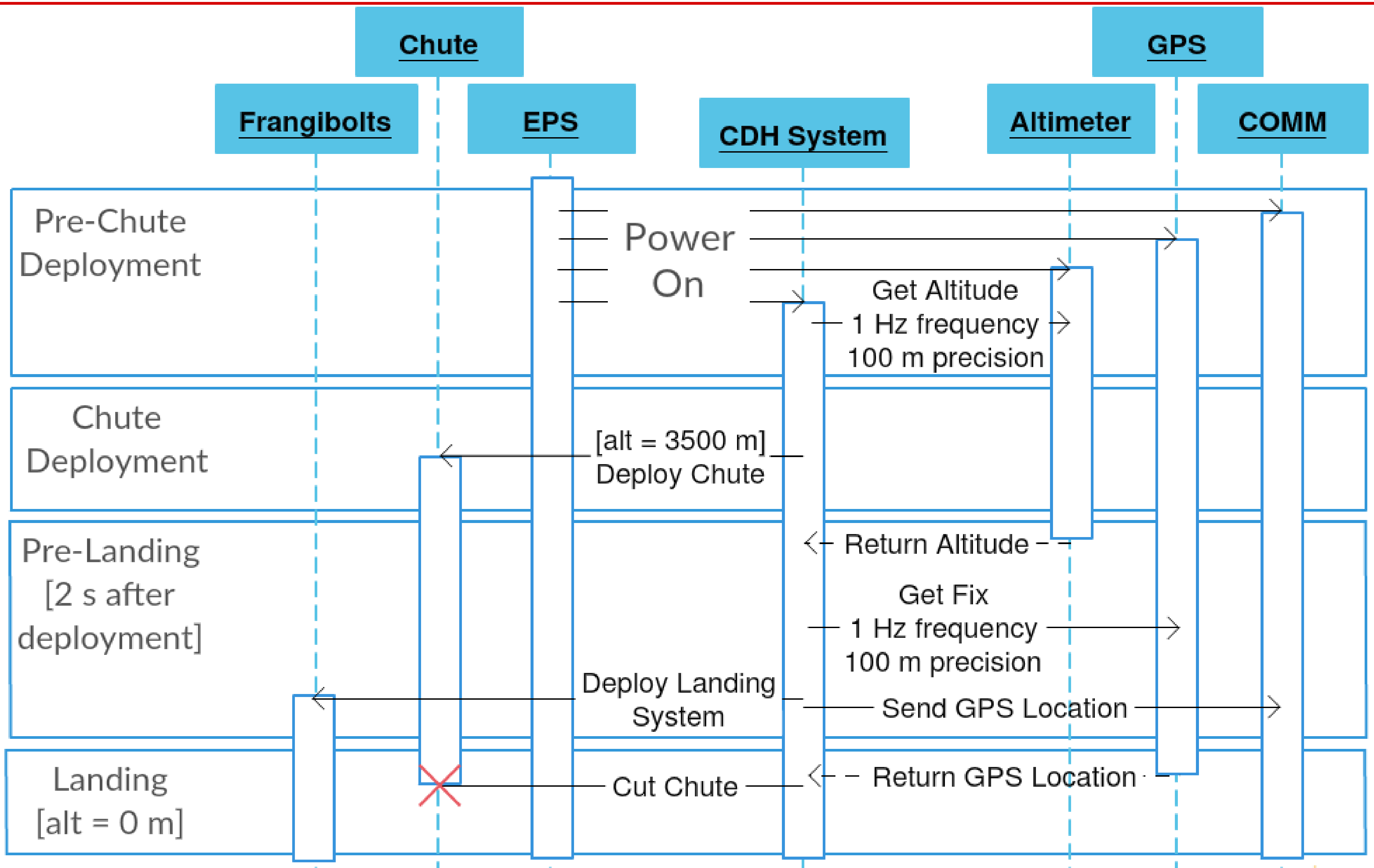
DR 4.1



	Signal Strength	Noise Figure
Estimated Signal	-155 dBm [Worst Case Stress Test]	N/A
Antenna Gain	-1 dBi	N/A
LNA Gain	28 dB	1.5 dB
Receiver Incident	-128.5 dBm	1.5 dB
Minimum Requirement	-145 dBm [Acquisition]	2.0 dB Max
Feasibility	✓	✓

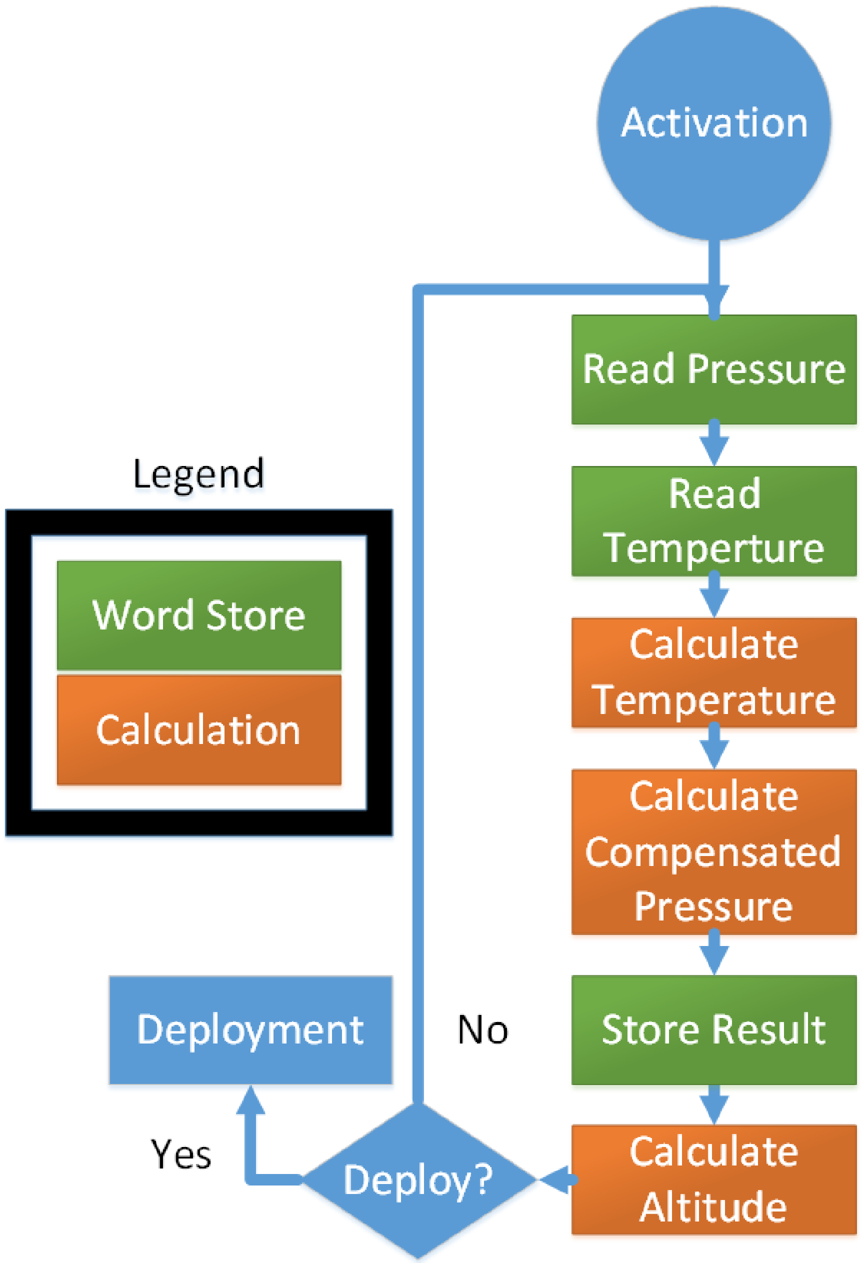
Command & Data Handling Sequence Diagram

Raytheon



Microcontroller Data and Processing Budget

Raytheon



Step	Storage Needed [Words] Over Flight	Execution Time [ms] Per Iteration
Read Pressure	1	6.8
Read Temperature	1	6.8
Calculate Temperature	0	2.07
Calculate Comp. Pressure	0	6.8
Store Result	2	12.6
Calculate Altitude	0	0.76
Subtotal	332	35.83
Code Overhead	5000	N/A
Look Up Table Overhead	1000	N/A
Maximum	8000	500
Total	6332	35.83
Feasibility	✓	✓

CDH Baseline Design Feasibility

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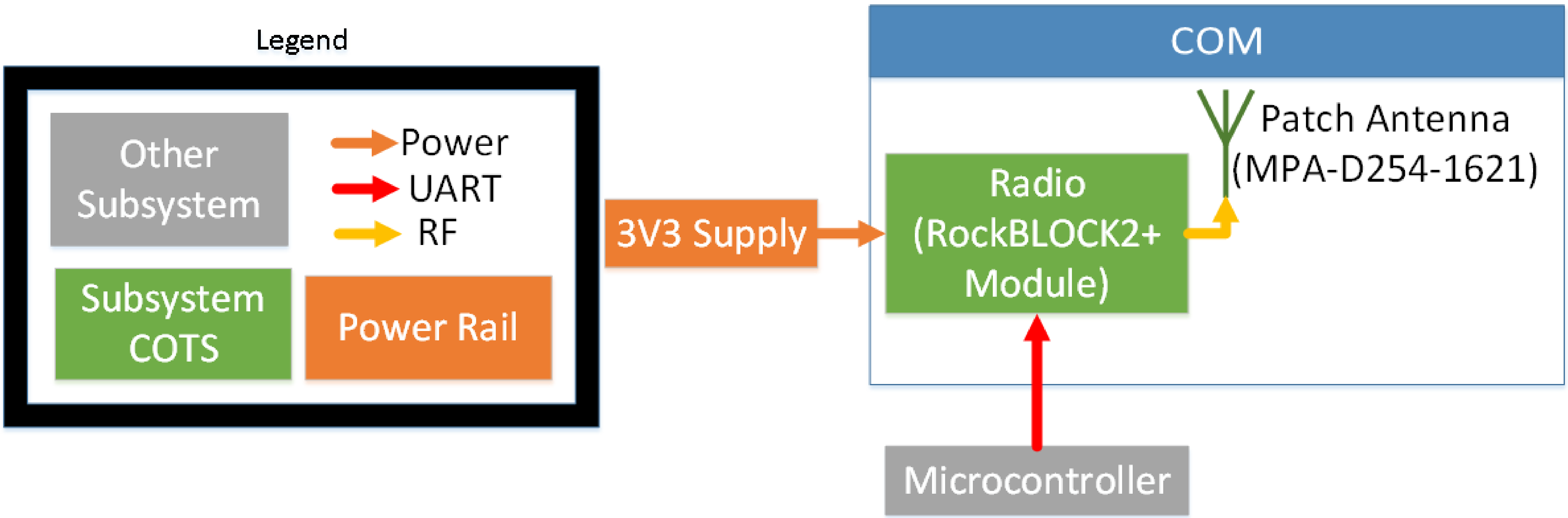
Design Selection	Required Spec	Achievable Value	Feasibility
GPS (Venus638FLPx)	• 100 m position knowledge precision • 1 Hz update rate • GGA NMEA output messages	• 2.5 meters min CEP • 20 Hz max update rate • Supports GGA formats	✓
Altimeter (MS5607-02BA03)	• 851 Pascal precision (100 m Altitude knowledge) • Update at 1 Hz	• 150 Pascal precision • Can Update at 10 Hz	✓
MicroController (MSP430FR5754)	• Process altimeter data at 1 Hz • Store all altimeter data	• Can process at 27 Hz • Can store 6 flights worth of altimeter data	✓

COM

Raytheon

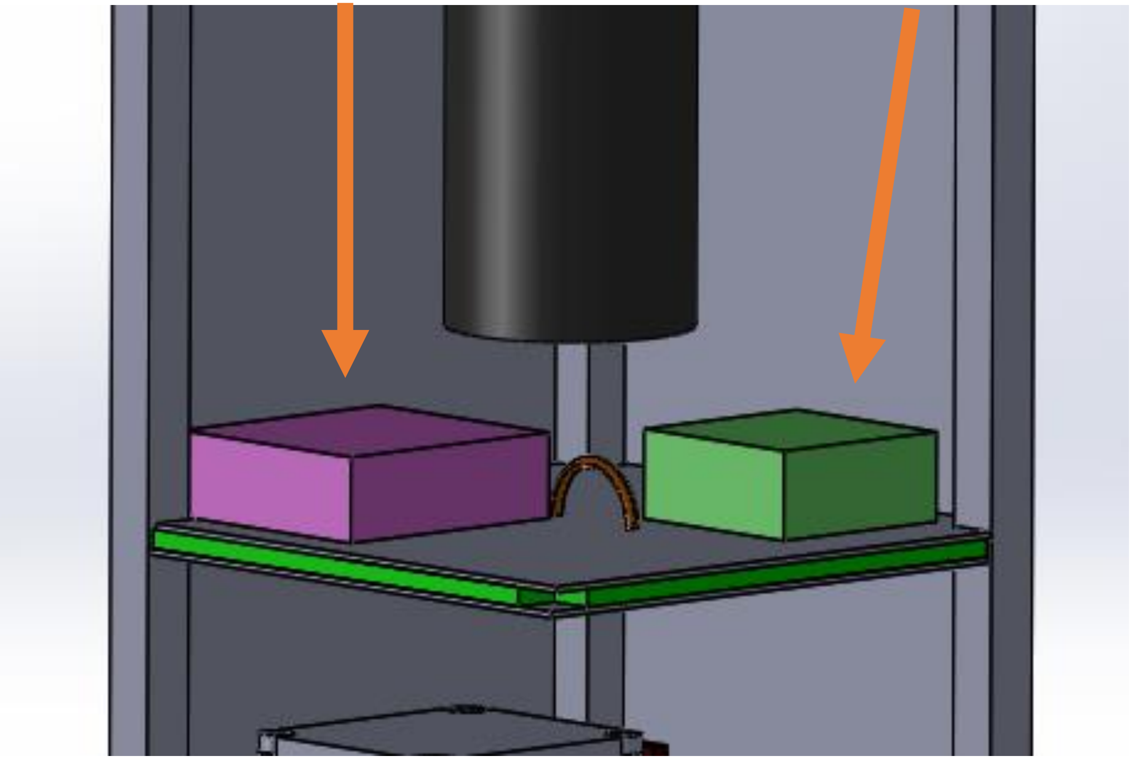
DR 4.1



Iridium Link Budget

Raytheon

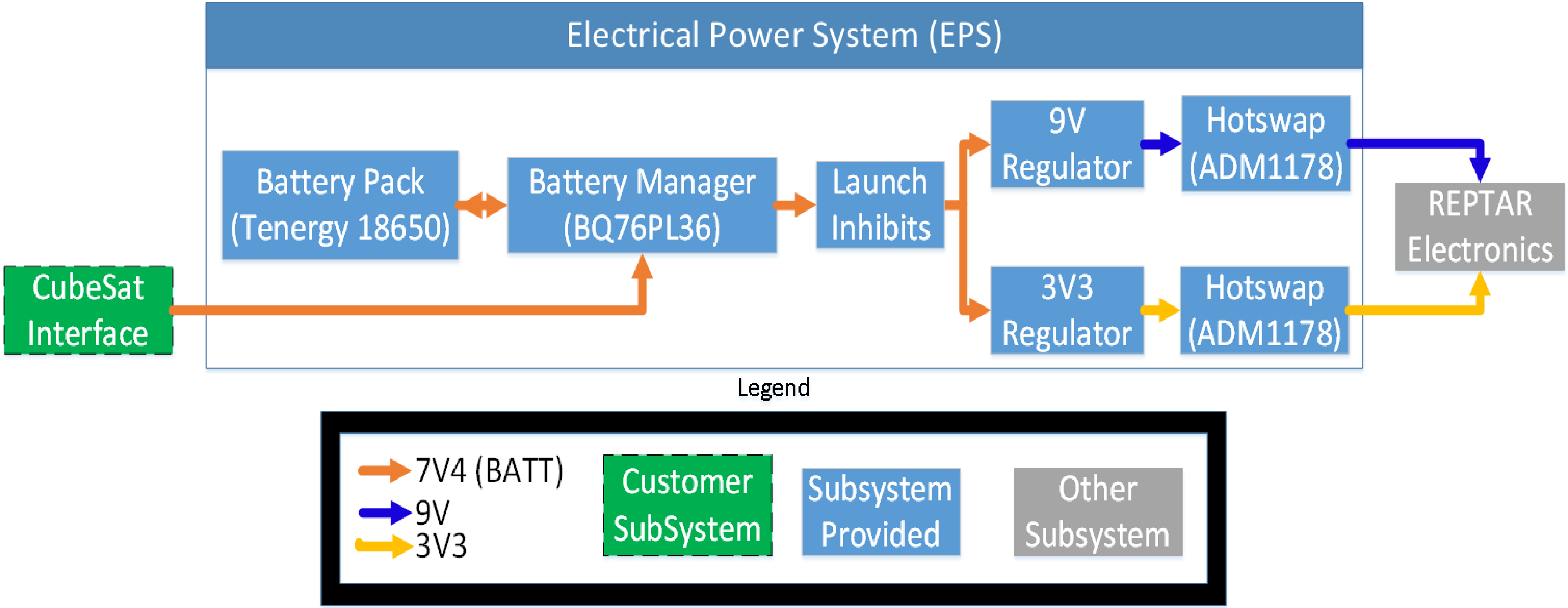
DR 4.1



	Signal Strength
Transmitter Output	32 dBm
Antenna Gain	2.5 dBi
Path Loss	143 dB
Misc. Loss	7 dB
Receiver Incident (without Antenna)	-115.5 dBm
Satellite Sensitivity	-117 dBm
Feasibility	✓

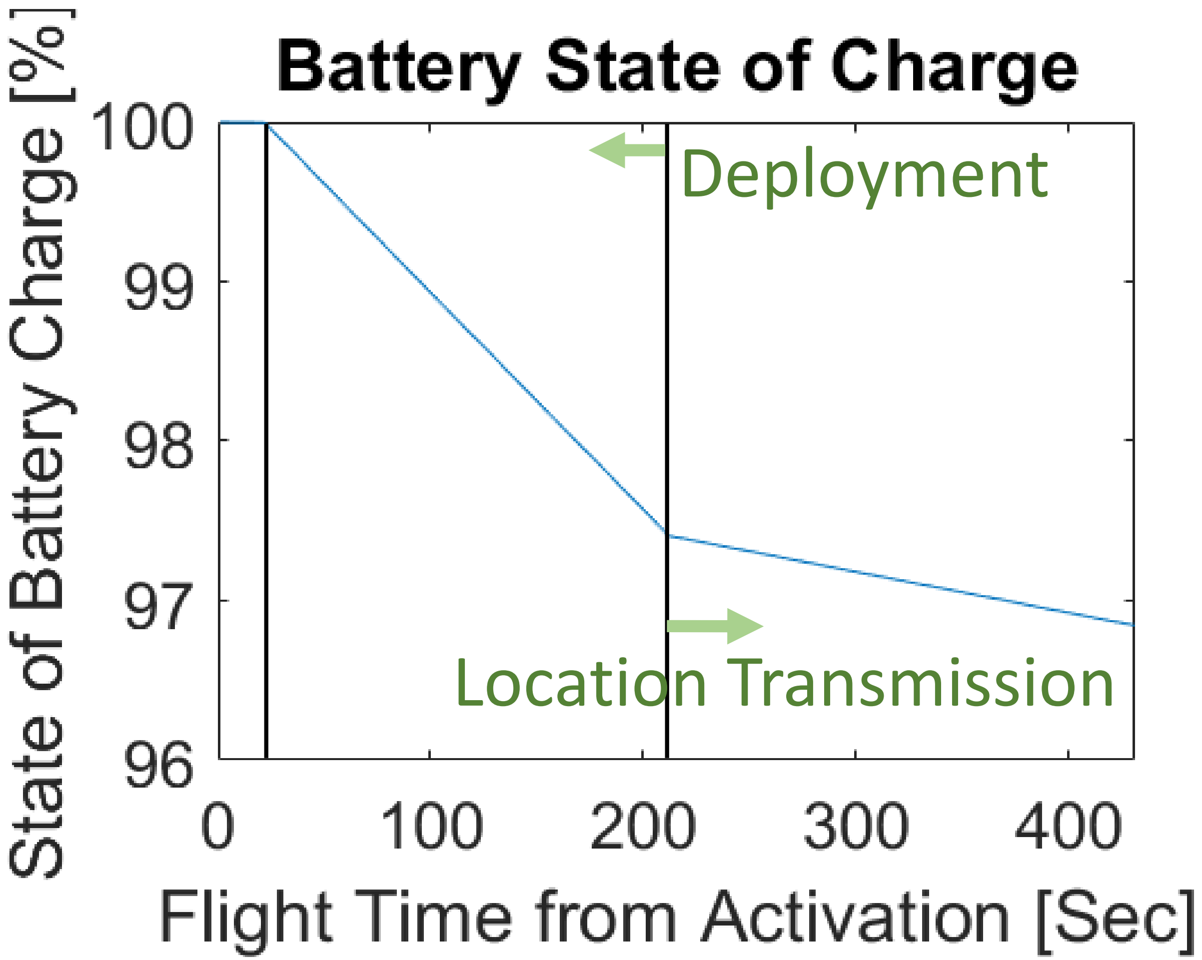
Electrical Power System (EPS)

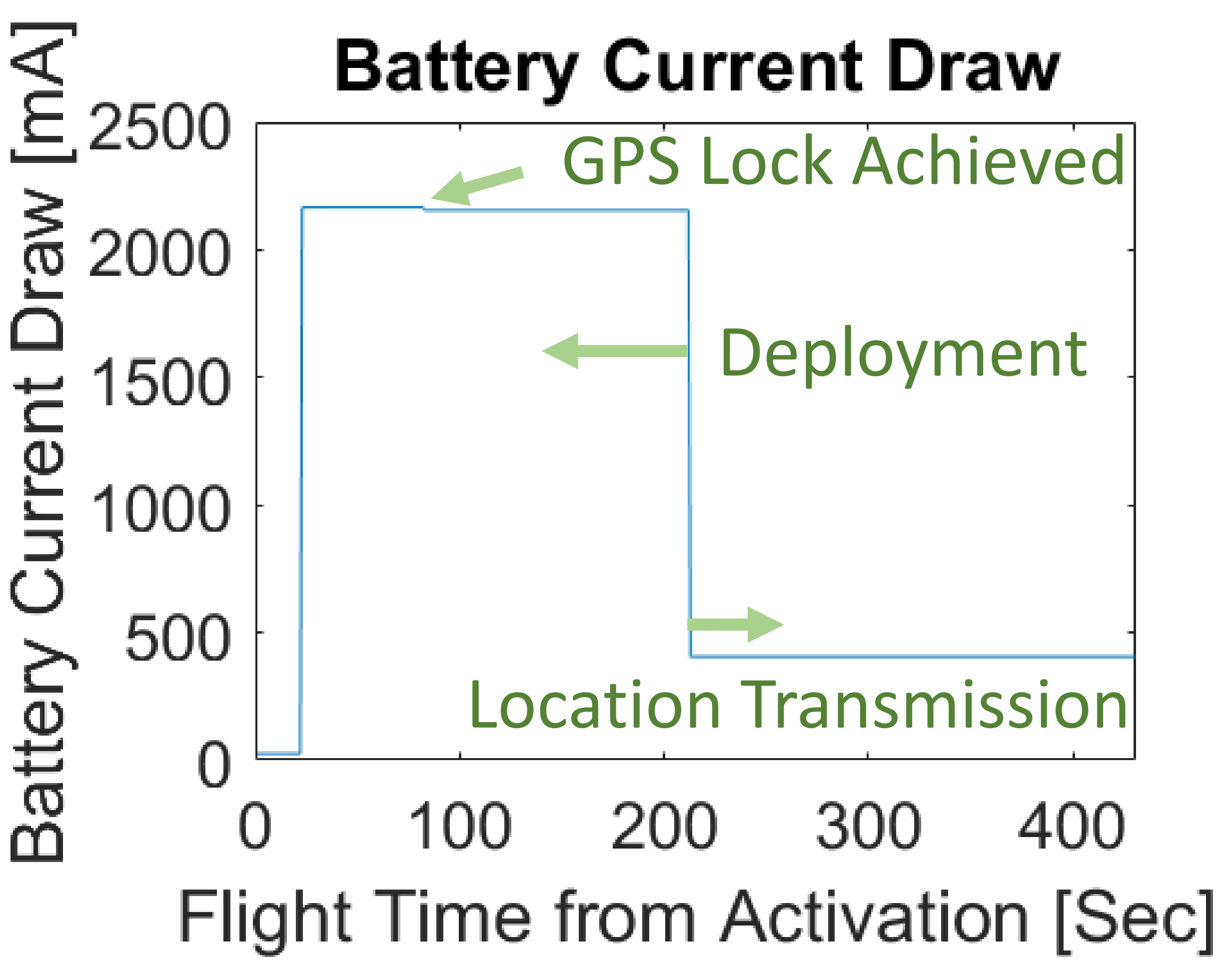
Raytheon



Power Budget

Raytheon





Assumes 80% Efficient Regulators

Baseline Design Feasibility

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Design Selection	Required Spec	Achievable Value	Feasibility
Maximum Battery Current Draw	• 5 Amperes maximum sustained current draw	• 2.12 Amperes maximum sustained current draw	✓
Maximum Regulator Current Draw	• 2.5 Amperes maximum draw for each regulator	• 1.85 Amperes Max (9V) • 0.5 Amperes Max (3V3)	✓
Battery State of Charge at Landing	• State of Charge must stay over 20% throughout mission life	• State of Charge minimum of 97.5% over mission life.	✓
Broadcast Time After Landing	• Broadcast ground location for at least 5 minutes.	• Can broadcast ground location for 920 minutes.	✓

Systems Integration and Summary

Systems Integration

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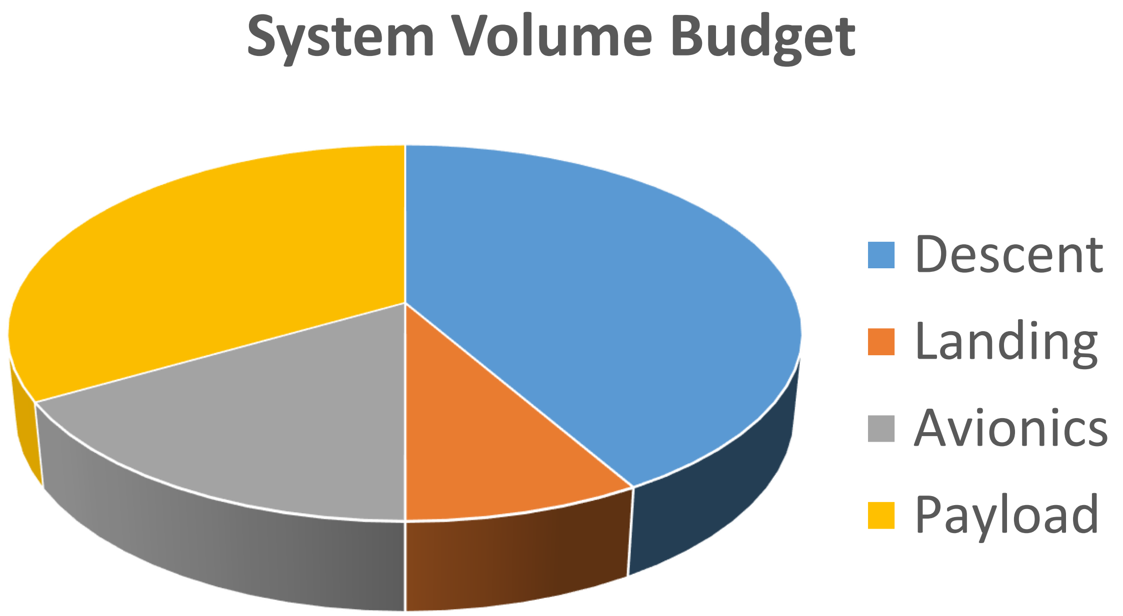
Subsystem	Volume	Mass	Cost
Descent	1.25 U	1.03 kg	$650
Landing	0.25 U	0.78 kg	$650
Avionics	0.5 U	0.5 kg	$850
Payload	1 U	1.33 kg	--
Frame	--	0.23 kg	$250
Total	3 U	3.87 kg	$2,400



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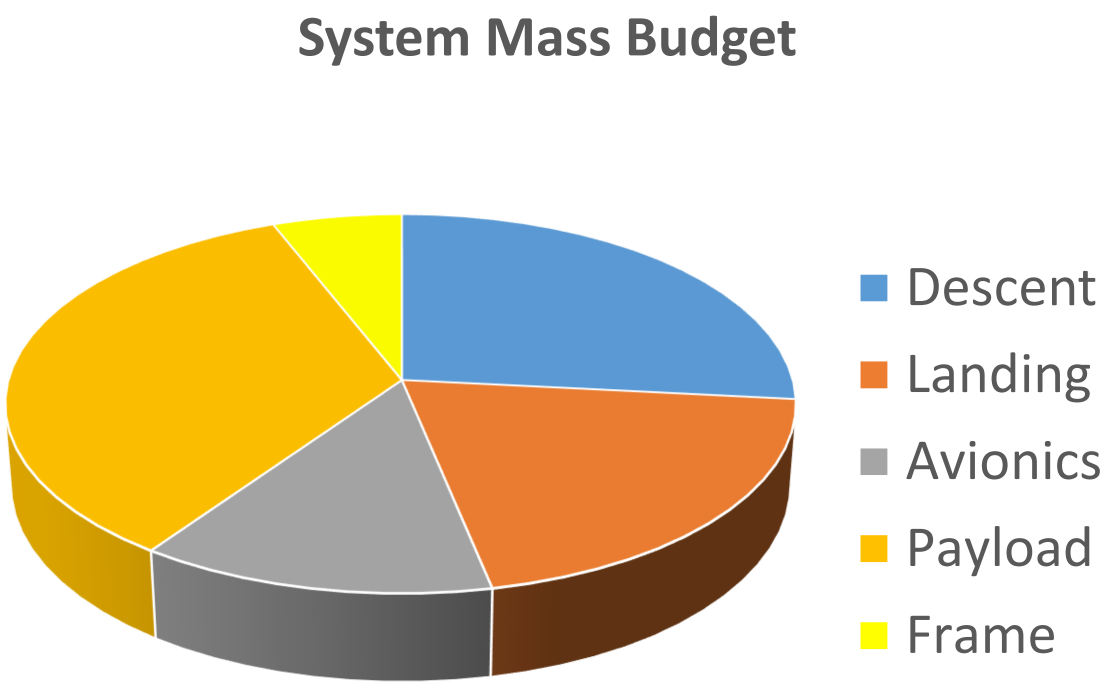

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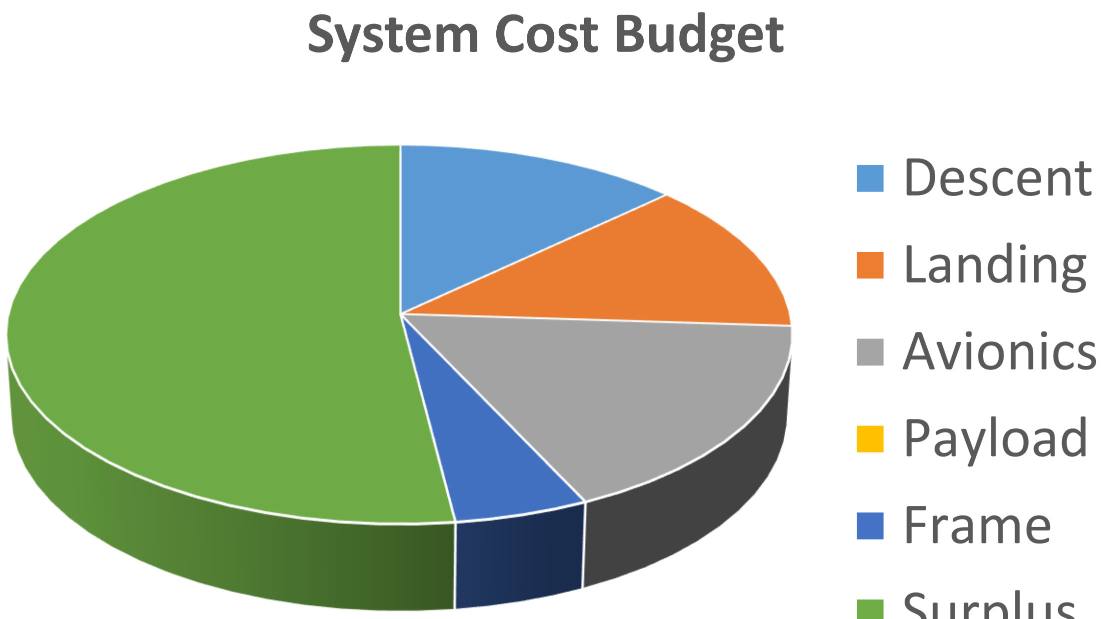
Frame	--	0.23 kg	$250
Total	3 U	3.87 kg	$2,400



Full System Space and Launch Survivability Tests

General Vibration Test (DR 1.4)	Environmental Chamber Test (DR 1.1 & DR 1.3)	High altitude drop test (DR 1.2 & DR 1.3)
• **Hardware/Software:** Full Integrated Unit • **Facility**: Cascade Tek (Longmont) • **Risk**: High	• **Hardware/Software**: Full Integrated Unit • **Facility**: Aero Dept. / Cascade Tek (Longmont) • **Risk**: High	• **Full System Test**: Drop from a height of greater than 3500 m MSL • **Hardware/Software**: Fully integrated unit • **Facility**: Plane • **Risk**: High

Future Work

- Sliders / Risers for Parachute Deployment
- Alternative Top Plate Deployment Methods
- Materials Selection
- Friction Analysis
- Antennae pattern
- CDH Algorithm Model
- Regulator Simulation

Questions?

Raytheon

Backup Slides

Thermal Analysis

Background

DR 1.5 & DR 1.6

- Temperature in space tends to stay between 2 and 5 K
- There may be a requirement for the satellite, or at least specific components, to be kept warm through the use of a heater
- Investigating whether a heater, which would take up space, is necessary

Requirements

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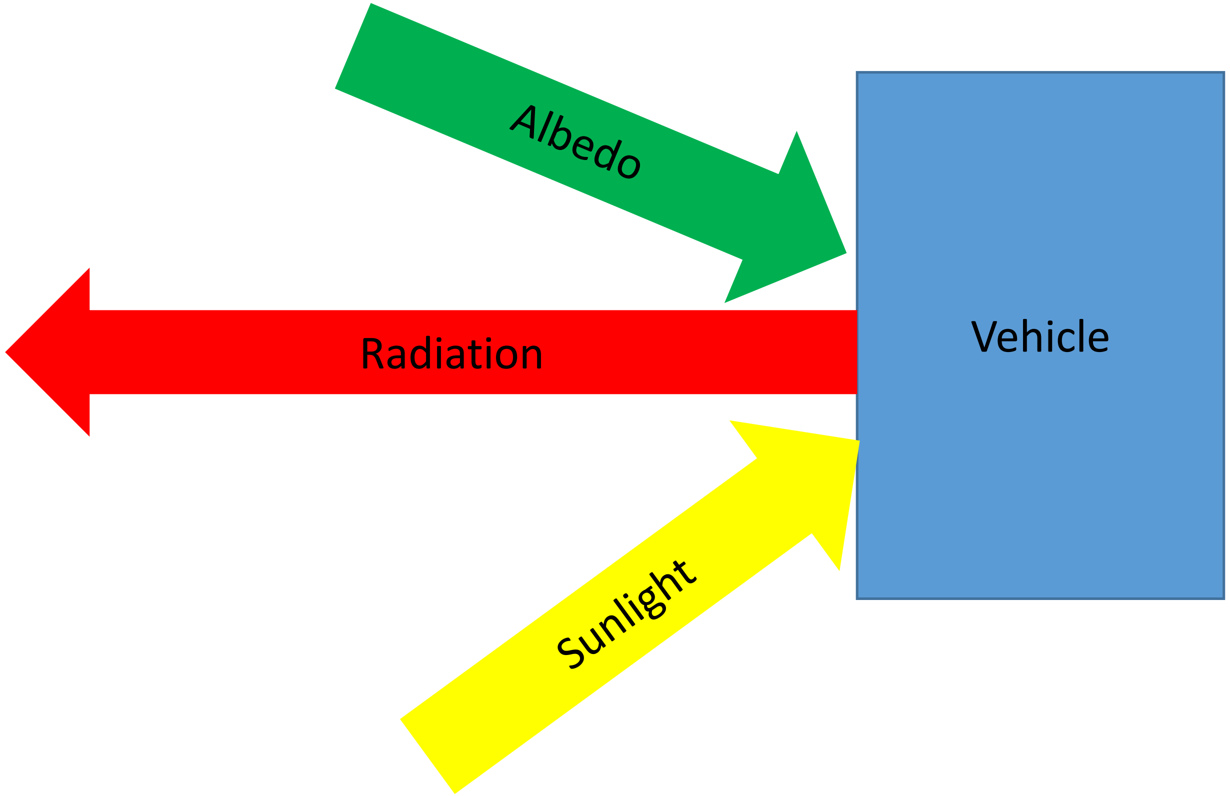
DR 1.5 & DR 1.6

- The electronics must be kept between 218 and 298 K
- The nylon parachute must be kept between 233 and 353 K (Professional Plastics)

Analysis

DR 1.5 & DR 1.6

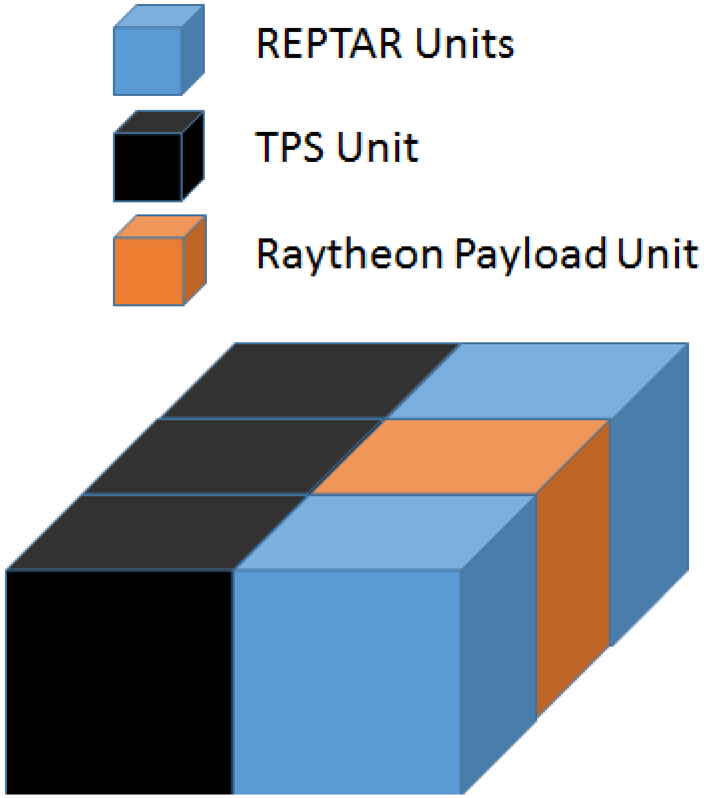
- As the satellite orbits the earth, it will rotate and different faces will receive sunlight
- Earth's albedo also causes the satellite to increase in temperature
- Throughout the orbit, all exposed sides of the satellite will be radiating heat away from the satellite



Assumptions

DR 1.5 & DR 1.6

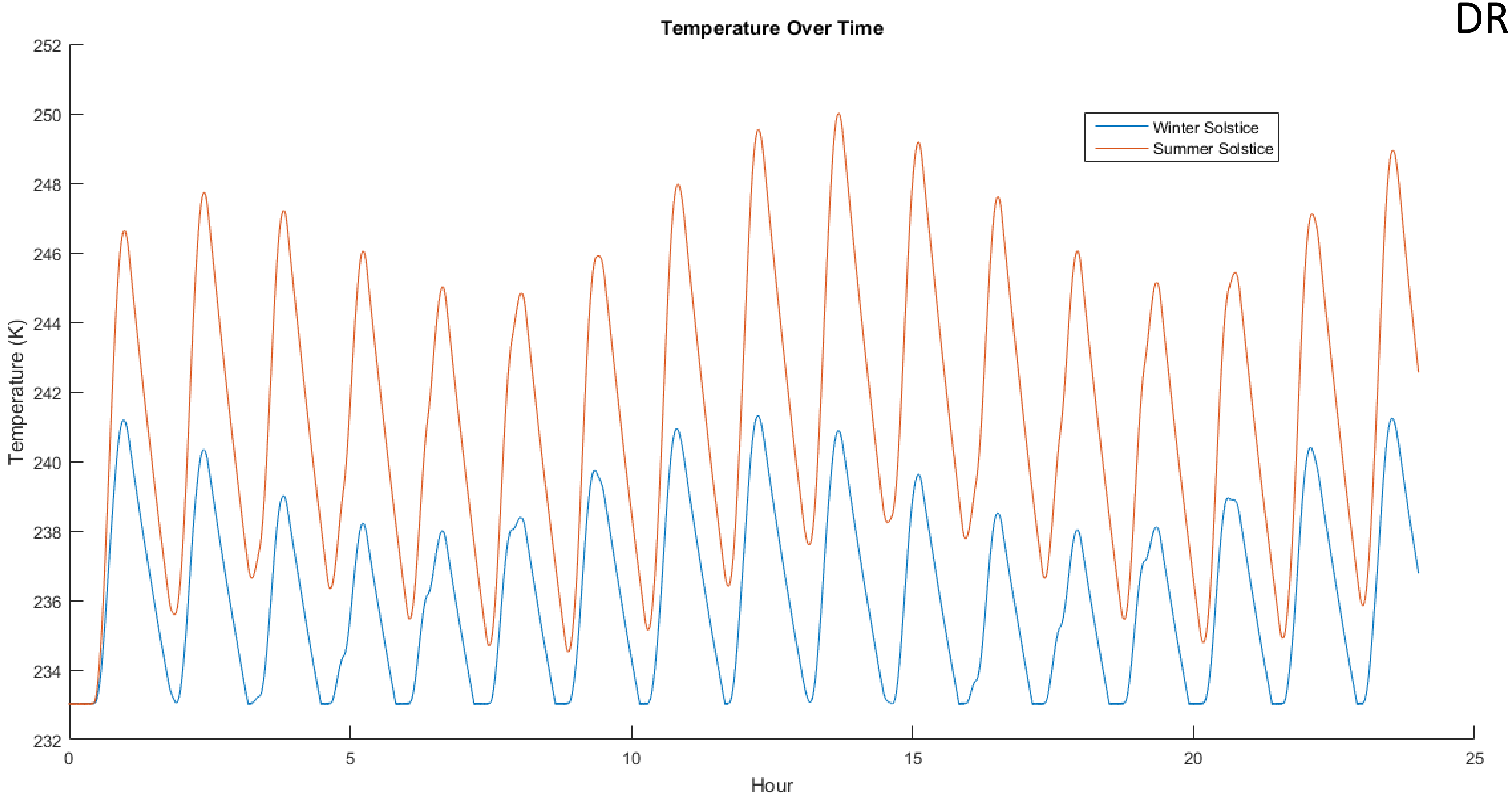
- Satellite is in a circular, 400 km altitude, 92.5 minute period orbit
- The satellite is a black body
- The satellite is composed entirely of aluminum
- The TPS is covering one long face of the satellite
- The payload does not generate heat while operational
- The only sources of heat addition are the sun and albedo
- The only source of heat loss is emission from the surface of the satellite



Variation in Temperature

Raytheon

DR 1.5 & DR 1.6



Descent

Descent Design Decision

Item	COTS/Manufactured	Source/Facility	Details
Iris Ultra 122 cm Compact Parachute	COTS	Fruity Chutes	121.9 g, $C_d = 2.20$, Packing volume 428 cm^3
Goex FFFFg Black Powder	COTS	Bass Pro Shop	0.1128 g for parachute
Parachute Containment Cylinder	Manufactured	ITLL/Aerospace Shop	Manufactured out of aluminum sheet
PinPuller P5	COTS	TiNi Aerospace	5 lbf with 0.25 in stroke
Ejection Canisters	COTS	Apogee Rockets	Tested for 9 and 12 VDC
Recovery Wadding	COTS	Apogee Rockets	Thermal protection for parachutes

Costs

Raytheon

Item	Source/Facility	Cost
2 x Iris Ultra 48” Compact Parachute	Fruity Chutes	$340
Goex FFFFg Black Powder	Bass Pro Shop	$30
Sheet Aluminum	Metals Depot	$40
50 x Ejection Canisters	Apogee Rockets	$100
200 x Recovery Wadding	Apogee Rockets	$10
2 x PinPuller Actuator	TiNi Aerospace	$ TBD
TOTAL COST:		**$650**

Cd of Parachute Sensitivity

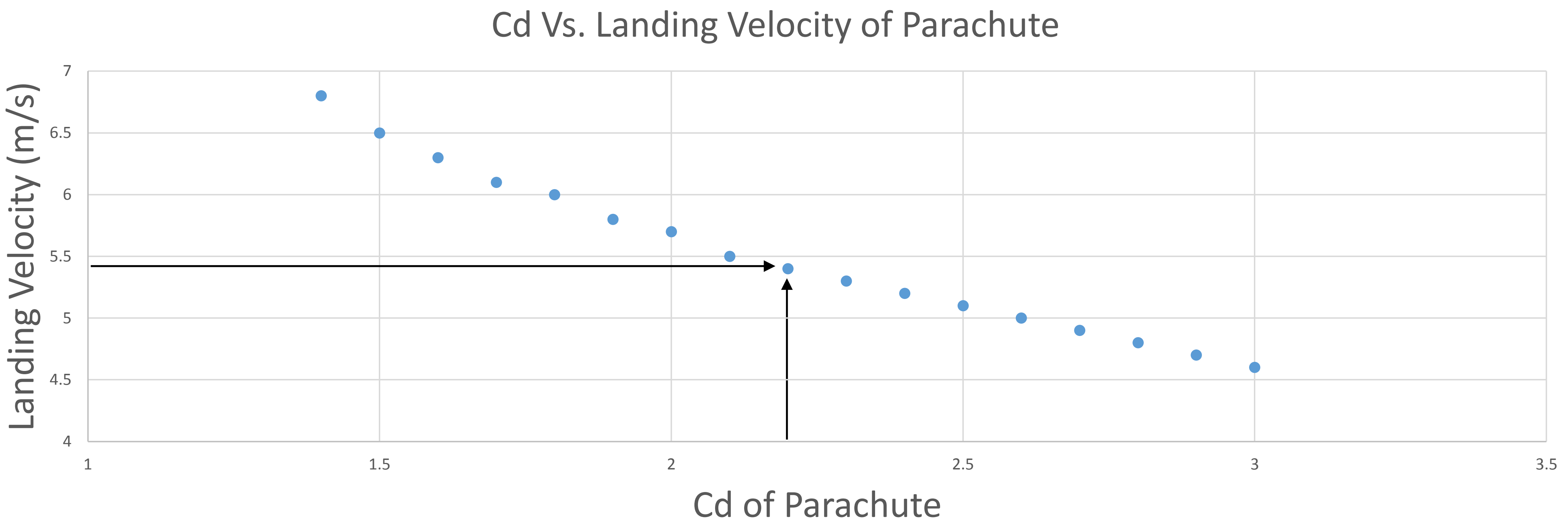
Raytheon

Assumptions:

- Area = 1.13 m^2
- Open Time = 0.46 Sec
- Chute Deploy = 3500 m MSL

Baseline:

- Cd = 2.20



Cd of Parachute Sensitivity

Raytheon

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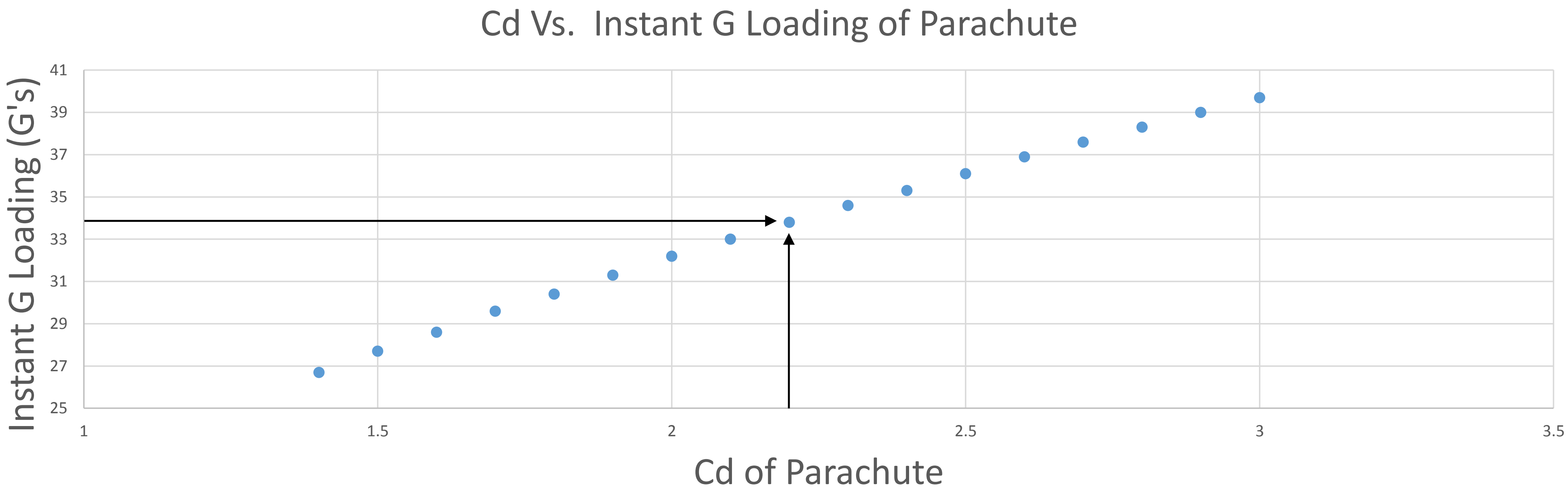


Overview | Descent | Landing | Avionics | Summary | Backup

Projected Area of Parachute Sensitivity

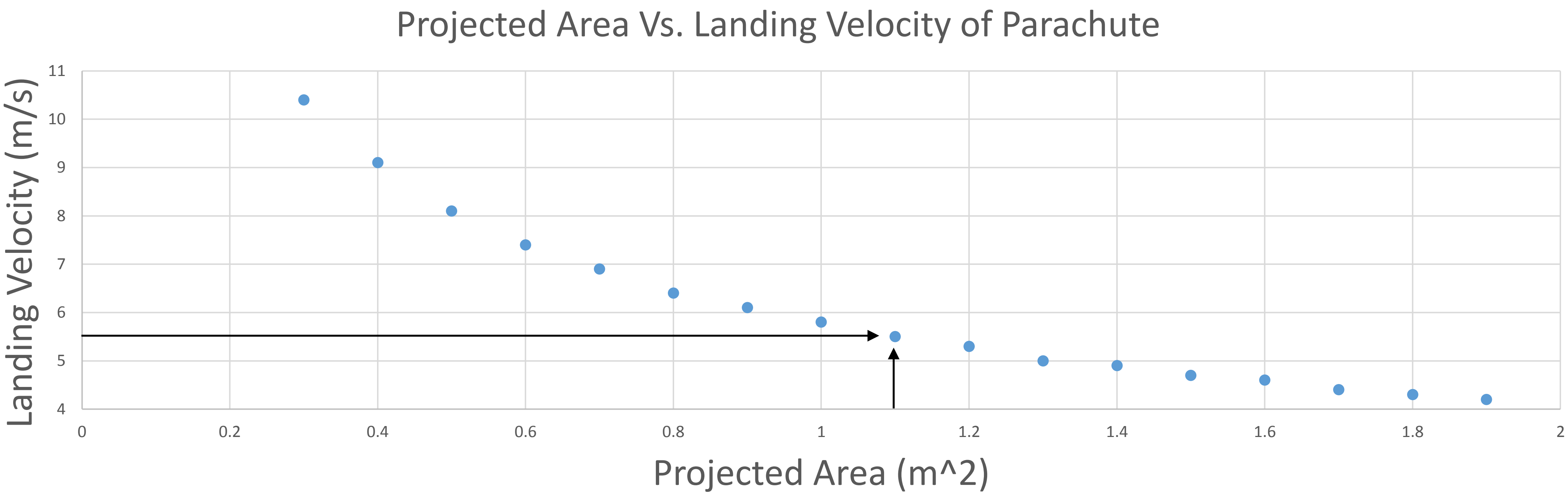
Raytheon

Assumptions:

- Cd = 2.20
- Open Time = 0.46 Sec
- Chute Deploy = 3500 m MSL

Baseline:

- Area = 1.13 m^2



Projected Area of Parachute Sensitivity

Raytheon

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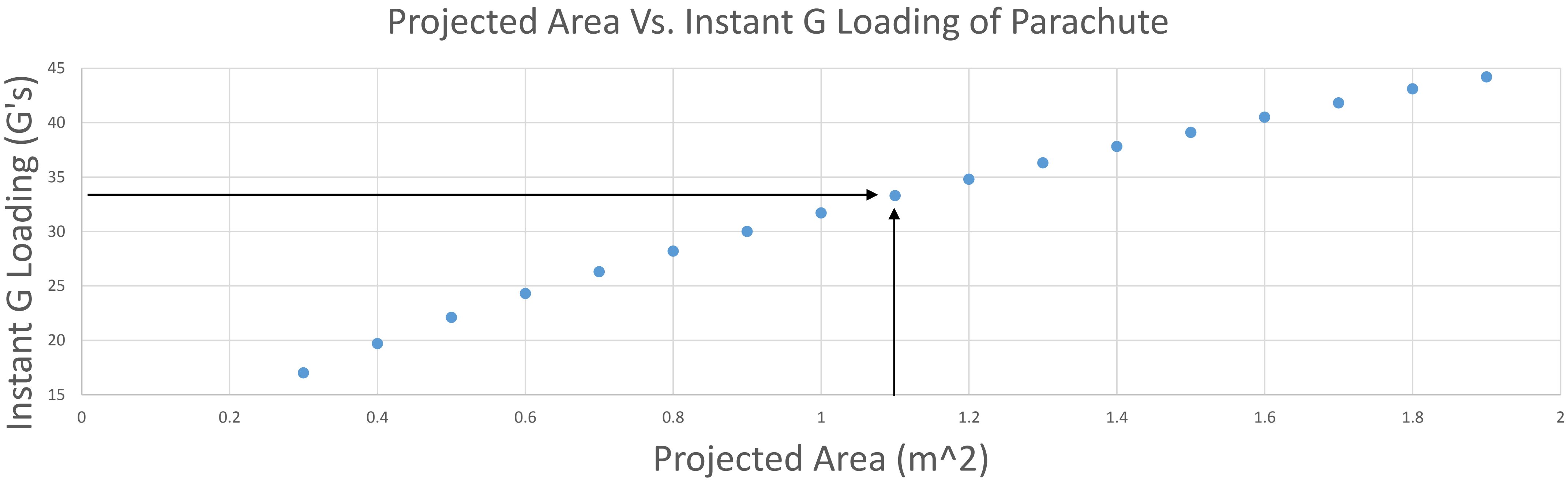
Baseline:

- Area = 1.13 m^2



Overview | Descent | Landing | Avionics | Summary | Backup

Time to Open Parachute Sensitivity

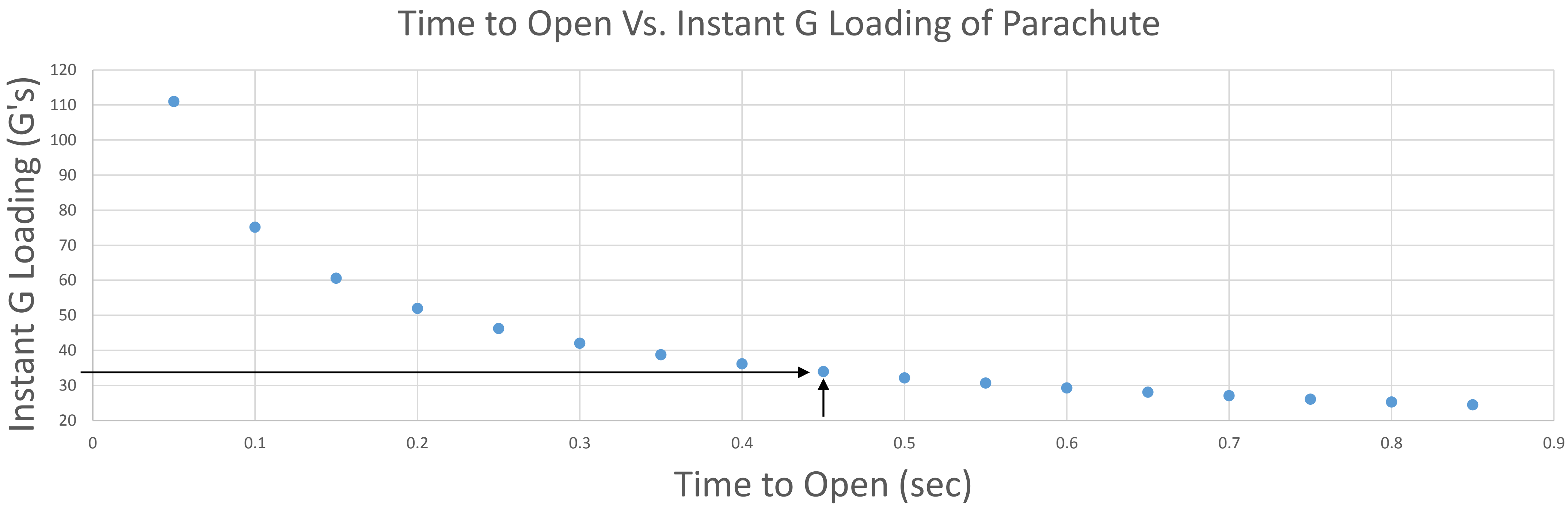
Raytheon

Assumptions:

- Cd = 2.20
- Area = 1.13 m^2
- Chute Deploy = 3500 m MSL

Baseline:

- Open Time = 0.46 sec



Overview | Descent | Landing | Avionics | Summary | Backup

Altitude of Deployment of Parachute Sensitivity

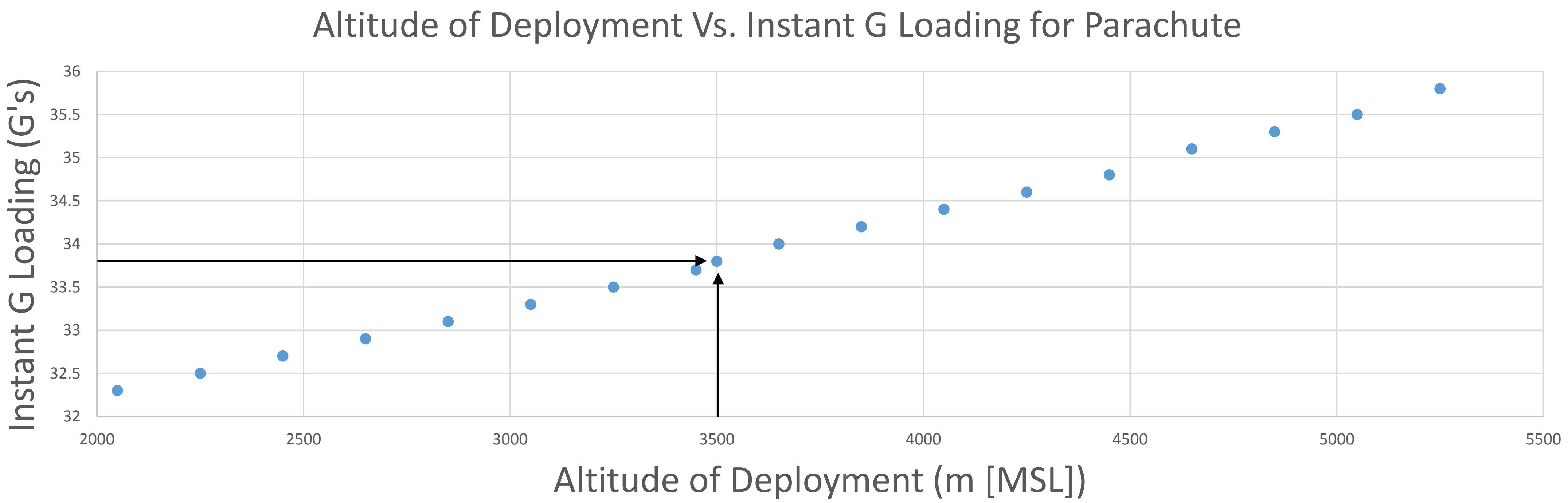
Raytheon

Assumptions:

- Cd = 2.20
- Area = 1.13 m^2
- Open Time = 0.46 sec

Baseline:

- Chute Deploy = 3500 m MSL



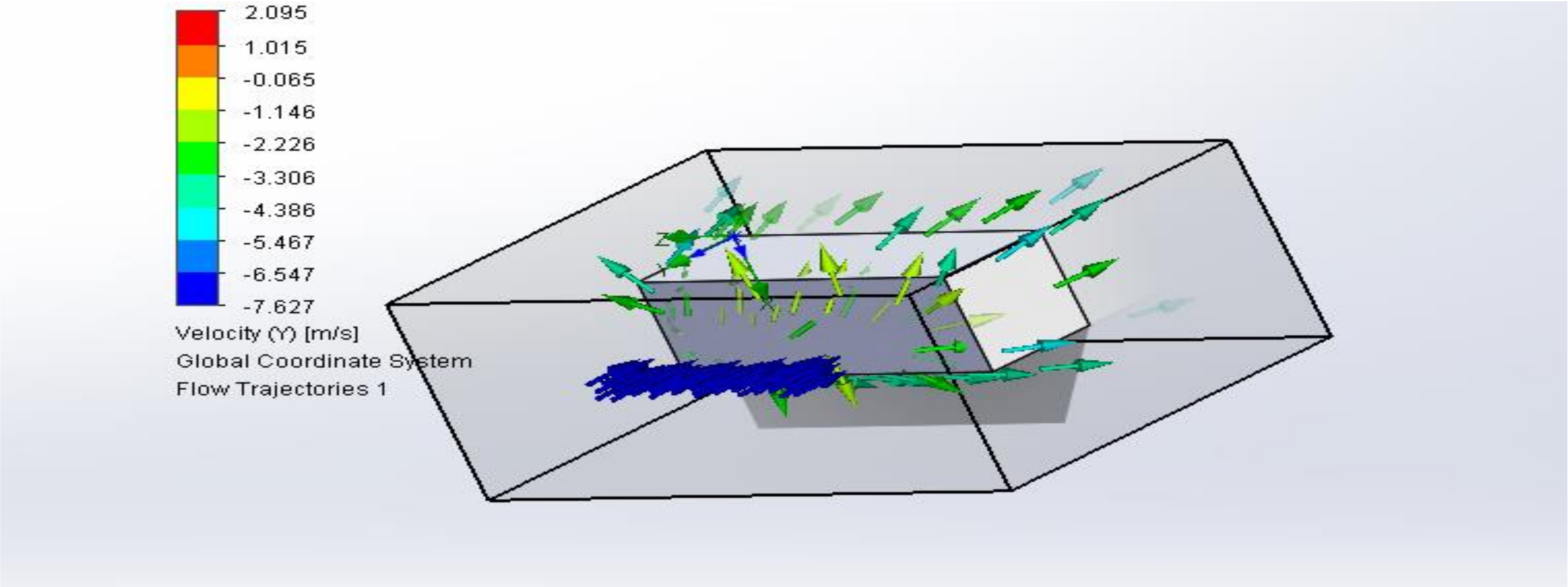
Overview | Descent | Landing | Avionics | Summary | Backup

Cd of 3U

- Designed in SolidWorks
  - Flow Simulation used to calculate drag in Z direction
  - Plugged into coefficient of drag equation
  - Took atmospheric conditions at different heights to calculate multiple values of Cd
  - Average of values used for MATLAB script, Cd = 1.07

Flow Simulations Cube

Raytheon



Parachute Time to Deploy

Raytheon

- $S_0 = 231.54\ ft^2$
- $D_0 = \sqrt{\frac{4 * S_0}{\pi}}$
- $n = 8^*$
- $t_{deploy} = \frac{n * D_0}{v_{term}}$ = 0.4551 s
- $G's = (\frac{Diff(V)}{t_{step}})/9.81 m/s^2$
- $t_{step} = 0.011\ \text{sec} \rightarrow milspec\ standard$

*Mohaghegh, F., and Jahannama, M. R., “Parachute Filling Time: A Criterion to Classify Parachute Types,” pp. 1–13.

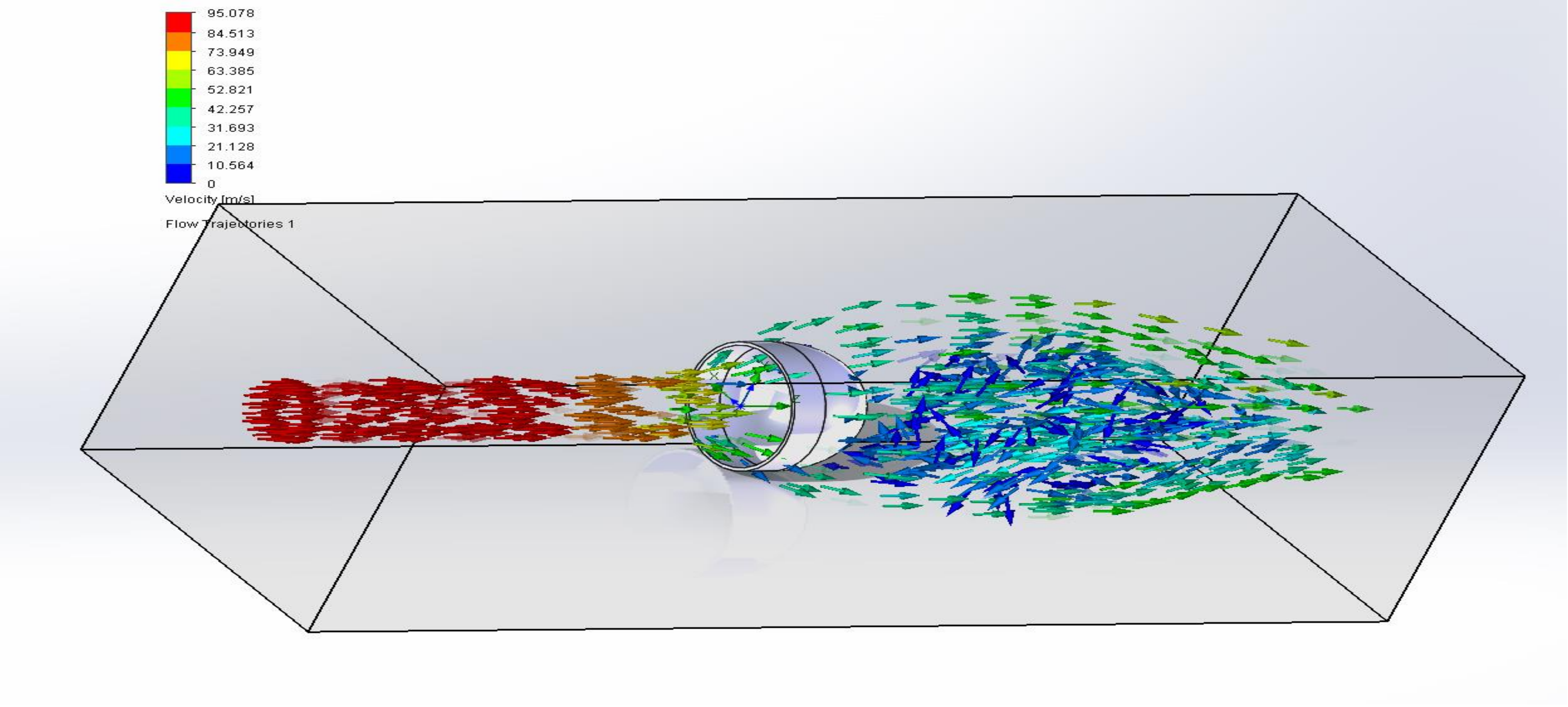
Black Powder Calculation

Raytheon

- $PV = NRT$
- $N = \frac{PV}{RT}$
- T = 1837.2 K (Black Powder Ignition Temperature)
- $N = \frac{1000 * (PSI\ x\ 6894.76\ (Pa))*(Volume\ (m^3))}{\left(287\ \frac{J}{Kg\ K}\right)*(1837.2\ K)}$ grams of BP in g
- At 20 PSI, 0.128 g of Black Powder required
- http://www.vernk.com/EjectionChargeSizing.htm

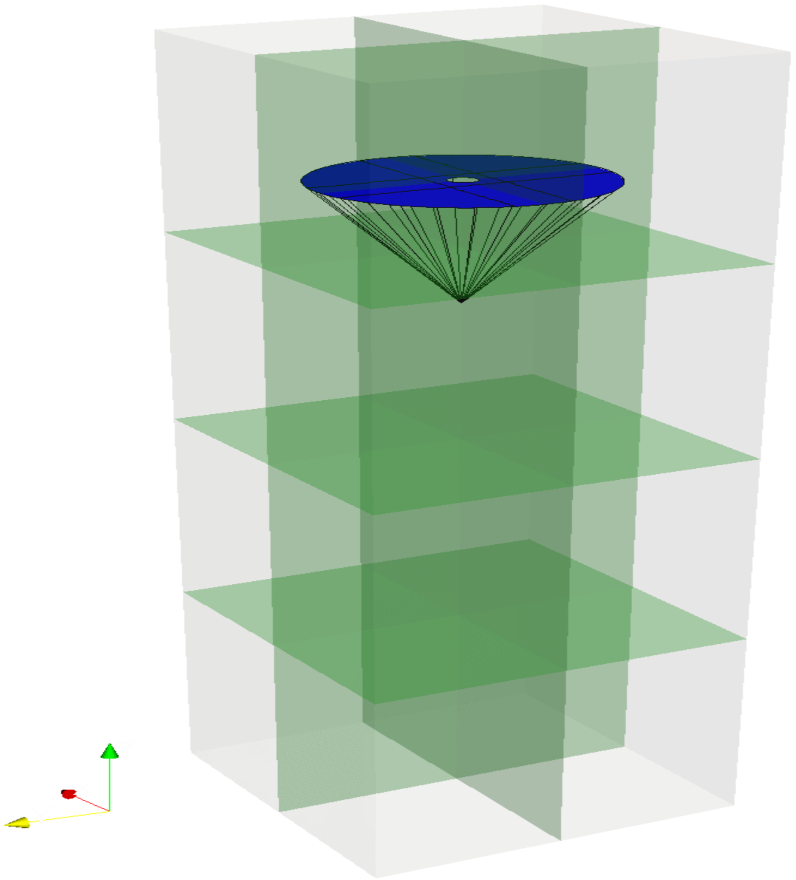
Flow Simulations Parachute

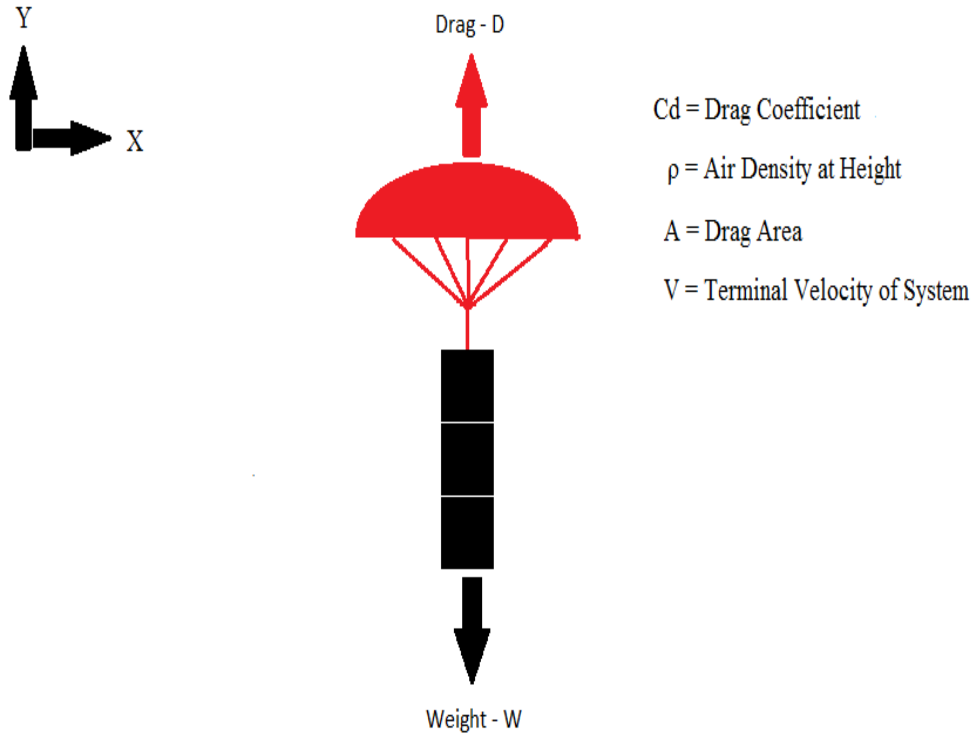
Raytheon



Flow Simulations Parachute

Raytheon





$$D = Cd * \rho * (0.5) * V^2 * A$$

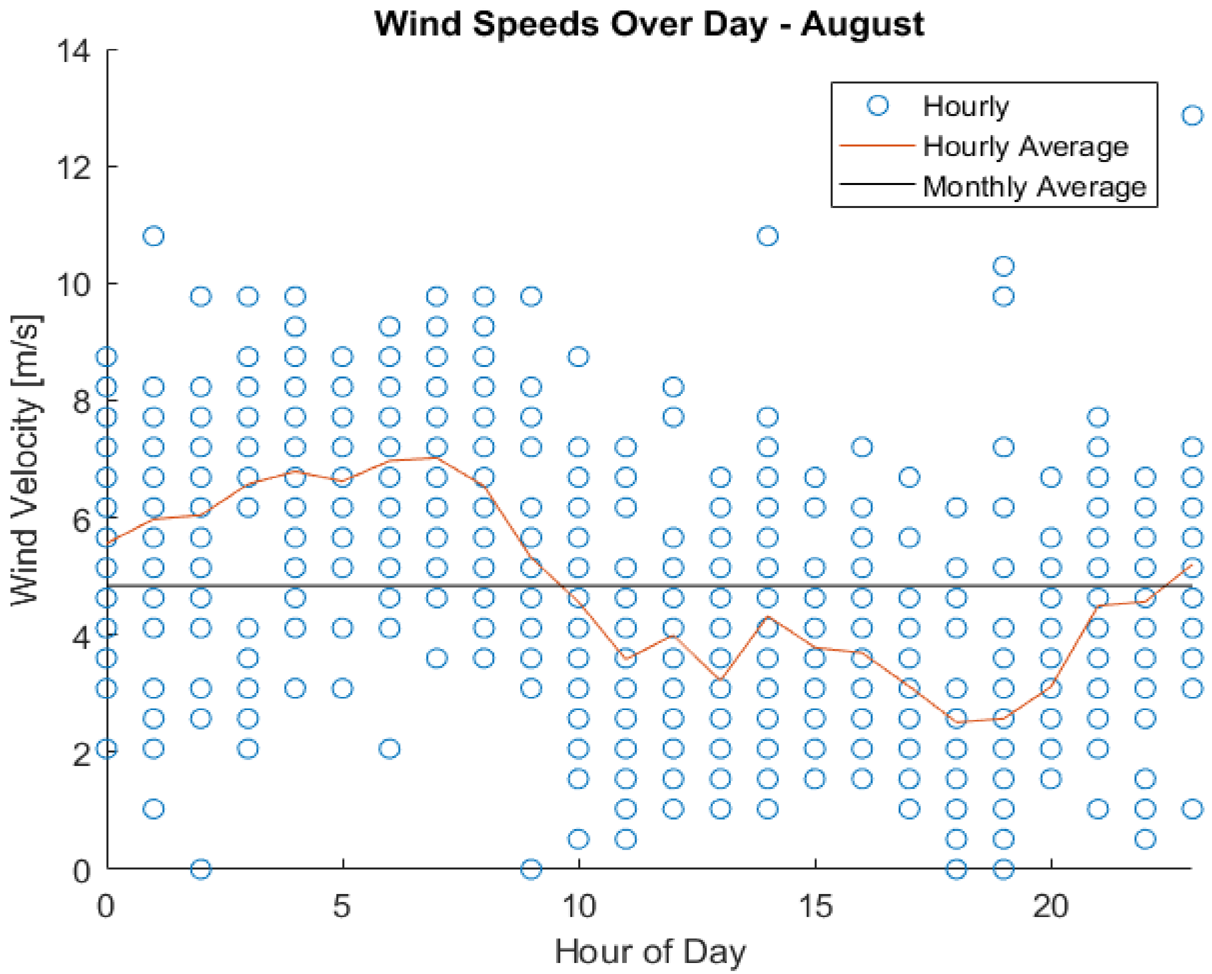
Force on Strings of Parachute

Raytheon

- Maximum Instant G Loading = 33.8 G's
- 33.8 G's * 9.81m/s^2 = 332 m/s^2
- F = ma = 3.99kg * 332 m/s^2 = 1323 N
- 1323N= 297 lbf
- 297 lbf / 8 strings = 37 lbf per string
- Each line is #400 Spectra, which means 400 lbf per string
- Factor of Safety of 10.8

Surface Wind Analysis by Hour

Raytheon

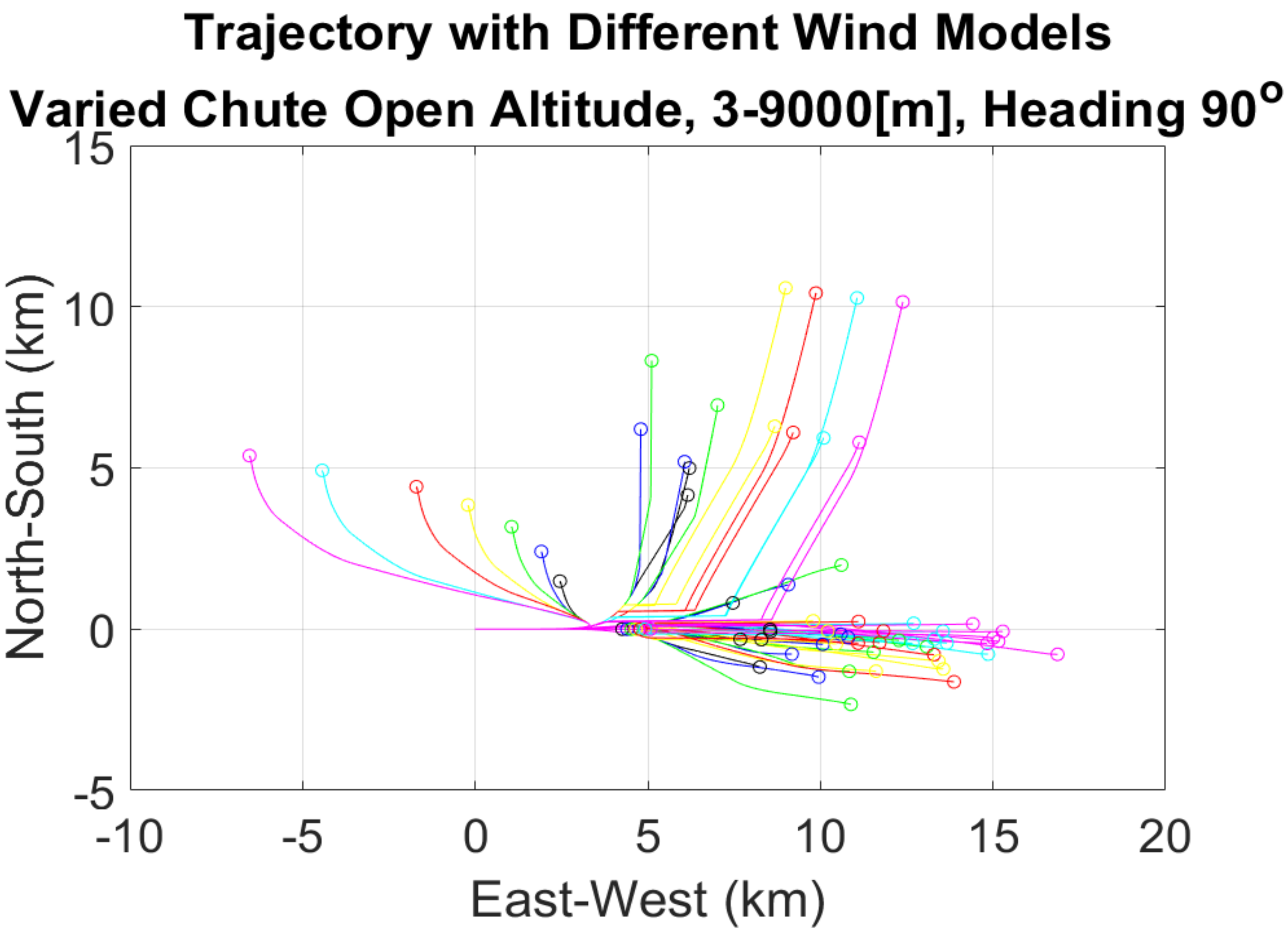


Windiest Month – August

Average wind speed for August 2016: 4.74 m/s.

Max daily average wind speed for August 2016: 7.02 m/s.

Effect of Parachute Deployment Altitude



Parachute deployment altitude significantly increases wind-drift spread due to high velocity winds at high altitudes.

Landing

Design Decision

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Item	COTS/Manufactured	Source/Facility	Details
Foam Legs and Internal Panel	COTS	ERG Aerospace	2.53 MPa Compression Strength
Side Legs	Manufactured	Machine Shop	Aluminum bulk purchase
3U Frame	Manufactured	Machine Shop	Aluminum bulk purchase
Frangibolt Actuator FD04	COTS	TiNi Aerospace	Price Unknown

Landing Deformation

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- Deformation was calculated using basic kinematic equations
  - Vertical deformation during initial landing
    - Acceleration = $a = g * \#G's$ = $9.81\frac{m}{s} * 40G's$
    - Change in Velocity= $\Delta V = V_{initial} - V_{final}$
    - Time = $t = \frac{\Delta V}{a}$ where ΔV is the velocity required to go from provided velocity from parachute descent to a 0 vertical velocity at rest.
    - Displacement = d = $V_{avg} * t$ = $\frac{\Delta V}{2} * t$

Landing Deformation

Raytheon

- Deformation during tipping over due to horizontal wind velocity
  - Angular velocity = $\omega = \frac{v}{r}$
  - Moment of Inertia = I $= \frac{m}{12} * (w^2 + h^2) + m\Delta D^2$ where w and h are the dimensions of the system
  - Kinetic Energy = Force*displacement => $KE = \frac{1}{2} I\omega^2 = Fd = mad$
  - Displacement = $d = \frac{\frac{1}{2}\omega^2\left(\frac{1}{12}(w^2+h^2) + \Delta D^2\right)}{g*\#G's}$ where mass, m, has been canceled out

Overview | Descent | Landing | Avionics | Summary | Backup

Landing Area

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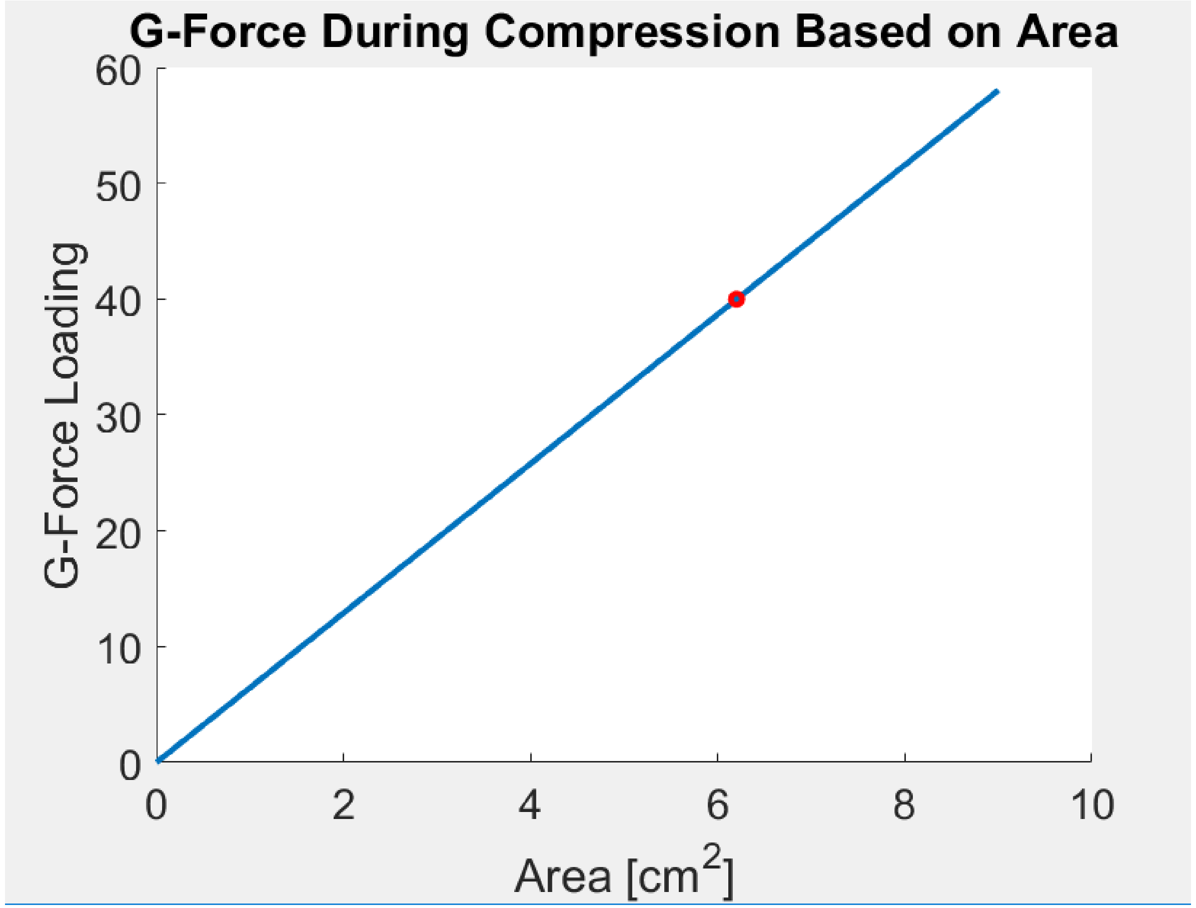
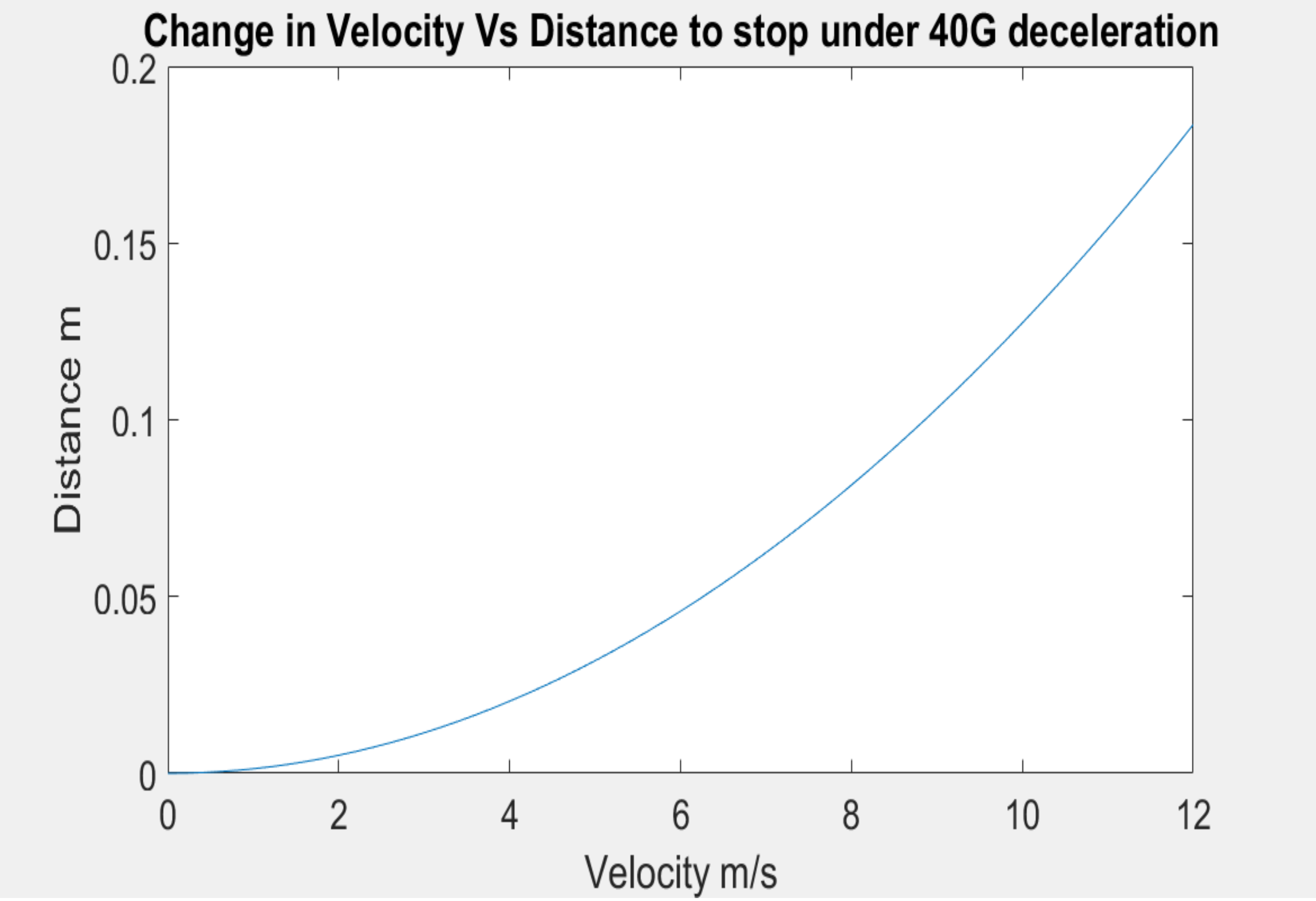
- Velocities able to be withstood during landing from different leg areas
  - Area = $A =$ varying areas as defined by system dimension limits
  - Deformation = $d = 60\% * Leg\ length$ (assumed to be 6cm)
  - $\sigma = 2.53 * 10^6\ Pa$ from the material specifications of aluminum foam
  - Force = $F = A\sigma$
  - Work = $W = Fd$
  - Velocity = $V = \sqrt{\frac{2W}{m}}$ from the KE equation ($KE = \frac{1}{2}mV^2$) where $W = KE$

Velocities of Landing vs. Area and Deformation

Raytheon





Assuming a 60% deformation of material for lower legs

Costs

Raytheon

Item	Source/Facility	Cost	Notes
Aluminum Sheet	McMaster Carr	$150	Machined into frame and sheets
8x Steel Pins (Side Legs)	McMaster Carr	$4.97 each	Machine to shorter length
4x Steel Pins (Base Legs)	McMaster Carr	$10.33 pack of 10	Dowel pin: Two different lengths of pins for two prices
Aluminum Foam	ERG Aerospace	$400	Pre-machined Material
TOTAL COST		**$634.56**	

Mass Budget - Landing

Raytheon

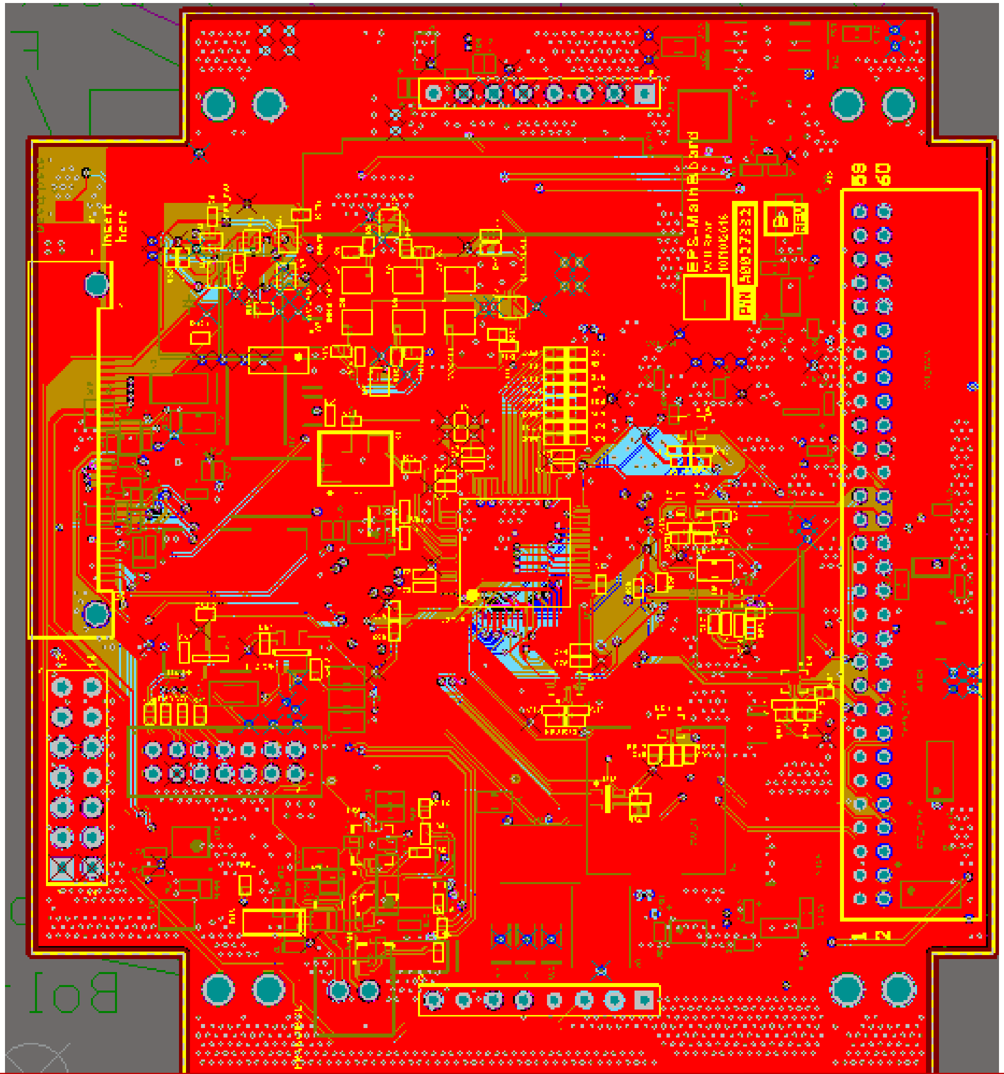
Item	Mass (g)
Aluminum Side Legs	680.4
Aluminum Foam Base Legs	13.62
Aluminum Foam Mid-Section Plate	61.03
Steel Pins	16.3
1x Frangibolt	7
Aluminum SmallSat Structure	225.25
TOTAL MASS:	**1003.6 g**

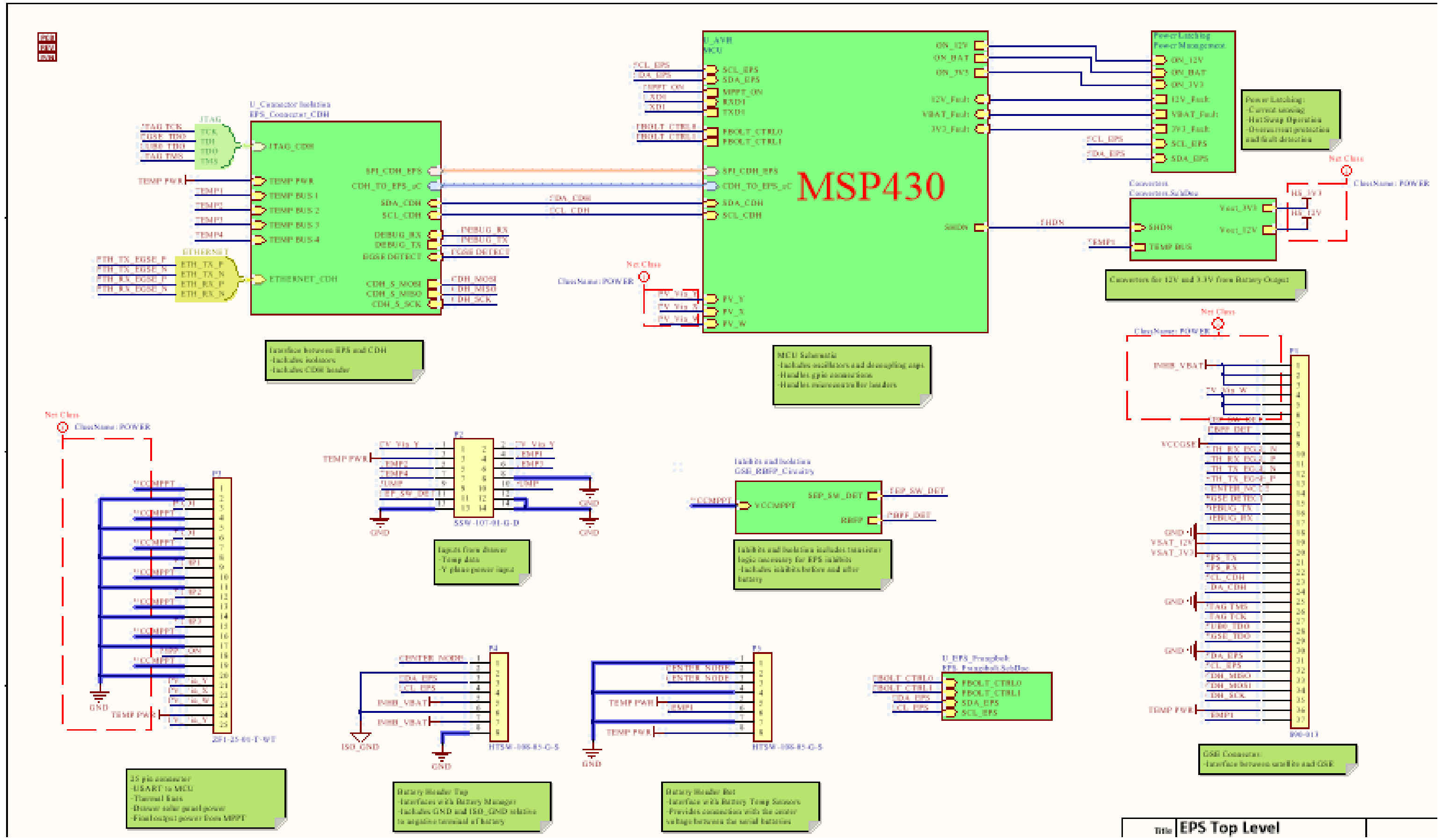
Item	Volume (cm^3)
Aluminum Side Legs	252
Aluminum Foam Base Legs	120 (Base 0.12U)
Aluminum Foam Mid-Section Plate	72.5
Aluminum SmallSat Structure	3000 (Total chassis volume contained, not included in total)
TOTAL VOLUME:	**444.5 cm^3**

Avionics Backup

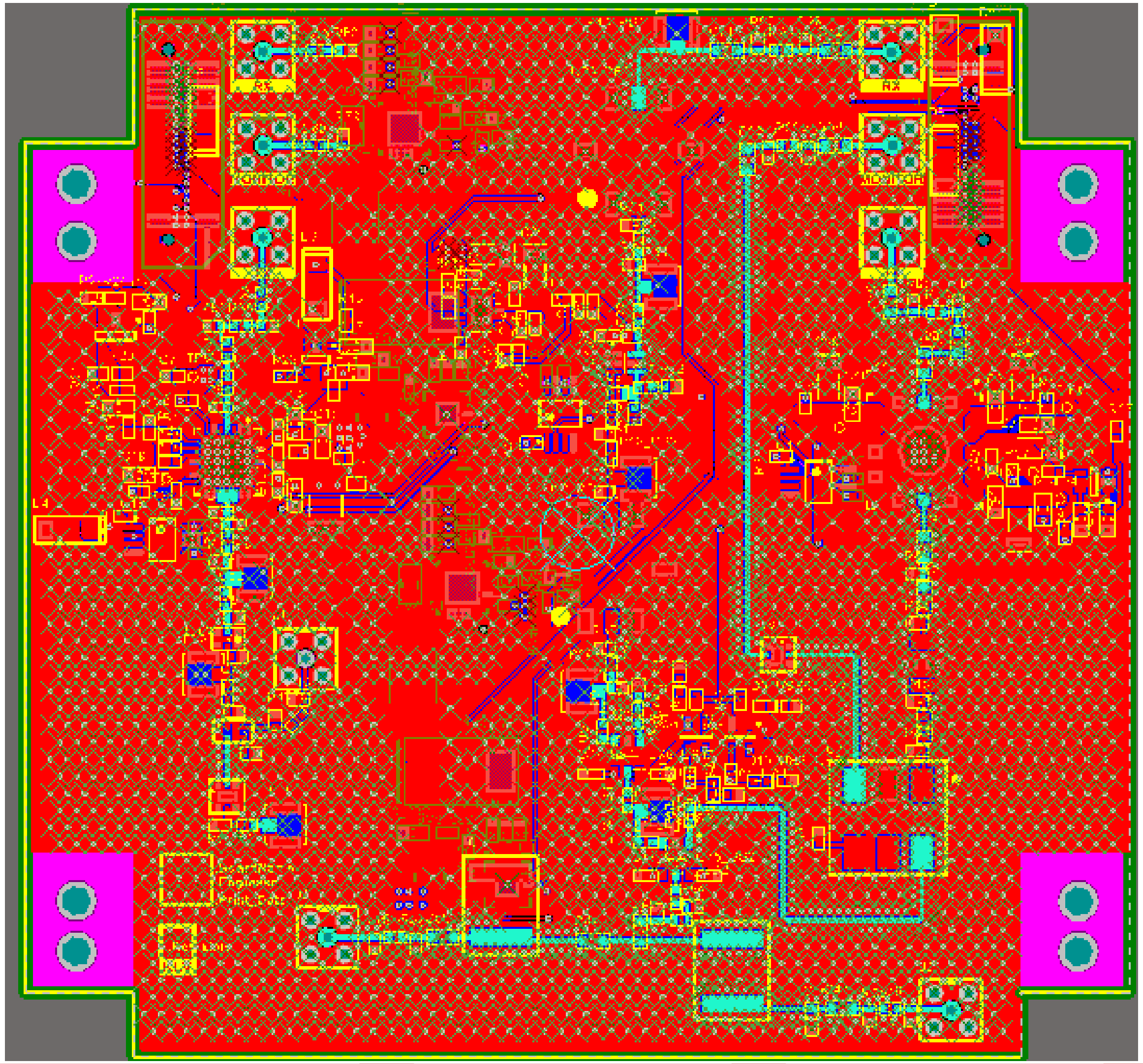
Previous PCB Design Pt1/2

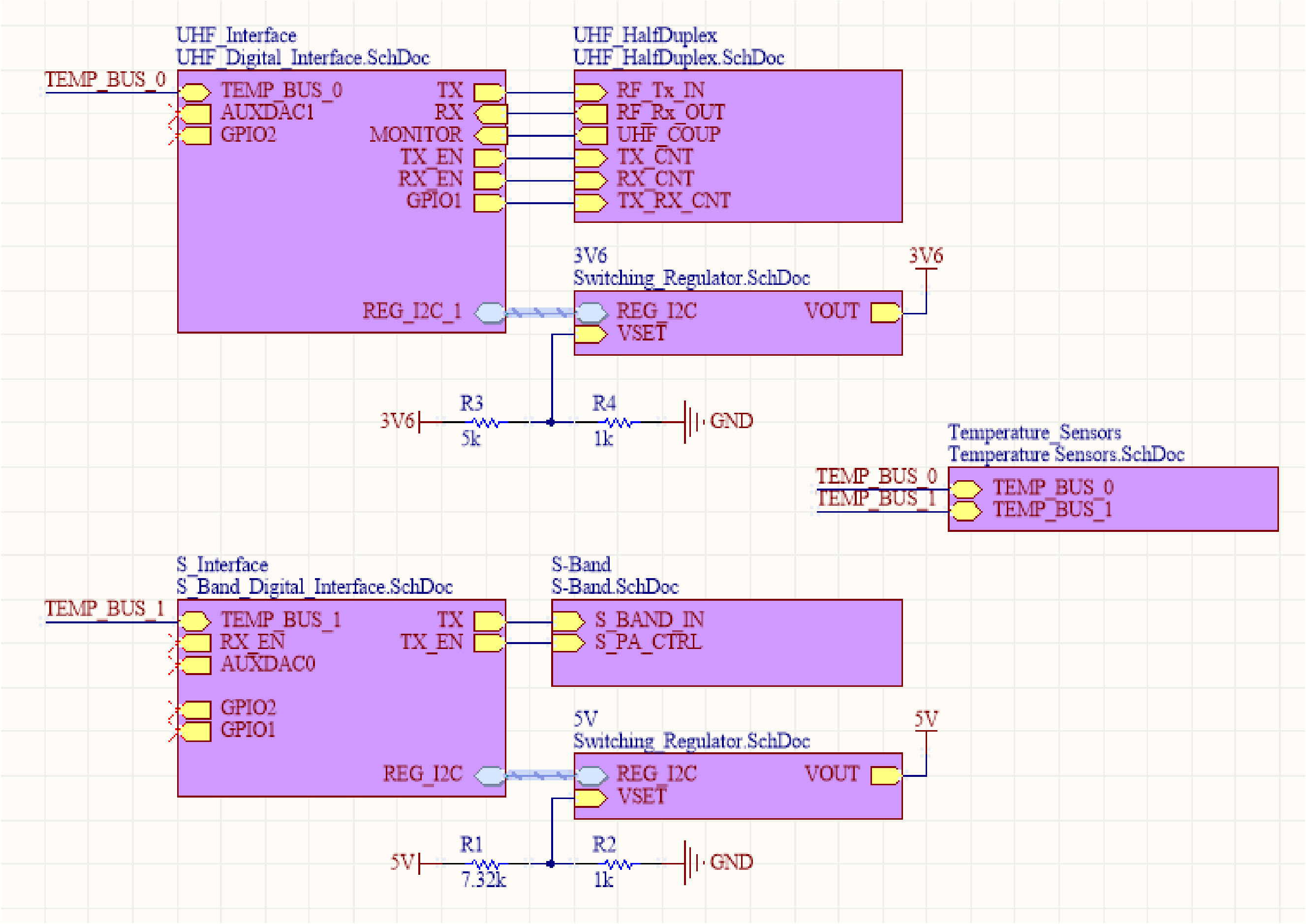
Raytheon





Previous PCB Design Pt2/2



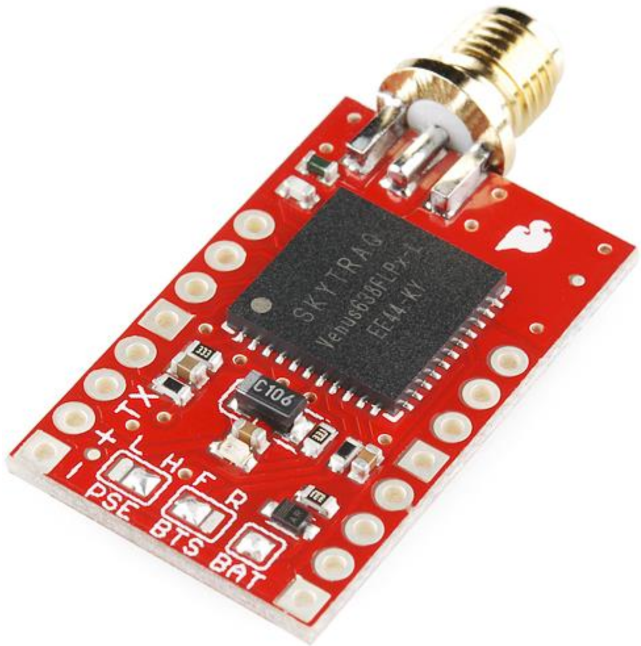


GPS Unit Selection

Raytheon

Venus638FLPx IC GPS on Breakout Board Selected

- Operation within Device's COCOM Limits
- Output: NMEA-0183 Binary Sentences at 96kbps or 115.2kbps
- Update Rates of up to 20Hz
- SMA Antenna Connector
- 2.5m 50CEP Accuracy
- 1 second hot start
- 3V3 Power Supply

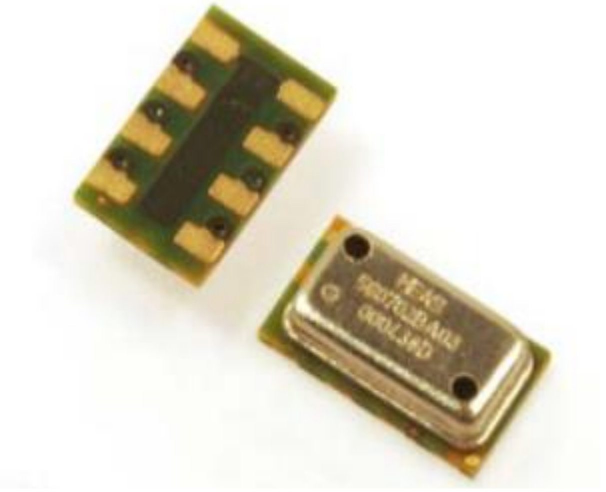


Altimeter Selection

Raytheon

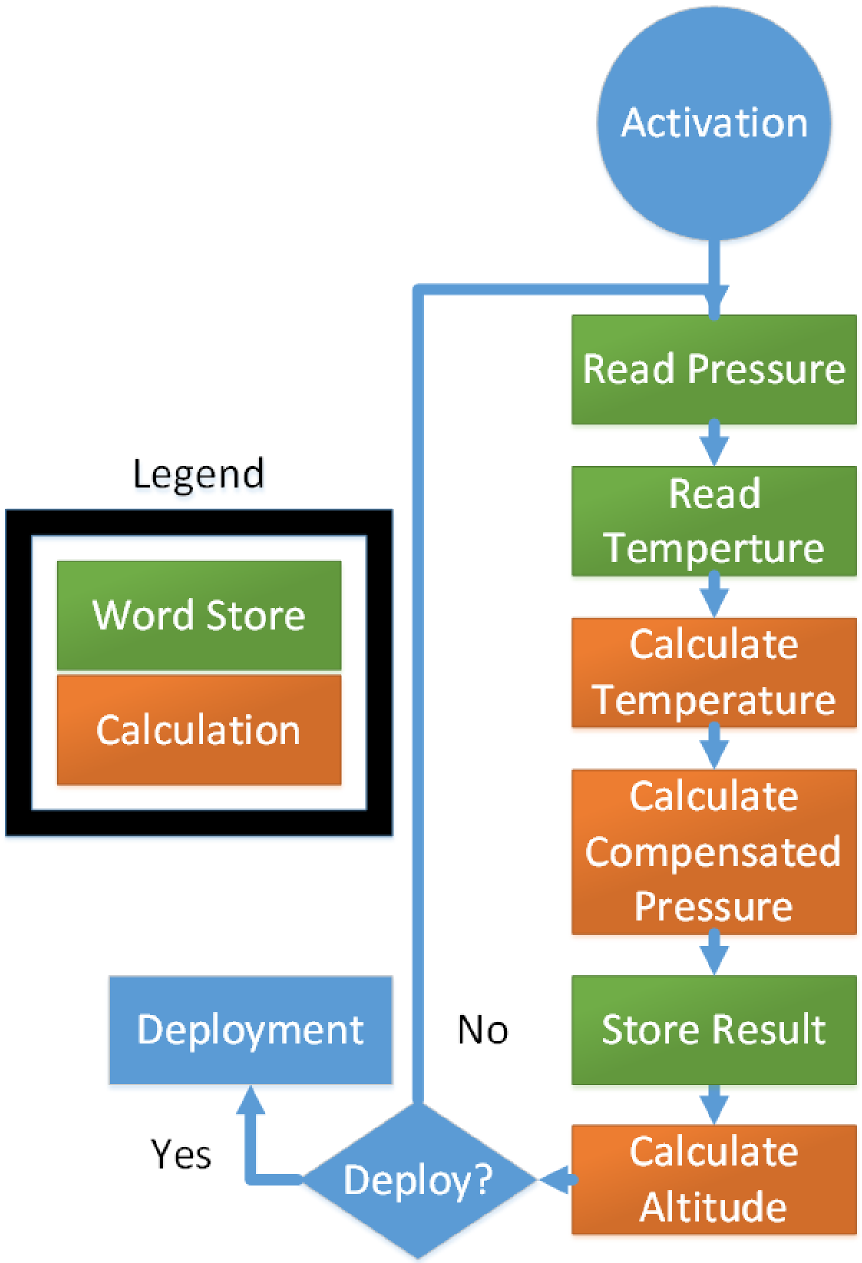
MS5607-02BA03 Barometric Pressure Sensor Selected

- 10-1200 mbar Pressure Sense Range
- 3V3 Power Supply
- I2C or SPI Digital Interface
- IC on Main Board
  - Minimizes Volume Requirements
  - Minimizes Wiring Complexity
  - Simple Implementation
- Includes Temperature Sensor
  - Temperature Sense Range of -40 to 85 C
  - Accurate to within 1^{o}C



Microcontroller Data and Processing Budget Backup

Raytheon



Step	Calculations	Cycles	Time [ms]
Read Pressure	N/A	N/A	0
Read Temperature	N/A	N/A	0
Calculate Temperature	3 Multiplication 3 Addition	321 Multiplication 12 Addition	2.07
Calculate Comp. Pressure	10 Multiplication 7 Addition	1070 Multiplication 28 Addition	6.8
Store Result	N/A	N/A	0
Calculate Altitude	2 Multiplication 2 Addition	114 Multiplication 8 Addition	0.76
Operation Cycles	Addition: 4	Multiplication: 107	N/A
Clock Frequency	14 MHz	N/A	N/A
Clock Period	6.2 ns	N/A	N/A
Total	N/A	N/A	9.63

Altimeter Specifications

Raytheon

- For a desired altitude knowledge of 100 meters, the pressure accuracy required is derived using the standard atmosphere model to relate pressure and altitude
- A vector of altitude values from 0 to 3500 meters by 100 meter intervals was mapped to a vector of pressure values

Value #	1	2	3	4	5	6	7	…	36
h [m]	0	100	200	300	400	500	600	…	3500
p [kPa]	101.3	100.1	99.0	97.8	96.6	95.5	94.3	…	65.8
$\|\Delta p\|$ [kPa]		1.20	1.18	1.17	1.16	1.15	1.14	…	0.851

Altimeter Specifications

Raytheon

- The difference between each pressure value corresponds to the necessary pressure resolution to obtain an accuracy of 100 meters in altitude. The lowest of these differences was used to derive the altimeter's minimum pressure accuracy:

$$p_{sens} = \min(|p_1 - p_2|, |p_2 - p_3|, |p_3 - p_4|, \dots) = 0.851\text{kPa}$$

Position Broadcast Accuracy

Raytheon

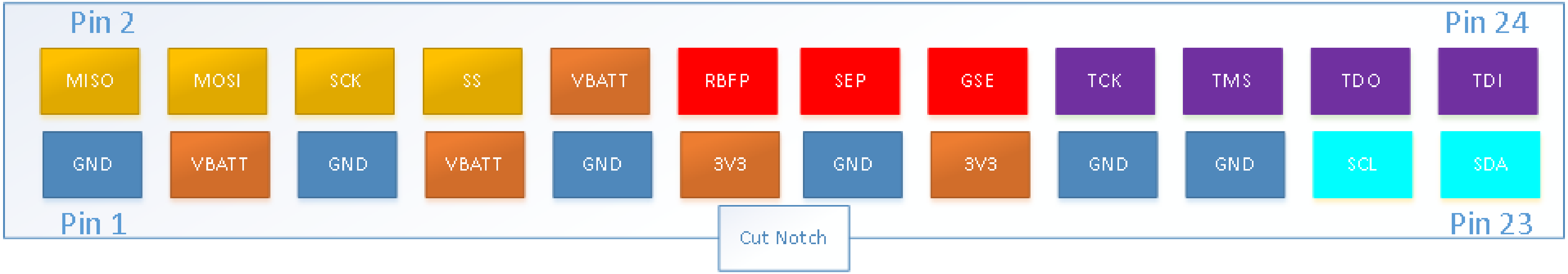
	Lat/Long Decimal Degrees	Military Grid Reference System
NW Corner	41.2576° -114.139°	11TQF 396 713
NE Corner	41.2967° -112.921°	12TUL 391 734
SW Corner	39.9459° -114.120°	11SQE 459 257
SE Corner	39.9933° -112.761°	12SUK 496 285
Accuracy	N/S ##.#### / 11.132m E/W #.### / 78.71m	ZZZZZ ### ### 100m accuracy
	10 total digits for 100m accuracy…Assumptions on location	11 total digits for 100m accuracy. No assumptions.

Raytheon EICD

Raytheon

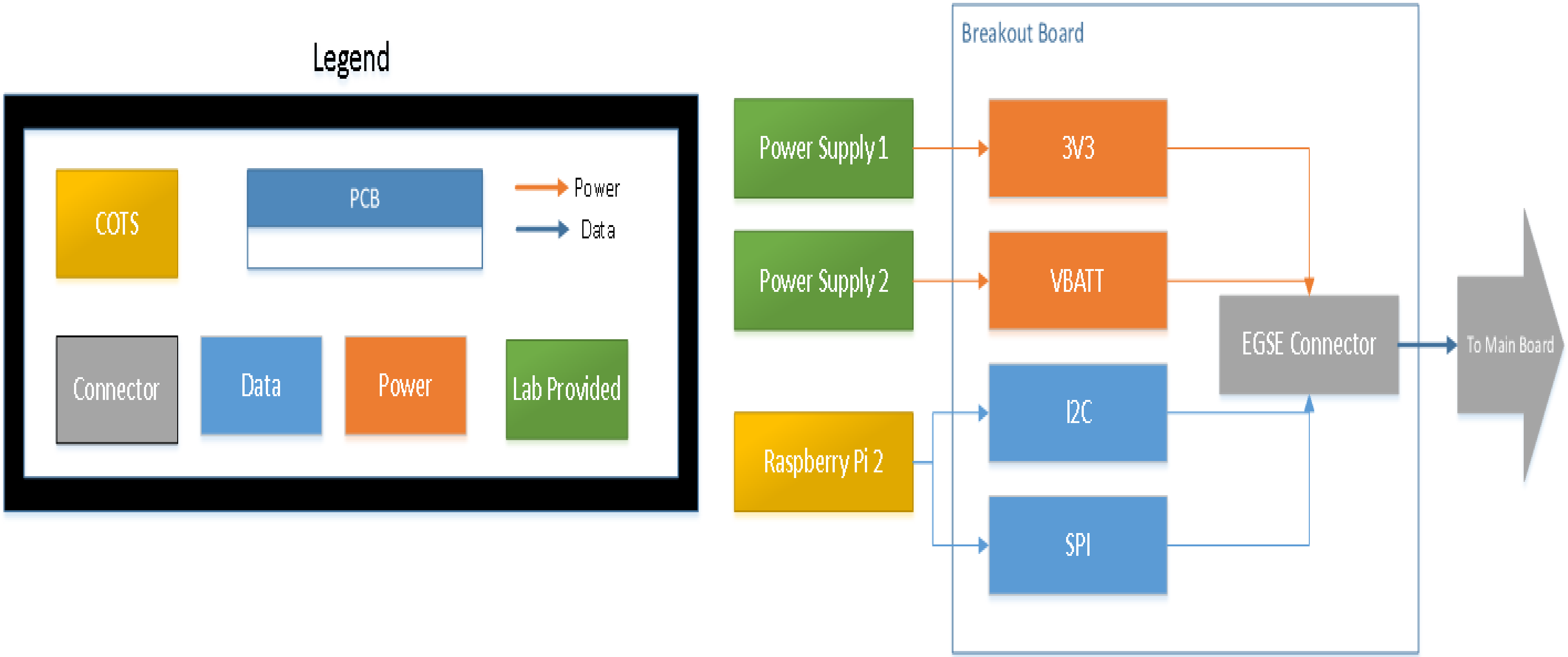
DR 2.1.1

ETMM 2.00mm Shrouded Terminal Strip Connector and the TCSD 2.00mm Ribbon Cable Assembly



Legend

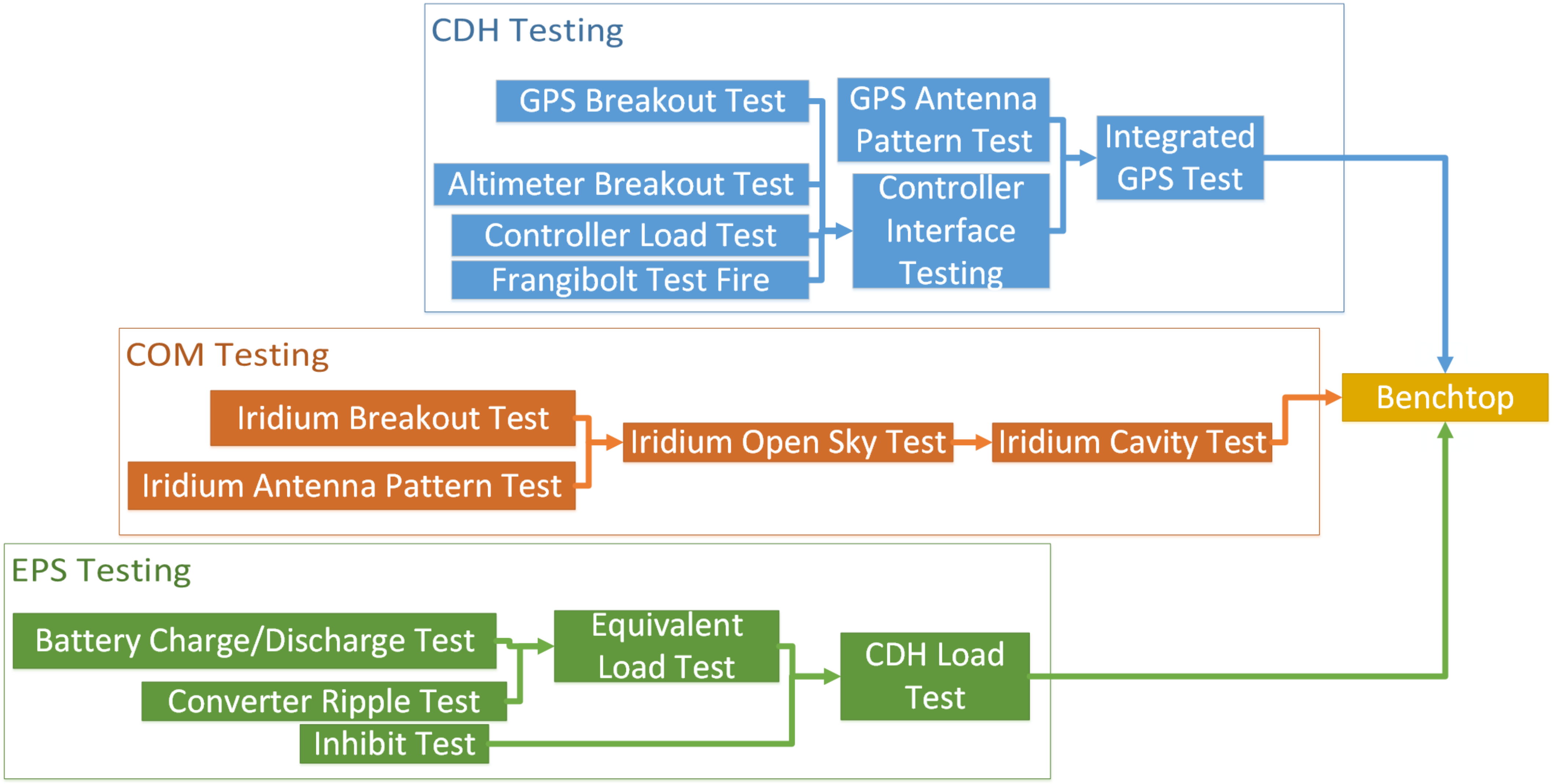
EGSE



Legend
COTS
PCB
Power
Data
Connector
Data
Power
Lab Provided
Breakout Board
Power Supply 1
Power Supply 2
Raspberry Pi 2
3V3
VBATT
I2C
SPI
EGSE Connector
To Main Board

Avionics Test Path

Raytheon



Avionics Mass and Cost Budget

Board/Element	Mass (g)	Cost
Main Board	120	$66 Per Panel + $40 per Board
Iridium Radio COTS Board	80	$250 + Per Byte Fee of $0.001
GPS COTS Board	80	$60
Battery Pack	200	$60

Risk Matrix

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Risk Identification	Probability	Impact	Risk Value	Risk Mitigation Plan
Black powder ignited during launch	LOW	HIGH	MED	Vibration and loading tests
Low temps of space make parachute material brittle	LOW	MED	LOW	Test in environmental chamber, keep REPTAR warm
Top of CubeSat is not jettisoned, drogue and parachute can not deploy	LOW	HIGH	MED	Frangibolt to release, pressure force, force of drogue deploying

Risk Matrix Cont'd

Risk Identification	Probability	Impact	Risk Value	Risk Mitigation Plan
Black powder does not ignite on command	LOW	HIGH	MED	Static and drop testing
Heat from ignition burns fabric of parachute/drogue	MED	MED	MED	Thermal recovery wadding place in cylinders below parachutes
G Loading during deployment tears drogue	MED	MED	MED	Drop testing
Altimeter has errors and misreads altitude	LOW	MED	LOW	Mitigating by cross-checking GPS, redundancy of timer
Drogue and parachute not removed at landing	MED	MED	MED	High accuracy location information during descent for quick recovery

Risk Matrix

Raytheon

Risk Identification	Probability	Impact	Risk Factor	Risk Mitigation Plan
Payload descends with a horizontal component to orientation	LOW	MED	LOW	Descent during later hours of the day while winds have been recorded to be smaller in magnitude
Legs don't deploy before landing	MED	MED	MED	Leg deployment is sensitive to G-Loadings
Legs for ground torque don't enter structure correctly	MED	HIGH	HIGH	Redundancy implementation of material for proper entrance orientation

Available Vibration Test Methods

Raytheon

MECHANICAL

Valid To: September 30, 2016 Certificate Number: 2582.02

In recognition of the successful completion of the A2LA evaluation process, accreditation is granted to this laboratory to perform the following tests on aircraft components, automotive components, marine components, coatings, packaging and containers, electronics and consumer goods:

Test:	Parameters:	Test Method(s):
Mechanical Vibration[1]: Includes: Sine Random Sine-on-Random Gunfire	(1 to 3,000) Hz 3" Stroke 40,000 lbs Force	ASTM D4169; BellCore GR-63-CORE 5.4.2, 5.4.3; IEC 68-2-59, Test Fe; IEC 68-2-34, Test Fd; IEC 68-2-35, Test Fda; IEC 68-2-6, Test Fc; JESD22 B103B; MIL-STD-810E, Method 514.4, 519.4; MIL-STD-810F, Method 514.5, 519.5; MIL-STD-810G, Method 514.6, 519.6; MIL-STD-167-1 (A SHIPS); MIL-STD-202G, Method 201A, 204D, 214A; MIL-STD-883G, Method 2005.2, 2007.3, 2026; MIL-STD-883H, Method 2005.2, 2007.3, 2026; MIL-STD-1344A, Method 2005.1; RTCA DO-160D, E, F, G, Sec. 8.0; RTCA DO-227 6/23/1995, Sec. 2.3.1; SAE J1455, Sec. 4.10; SAE J1211, Sec. 4.7; UN ST/SG/AC.10/11 Rev. 5, Para. 38.3.4.3

Static Parachute Deployment Testing

Raytheon

Bench Top Test : Both for Top side removal and Chute Deployment

- Hardware needed: CDH, EPS, Pinpuller, Black Powder, Ejection Canisters, Parachute, Thermal Paper
- Skills needed: Packing of black powder and chutes, manufacturing
- Safety Measures: Hearing and eye protection
- Cost: TBD
- Facility: Boulder Airport
- Frequency of test: 3-4 Attempts
- Risk Factor: Low mitigated by keeping other sensitive components away
- Areas of concern: Burning parachutes, over pressurization

Static Ignition Testing

Raytheon

Bench Top Test (without CDH, EPS) : Both for Top side and Chutes Deployment

- Hardware needed: Power Source, Pinpuller, Black Powder, Ejection Canisters
- Skills needed: Packing of black powder, manufacturing
- Safety Measures: Hearing and eye protection
- Cost: TBD
- Facility: Boulder Airport
- Frequency of test: 3-4 Attempts
- Risk Factor: Low
- Areas of concern: Over pressurization of cylinders

Parachute Drop Testing

Field Test I : Drop from a height of TBD meters

- Hardware needed: Power Source, Accelerometer, High Speed Camera, Sensors (Accelerometers, Parachute, Dummy Payload)
- Skills needed: Parachute re-packing, personnel safety
- Safety Measures: Damage to payload
- Cost: TBD
- Facility: Local fire tower
- Frequency of Test: 4 Attempts
- Risk Factor: High due to the possibility of damaging the unit significantly.
- Areas of concern: Real-time processing of the altitude and/or accelerometer measurement

Requirements

- FR.1 REPTAR shall survive launch and standby period in space.
  - – DR 1.1 REPTAR shall survive vacuum.
    - * Motivation: Derived from the space environment conditions.
    - * V&V: Environmental Testing Facility at CU.
  - – DR 1.2 REPTAR shall survive the 8.5 G's that will be experienced during launch.
    - * Motivation: Derived from the launch environment conditions based on the popular launch vehicles such as Falcon 9 and Delta 4.
    - * V&V: Simulation/Analysis.
  - – DR 1.3 REPTAR shall survive an instantons G Loading of 40 Gs
    - * Motivation: Derived from MIL Spec
    - * V&V: Drop testing
  - – DR 1.4 REPTAR shall have a natural frequency greater than 100 Hz
    - * Motivation: Derived from launch environment conditions based on the popular launch vehicles
    - * V&V: Simulation/Analysis and maybe 40 Gs
  - – DR 1.5 REPTAR's components shall survive environmental temperature as low as 3 Kelvin.
    - * Motivation: Derived from the space environment conditions.
    - * V&V: Environmental Testing Facility at CU.
  - – DR 1.6 REPTAR's components shall survive temperatures as high as 400 Kelvin.
    - * Motivation: Derived. REPTAR should not be more sensitive than the payload to high temperatures. As defined by Raytheon, the payload can survive temperatures as high as 400 Kelvin.
    - * V&V: Environmental Testing at CU.

Requirements

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- FR.2 REPTAR shall conform to industry CubeSat standards.
  - – DR 2.1 REPTAR shall interface with the Raytheon Unit.

    * DR 2.1.1 REPTAR shall have an electrical interface according to Raytheon provided ICD.
      - Motivation Derived. REPTAR will need power and signal interfaces in order to carry out its mission objectives. Therefore, it needs to be charged before re-entry. Hence, it will have an interface with the Raytheon Unit to provide necessary power to perform the mission and signal when the REPTAR unit should activate.
      - V&V: Bench Top Test.

    * DR 2.1.2 REPTAR shall structurally interface with the 1U Raytheon payload.
      - Motivation Derived. REPTAR will need to be built in a way that the 1U payload can be added to the vehicle by Raytheon.
      - V&V: Demonstration by inspection.

Requirements

Raytheon

- FR.3 REPTAR shall keep the payload safe during descent and landing.
  - – DR 3.1 The payload shall not experience loading exceeding 8.5 G's during any stage of the mission.

    * Motivation: Derived. The payload can survive the loading experience during launch, therefore it should be kept within the launch limits to ensure its safety.

    * V&V: Simulation/Analysis. Possibility of vibration testing at CU facility or around the Boulder area.

Requirements

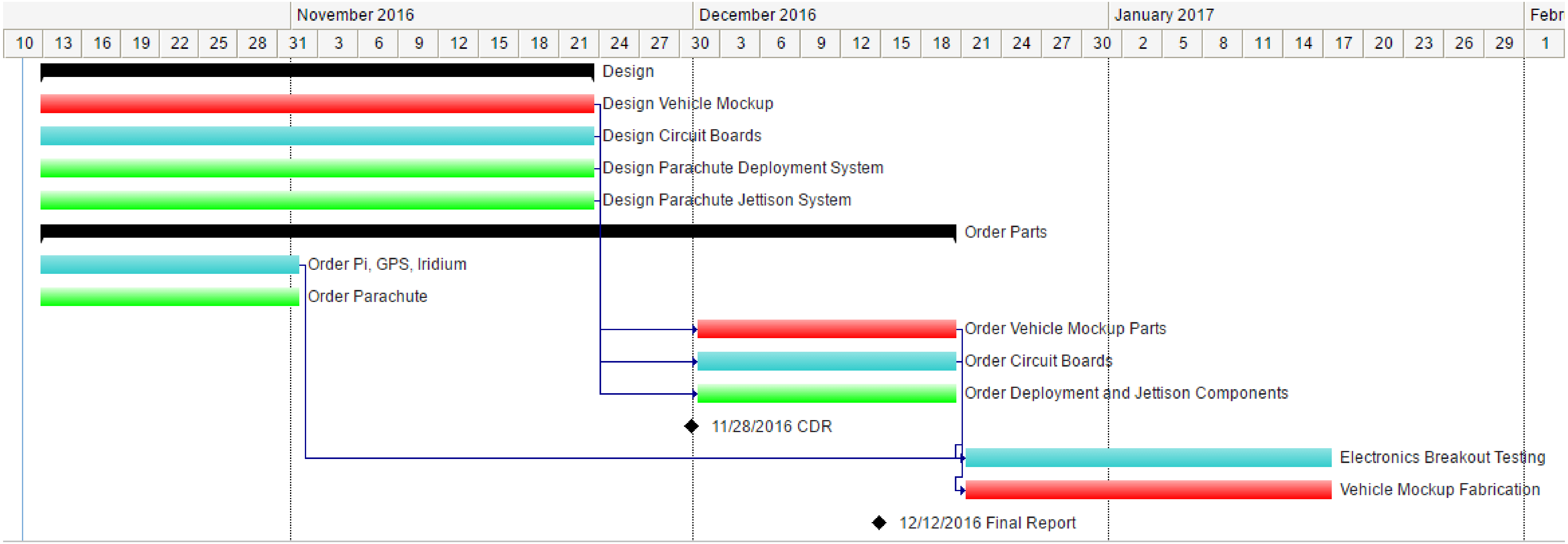
Raytheon

- FR.4 REPTAR shall be locatable.
  - – DR 4.1 REPTAR shall communicate its location over a radius less than or equal to 20 miles.

    * Motivation: Derived from the map of Utah Testing and Training Range(UTTR). The 20 mile range covers half of the range, therefore needing one search team each in the Northern or Southern regions of the range.

    * V&V: Demonstration by field test.

Gantt Chart



Overview | Descent | Landing | Avionics | Summary | Backup

References

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Datasheets for products reviewed as applicable