ASEN 4018 Senior Projects Fall 2018
Preliminary Design Review

BEACAN

Buoy-Enabled Analysis of Currents via Aerial Navigation

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Customer: Robert Leben

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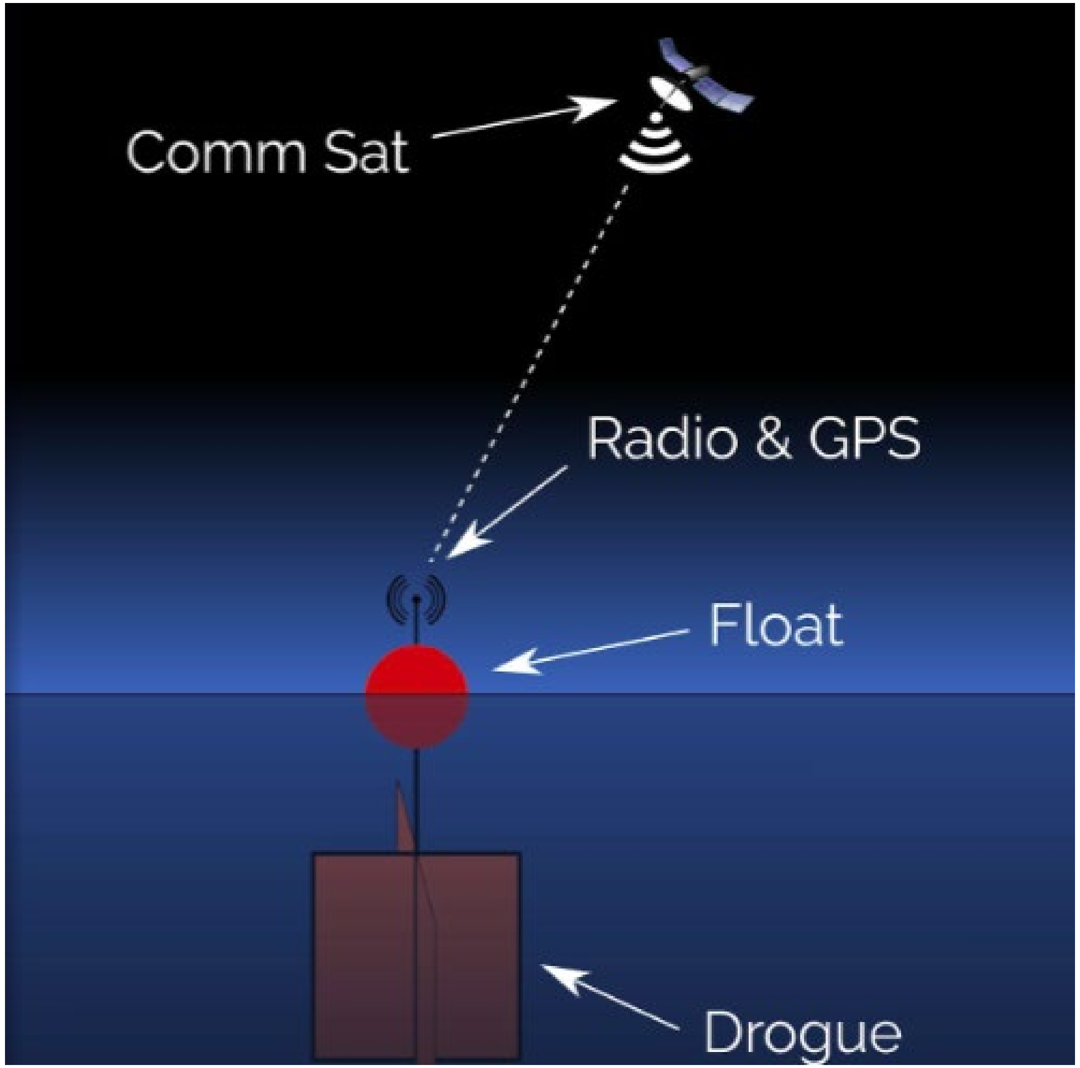
Project Objectives

- **<u>Mission Statement</u>**: BEACAN will develop a **miniaturized** ocean drifter that shall be deployed via UAV. The drifter shall be capable of following ocean currents, collecting positional coordinates, and transmitting coordinates to a ground station. Secondary, the team will develop a drifter deployment system that the customer can use to attach to the wing of a TBD UAV.

- **<u>Final Customer Deliverables</u>**:
- 1 deployment mechanism, 2 drifters (1 for testing)
- Method for comparing performance metrics of BEACAN drifter to drifters currently on the market

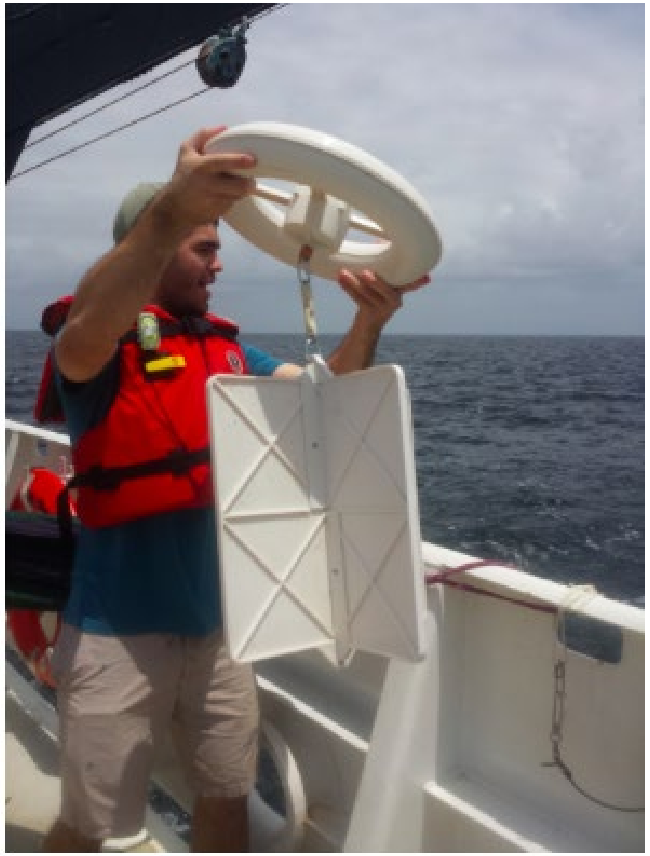
What is a drifter?

A drifter is an oceanic device that floats either on or near the surface of the ocean and reports their position for purposes of studying ocean currents



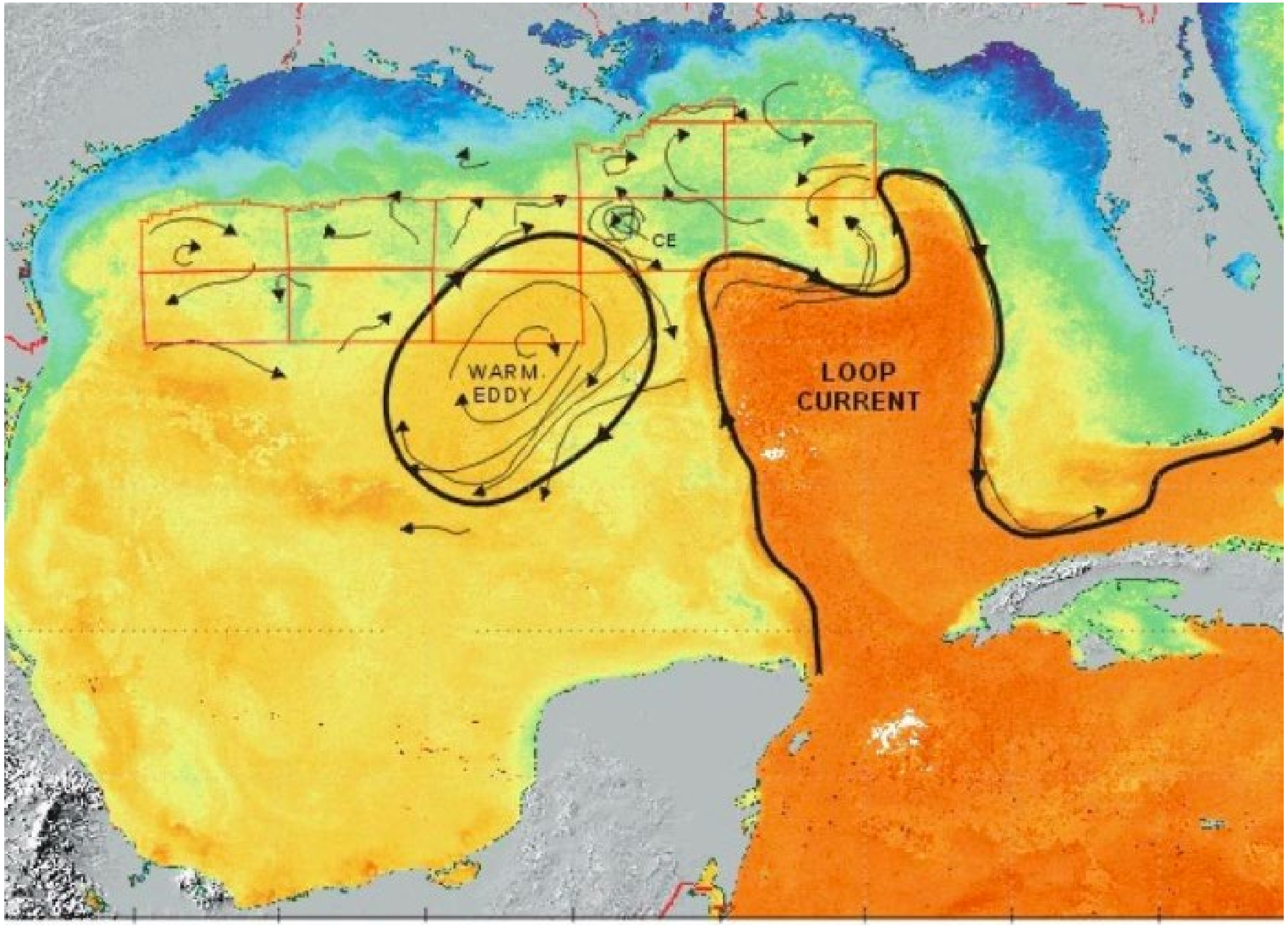
Why miniaturize the drifter?

- Current Drifters are bulky which limits deployment methods to large vessels.
- Ship time is COSTLY. Can exceed $10,000 /day
- Save costs by deploying via UAV



Further Motivation

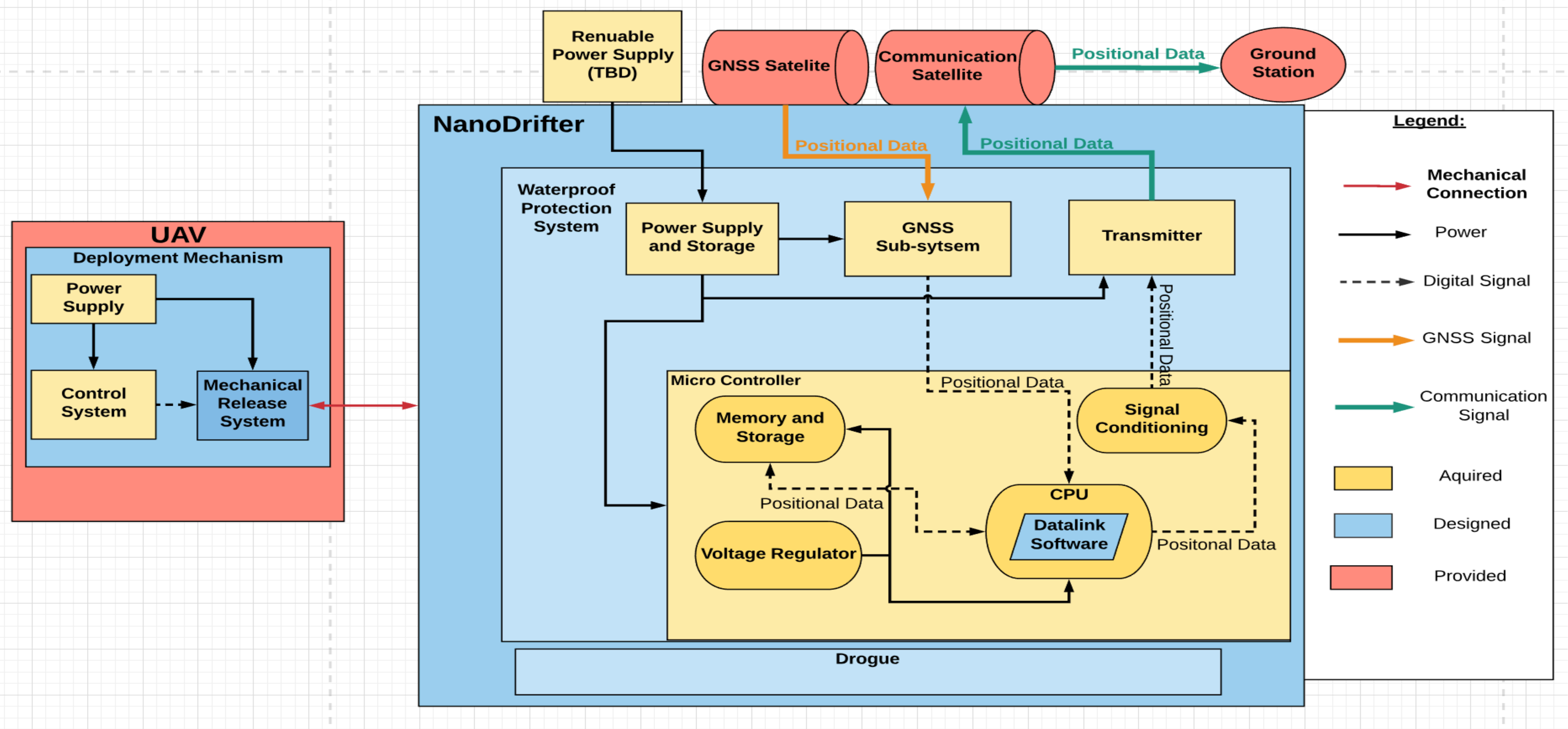
- Allow precise deployment in the Gulf of Mexico
- Further study of the Loop Current and mesoscale eddies in the Gulf of Mexico
- The 2010 Deepwater Horizons oil spill highlighted the need for further understanding of currents in the Gulf



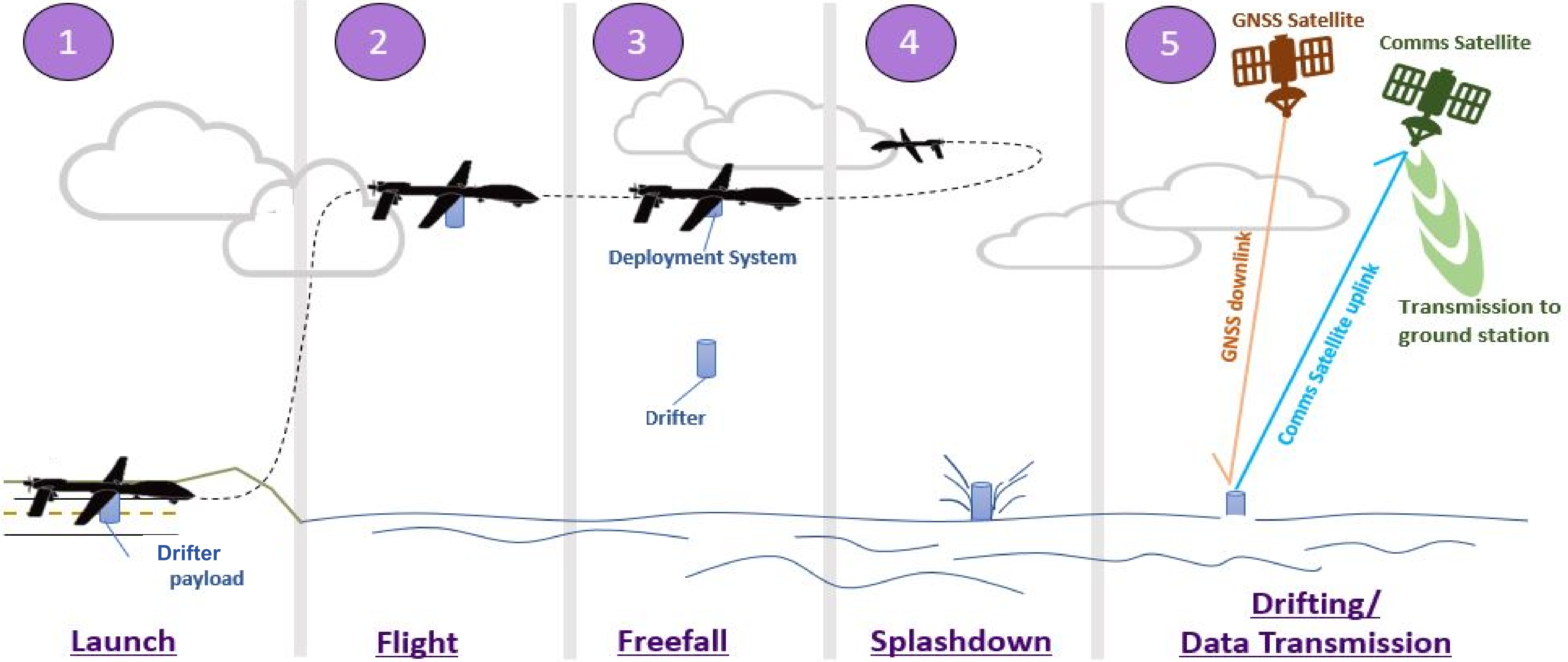
Functional Requirements

Functional Requirement	Description
FR 1.0	Drifter shall be capable of following ocean currents in the Gulf of Mexico
FR 2.0	Drifter shall maintain a 3 month lifespan
FR 3.0	Drifter shall maintain full structural integrity and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]
FR 4.0	When following a current, the drifter shall triangulate and store position coordinates with an accuracy of 60 [m] on average every 5 minutes
FR 5.0	Drifter shall transmit stored position coordinates to a ground station up to 800 [km] away with a latency less than 24 hours
FR 6.0	Mass of 4 drifters and 2 deployment mechanisms shall not exceed 2.7 [kg]
FR 7.0	Each deployment system shall store 2 drifters and release each drifter individually
FR 8.0	Cost of manufacturing 1 drifter and required communications package shall not exceed $1000

Functional Block Diagram

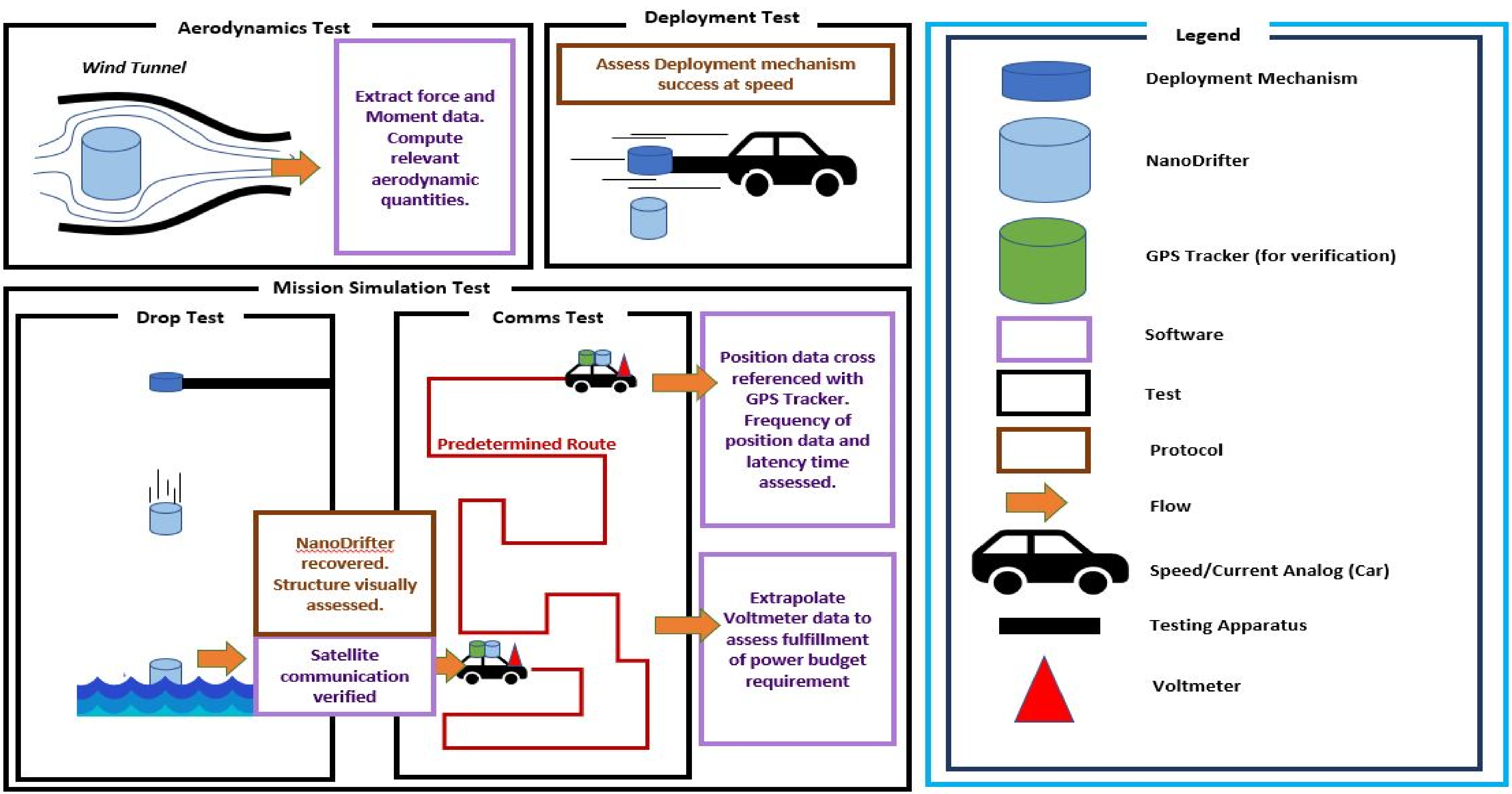


Operation CONOPS



Launch	Flight	Freefall	Splashdown	Drifting/ Data Transmission
Uav, with Drifter payload launches from Marco Is, FL	UAV flies to target location along Loop Current	Deployment initiated by onboard autopilot. Drifter falls into Gulf of Mexico	Drifter splashes down. UAV returns to ground station.	Drifter follows surface currents until end of life. GNSS lock is established, and periodic transmission to comms satellite begins.

Project CONOPS



Baseline Design and Critical Elements

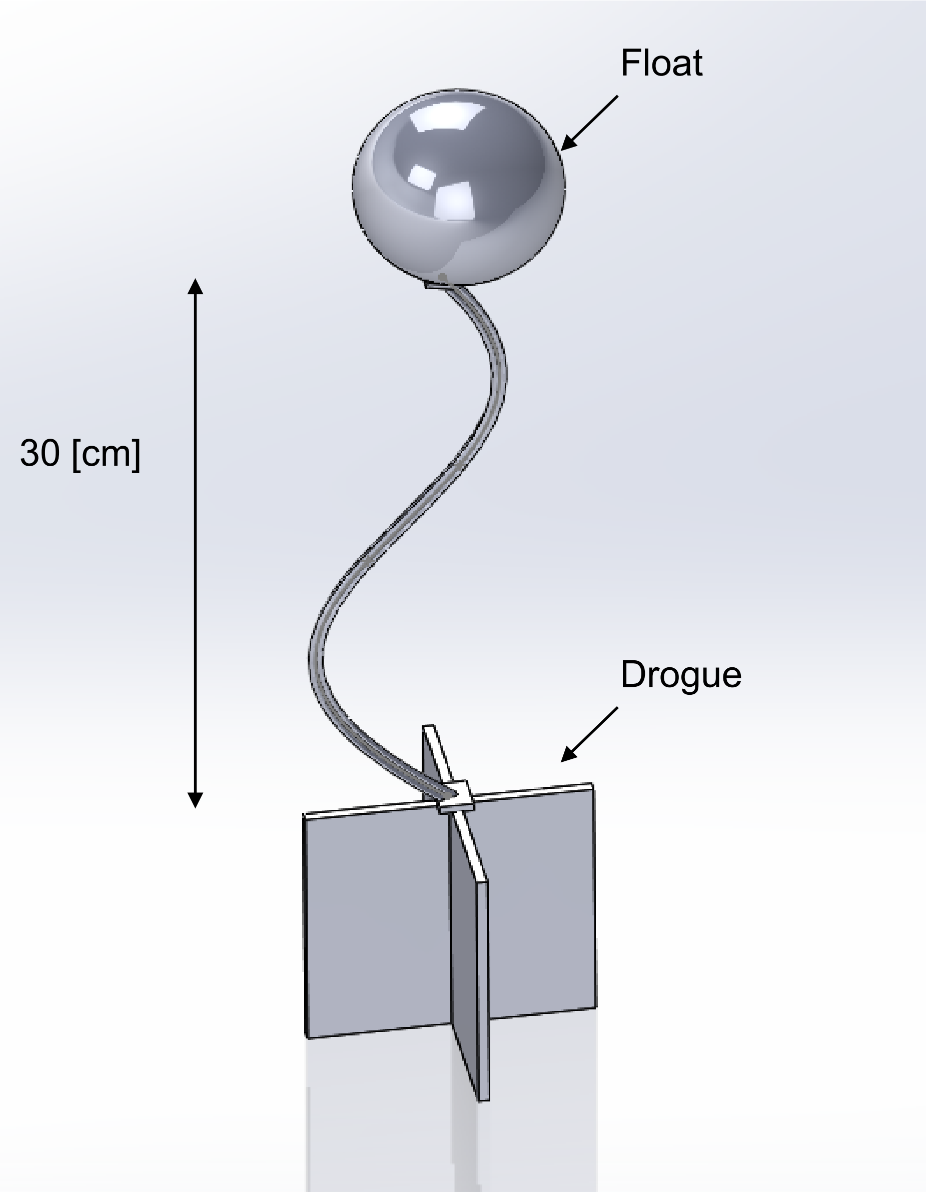
Critical Project Elements

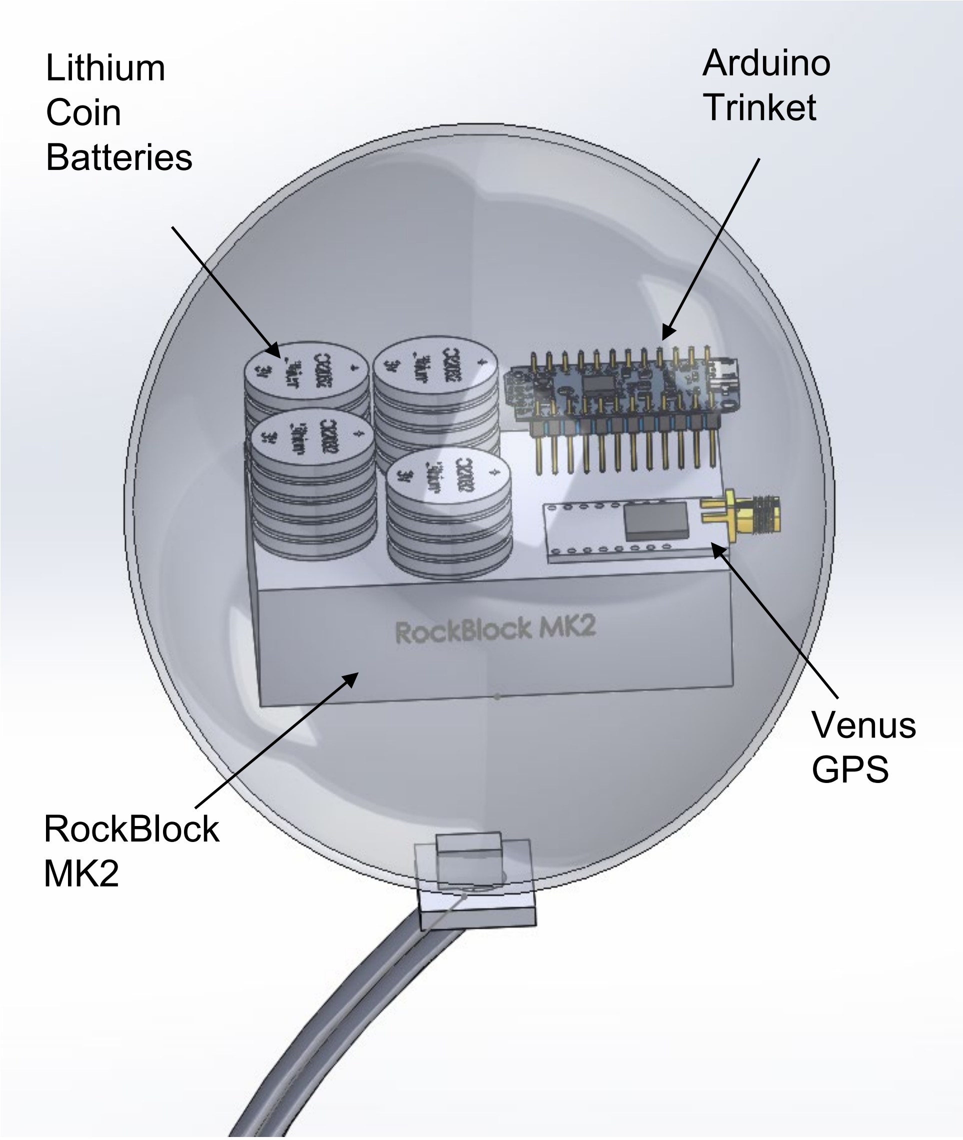
CPE	Driving Requirements
Communication Systems	• Shall take position data every **5 minutes** to an accuracy of **60 [m]** • Shall transmit position data every **24 hours**
Electronics/Power Systems	• Shall survive impact at **terminal velocity** • Shall provide suitable power to communication system for **3 months**
Deployment Mechanisms	• Shall carry **two drifters**, deploying each **separately** • Shall deploy drifter to within a **1000 [m]** radius of drop point
Structures	• Shall survive impact at **terminal velocity** • Shall follow currents at nominal depths of **30-100 [cm]** • Shall not be perturbed by **wind** and **surface effects**

Cost of manufacturing one drifter and required communications package shall not exceed **$1000**

Mass of four drifters plus two deployment mechanisms shall not exceed **2.7 [kg]**

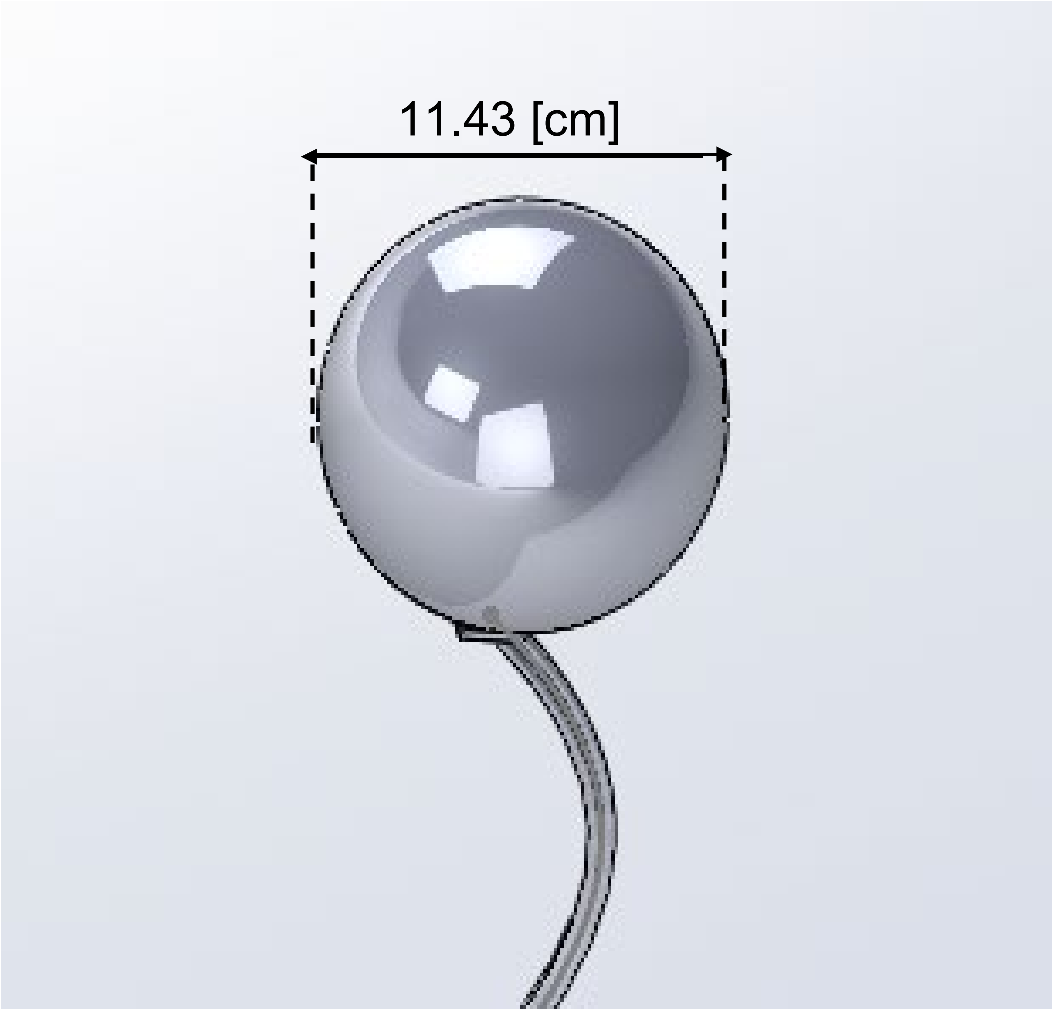
Overall Design





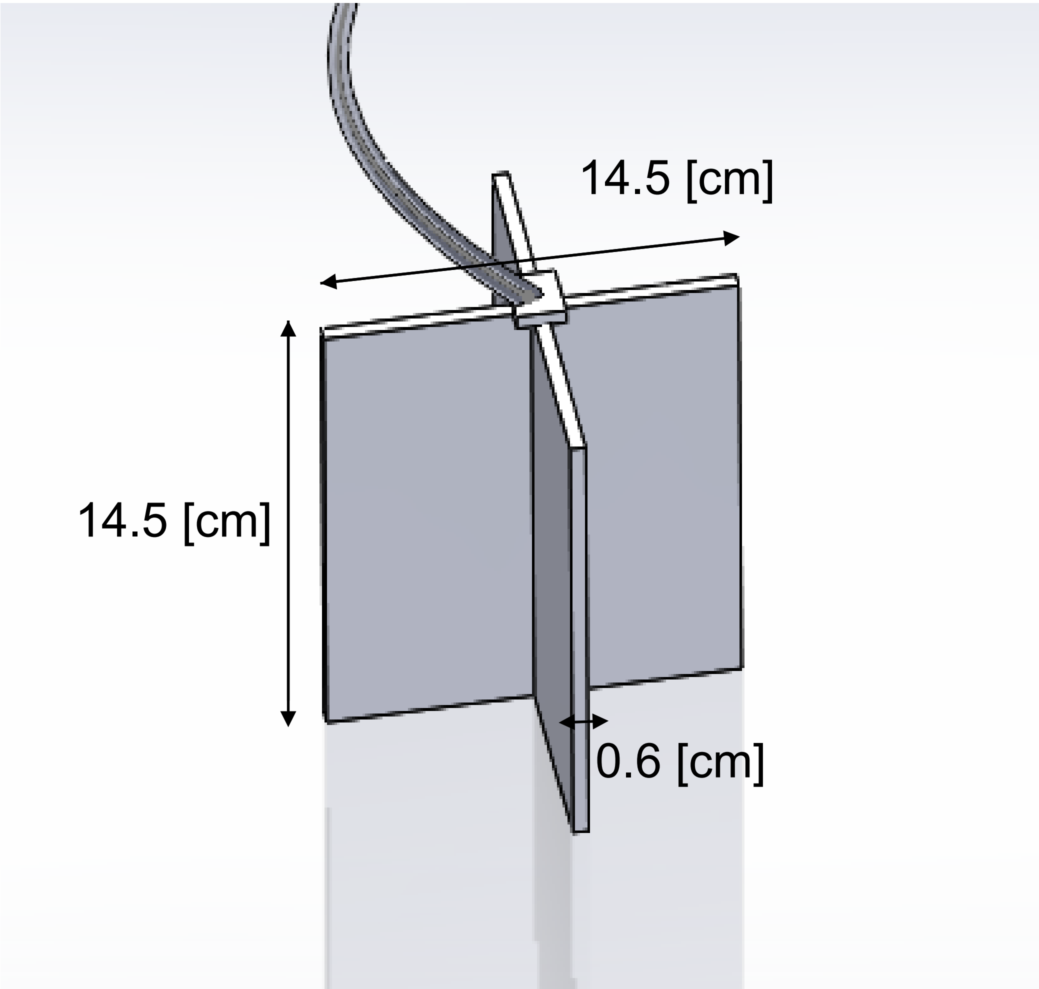
Baseline Design: Float Configuration

- Hollow Sphere
  - Diameter = 11.43 [cm]
  - Wall thickness = 0.15 [cm]
  - Mass = 50 [g]
  - Useable volume = 741.9 [cm^3]
- Completely encloses electronic and communication subsystems
  - Protects sensitive components upon impact



Baseline Design: Drogue Configuration

- Flat Plate Cross-Area
  - Two Plates: 14.5 [cm] x 14.5 [cm]
    - Wall thickness = 0.6 [cm]
    - Surface area = 210.25[cm^2]
    - Total mass = 270 [g]
    - Total volume = 741.9 [cm^3]
- Provides drogue-to-float drag ratio of 45.3
  - Enables undercurrent drag force to dominant over surface drag force in drifter dynamic model



Baseline Design: Material Selection

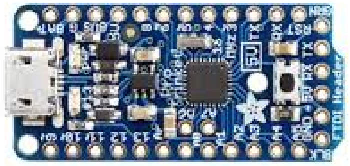
- Float: High-density polyethylene (HDPE)
  - Absorptivity = 0.01 [%]
  - Compression Yield Strength = 12.6 [MPa]

- Drogue: Polyvinyl chloride (PVC) sheets
  - Absorptivity = 0.015 – 0.3 [%]
  - Bending Modulus = 1,690 – 1,793 [MPa]

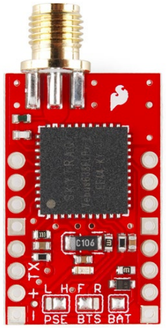
Baseline Design: Electronics

Microcontroller: Arduino Trinket Pro

- Robust
- Lightweight



GNSS Receiver: Venus 638FLP



- Inexpensive
- Lightweight
- Low Power Consumption

Sat/Com Module: Iridium RockBlock mk2

- Mid-range option: Cost, Weight, Data Cost, Transmission Rate
- All-in-one package

Battery: Lithium Coin Cell (BR-2477A/HBN)

- Best capacity-to-weight ratio
- Best capacity-to-cost ratio

Baseline Design: Preliminary Power Budget

- Back-of-the-envelope Calculation

$$\longrightarrow W_{batteries} = T w_i \sum I = 12\ [kg]$$

90 days

$\frac{8\ [grams]}{1\ [Ah]}$

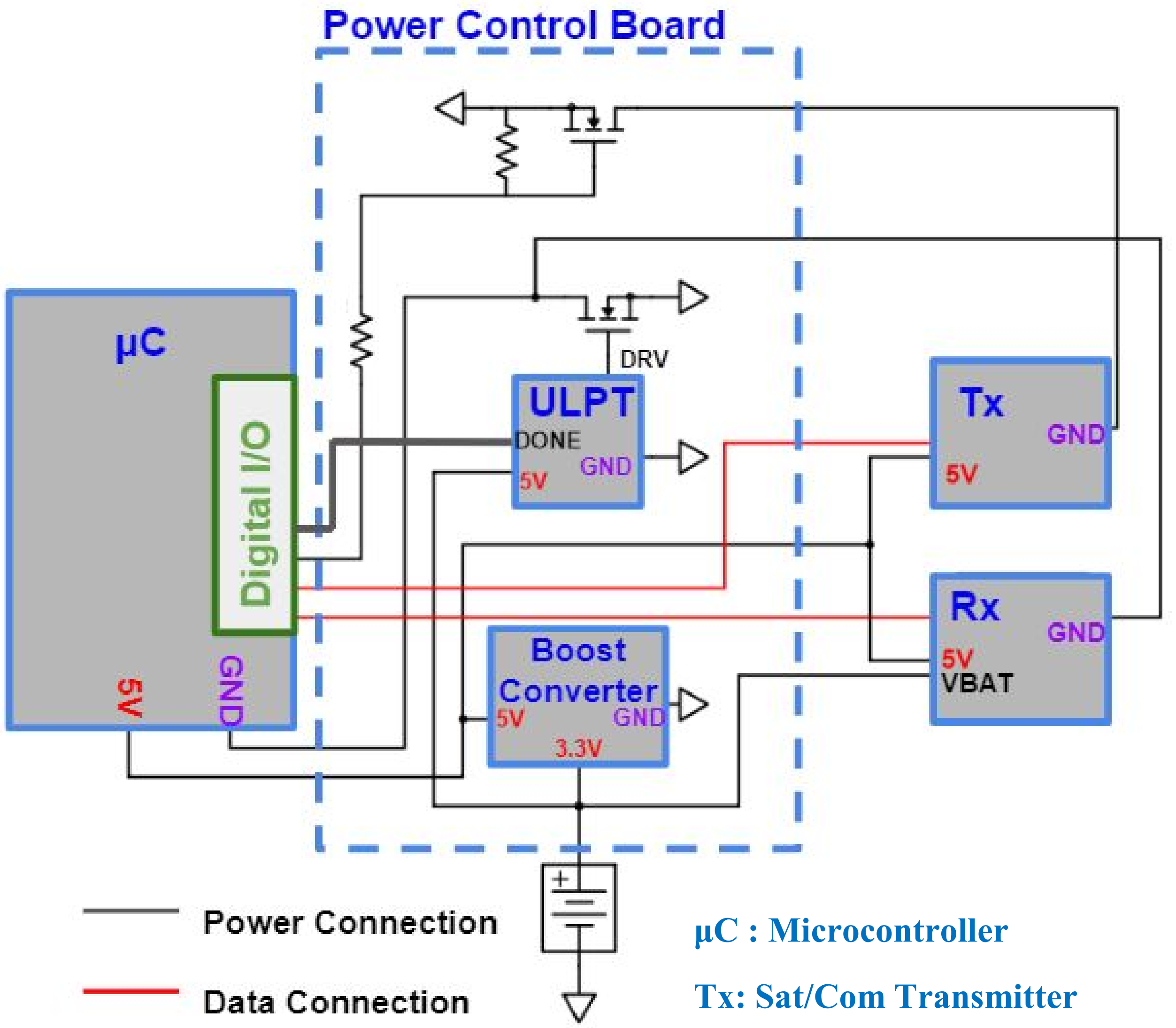
Sum of current over all components

2400 % of our weight budget

Solution

We need to be able to turn components off and on

Baseline Design: Power Management System



HIGH Voltage

Current

μC : Microcontroller

Tx: Sat/Com Transmitter

ULPT: Ultra-Low Power Timer

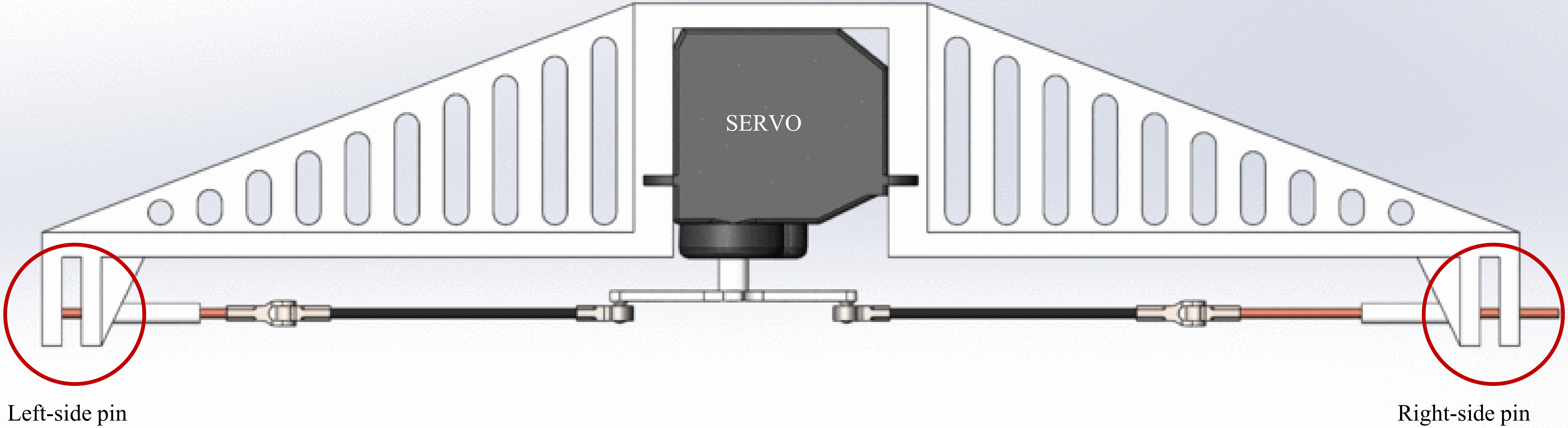
Rx: GNSS Receiver

Baseline Design: Parachute

- Iris Ultra Zero Light with spectra lines
  - Projected C_d: 2.20
  - Reference Diameter: 0.762 [m]
  - Mass: 27.78 [g]
  - Cost: $100

Baseline Design: Deployment Mechanism

- Servo rotates 45° counter-clockwise to release left-side pin
- Servo rotates another 45° counter-clockwise to release right-side pin



GNSS Feasibility

GNSS

FR 4.0

When following a current, the drifter shall triangulate and store position coordinates with an accuracy of 60 [m] on average every 5 minutes

Problem :

Needs to establish positional coordinates via GPS surveying techniques

Solution:

Validate with link budget

GNSS Model: Assumptions

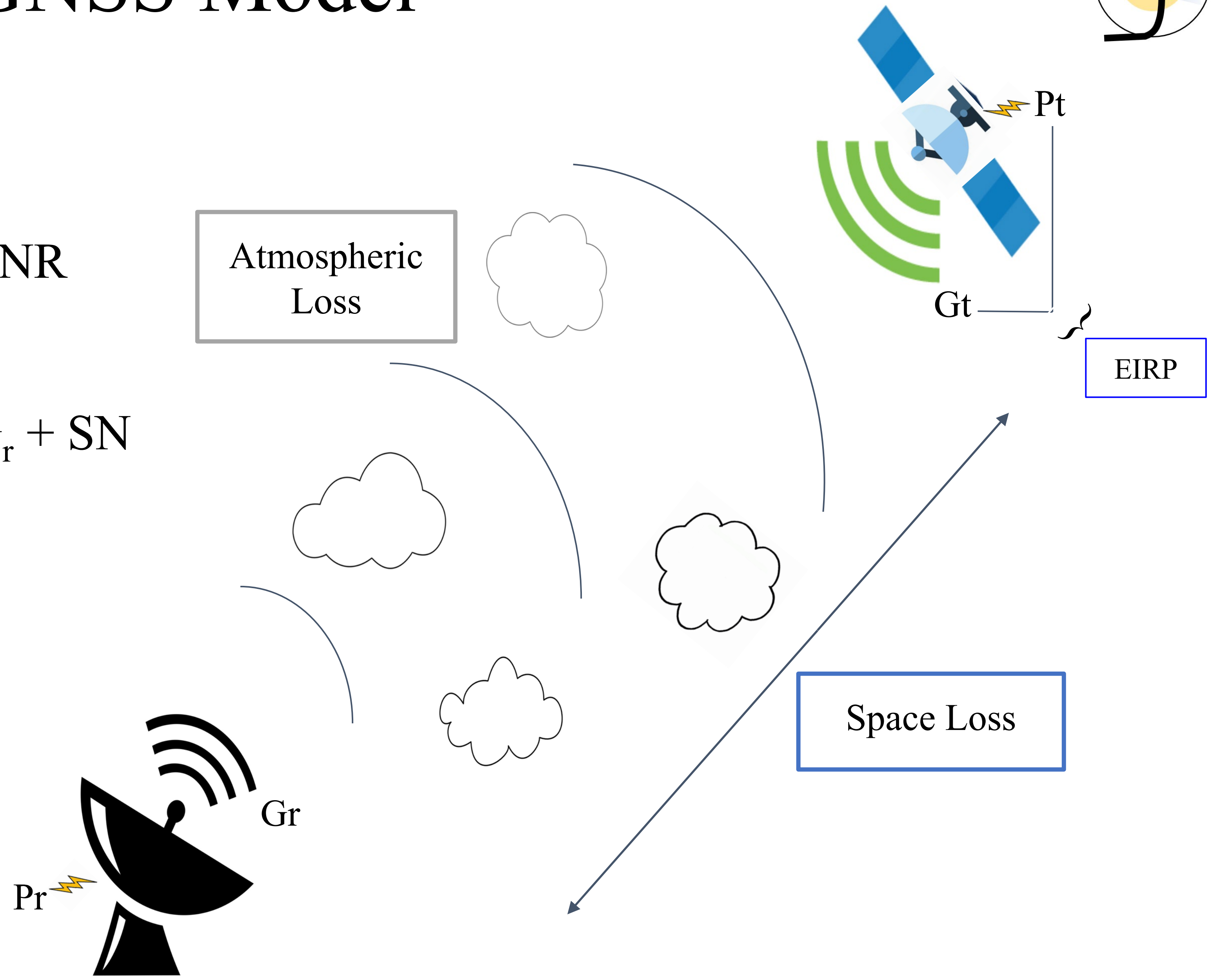
- Atmospheric Losses ~ 2.6 [dB]
- Pointing Loss ~ 3 [dB]
- System Temperature ~ Atmospheric Sea Level ~ 288.15 [K]
- Baud Rate (z) ~ 9600 [bit/sec]
- Frequency (f) = 1575 [MHz]
- Range (Medium Earth Orbit) = 20200 [km]

GNSS Model

Link Budget = Actual SNR – LSNR

$$\text{Act SNR} = L_{space} + \text{EIRP} + L_{atm} + G_r + SN$$

$$\text{LSNR} = \frac{P_r}{kT_S z}$$



Link Budget

Link Budget	Notation	
Equivalent Isotropically Radiated Power	EIRP	27 [dB]
Total Losses	Ltotal	-188.088 [dB]
Receiver Power	P_r	-141 [dB]
System noise power	SN	24.6 [dB]
Minimum Carrier to Noise ratio	LSNR	[illegible]
Actual Carrier to Noise ratio	Actual SNR	66.37 [dB]
Link budget	LB	3.41 [dB]

FEASIBLE ~ LB > 0 dB

Satellite Communications Feasibility

Buoy-Enabled Analysis of Currents via Aerial Navigation

Satellite Communication Module

FR 4.0

When following a current, the drifter shall triangulate and store position coordinates with an accuracy of 60 [m] on average every 5 minutes

FR 6.0

The drifter shall transmit stored position coordinates to a ground station up to 800 [km] away at least every 24 hours

FR 8.0

Cost of manufacturing one drifter and required communications package shall not exceed $1000

Satellite Communication Module

Problem:

Position data, with 60 [m] of accuracy, must be sent to a server 800 [km] away with 24 hours of latency. The cost of communication package must be minimized in order to save money for manufacturing and other subsystems.

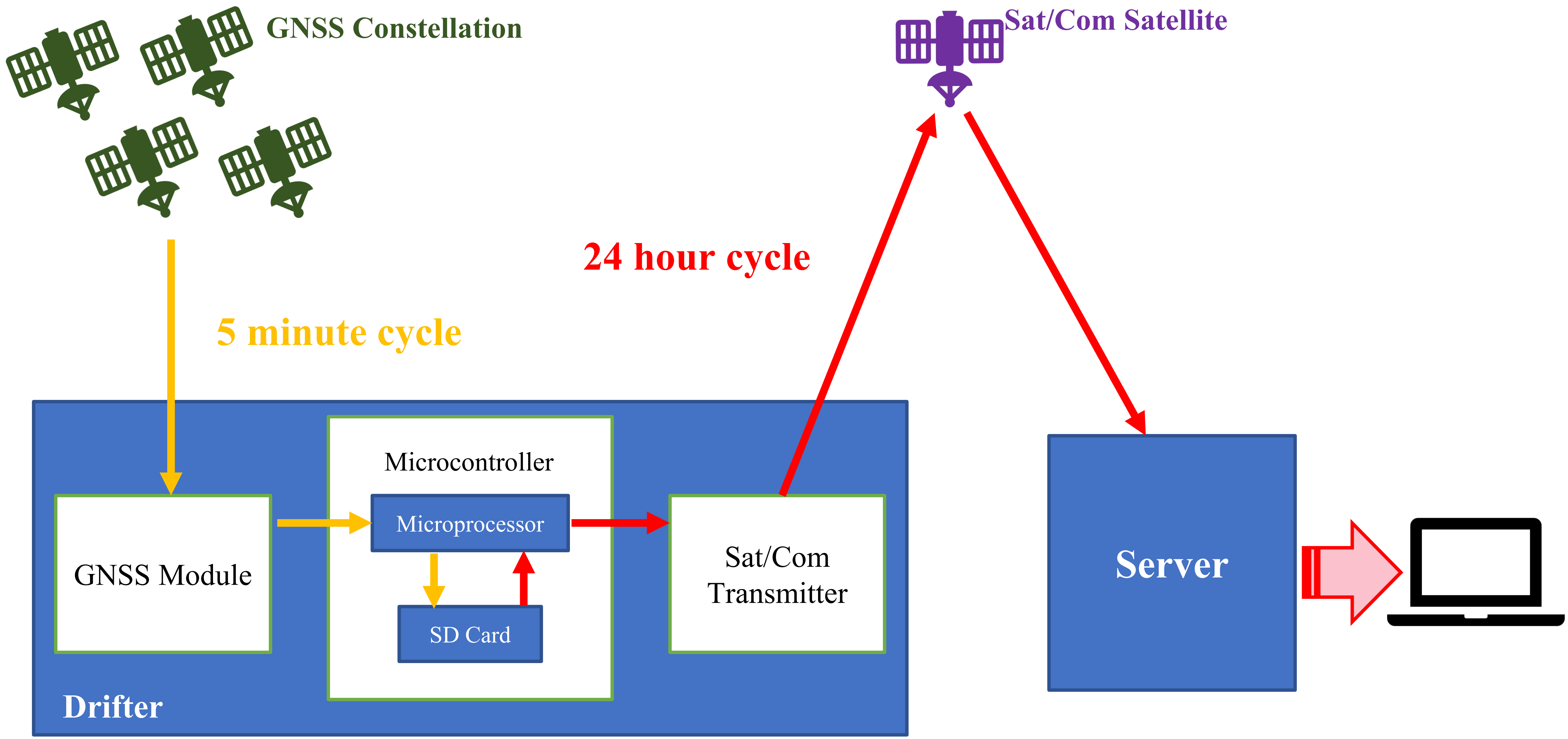
Solution: **Iridium Rockblock mk2**

- Sends 340 bytes of data per messages
- A maximum of 2857 messages per data subscription
- Requires 10 seconds of latency
- Takes 20 seconds from power up to successful transmission

Assumptions:

- Iridium Rockblock mk2 can establish a communication link whenever turned on
- Iridium Company is responsible for sending data to the customer once the satellite receive all position data

Data Flow Diagram



Satellite Communication Module: Model

Received a position data in NMEA format

- Size : 82 bytes

*$GPGGA,181908.00,3404.7041778,N,07044.3966270, W,4,13,1.00,495.144,M,29.200,M,0.10,0000*40*

- $GPGGA – Format ID
- 181908.00 – UTC Time
- 3404.7041778,N – Latitude
- 07044.3966270, W – Longitude
- 4 – Quality Indicator
- 13 – Satellites
- 1.00 – Horizontal Dilution of Precision
- 495.144,M – Altitude of Antenna
- 29.200,M – Geoidal Separation
- 0.10,0000 – Age of Correction

Data Compression Method

Step 1 : Extract required data

- Precision information will be used to validate position data before saving, but only timestamp and coordinates will be transmitted

	Time Stamp [hhmmss.sss]	Latitude [ddmm.mmm]	N/S Indicator	Longitude [dddmm.mmmm]	W/E Indicator
Format	092204.999	04250.5589	S	14718.5084	E
Size	4 [Bytes]	4 [bytes]	1 [bytes]	4 [bytes]	1 [bytes]

Satellite Communication Module: Model

Step 2 : Compress Indicators into Latitude and Longitude

- 60 [m] accuracy Requirements
- Check how precise the latitude and the longitude must be

$$\theta = \frac{d}{R} = \frac{60}{6371 * 10^3} = 1.94 \ seconds$$

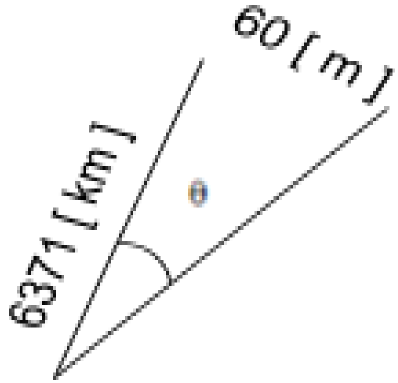
FR 4.0 When following a current, the drifter shall triangulate and store position coordinates with an accuracy of 60 [m] on average every 5 minutes

N/S Indicator is included in the latitude value such that:

- North : [0 : 90] degrees
- South : [90 : 180] degrees

W/E Indicator is included in the longitude value such that

- West : [0 : 180] degrees
- East : [180 : 360] degrees



	Time Stamp [hhmm]	Latitude [dddmm.mm]	Longitude [dddmm.mm]
Format	0922	04250.55	14718.50
Size	2 [bytes]	4 [bytes]	4 [bytes]

Sat/Comm Module: Data Feasibility

	Data Summary
Data Format	HHMMDDDMMSSDDDMMSS (Time / Latitude / Longitude)
Bytes per Location	10 [Bytes]
Bytes per Message	340 [Bytes]
Location Readings [illegible]	34
Bytes per Day	[illegible] [Bytes]
Transmitted Messages per Day	[illegible]
Time Required for Transmission	[illegible]
Data Cost per Day	$ 2.862
Transmitted Messages for 90 Days	810
Data Cost for 90 Days	$ 257.58

FR 6.0 The drifter shall transmit stored position coordinates to a ground station up to 800 [km] away at least every 24 hours

FR 8.0 Cost of manufacturing one drifter and required communications package shall not exceed $1000

Power Budget Feasibility

Power Budget

FR 2.0

Drifter shall maintain a 3 month lifespan

FR 7.0

Mass of 4 drifters and 2 deployment mechanisms shall not exceed 2.7 [kg]

FR 8.0

The cost of manufacturing 1 drifter and communications package shall not exceed $1000

Problem:
How to provide enough power for three months while meeting budget and mass constraints

Solution:
Power management system

Power Budget: Assumptions

1. Battery self-discharge is negligible (~0.3%/month)
2. Internal battery impedance is negligible
3. Batteries will provide suitable voltage until their capacity drops below 10%
4. MOSFET transistors act as ideal electronic switches
5. All current loads are constant
6. Voltage booster efficiency is 92% for currents greater than 1 [mA] and 75% for currents less than 1 [mA]
7. All other component inefficiencies are negligible

Power Budget: Model

Q : Charge on battery
I : Current draw
λ_s: Self Discharge rate
t : time

Governing Equation:

$$\dot{Q} = -I(t) - \lambda_s Q$$

$$\longrightarrow Q(t) = e^{-\lambda_s t}\left(Q_0 - \int_{t_0}^{t} I(\tau) e^{\lambda_s \tau} d\tau\right)$$

Assume: $\lambda_s \sim 0 \ \rightarrow \ e^{\pm\lambda_s t} \sim 1$

$$\longrightarrow Q(t) = Q_0 - \int_{t_0}^{t} I(\tau) d\tau$$

Assume: $\frac{\partial I}{\partial t} = 0$

$$\boxed{Q(t) = Q_0 - I_{Av} t}$$

Constraints:

1. $Q(90\ days) = Q(T) \geq \eta_B Q_0$
   - where η_B is the proportion of the batter capacity at which it can no longer draw a suitable voltage
   - $\eta_B \sim 10\%$
2. $Q_0 \left(\frac{mass}{capcity}\right)_{battery} \leq 675\ [g] - m_{buffer}$

FR 2.0 The drifter must have power to collect position coordinates along with power for transmission for 3 months

FR 7.0 Mass of 4 drifters and 2 deployment mechanisms shall not exceed 2.7 [kg]

Power Budget: Results

Parameter	Symbol (X)	Mass Coefficient (α_X) [g/s]	Nominal Value	Margin [s]
Average Microcontroller Process Time	$t_{\mu C}$	18.4084	2 [s]	2
Average GNSS Cold Start Time	t_{CS}	0.230187	30 [s]	30
Average transmission Process time	t_{Tx}	0.393061	110 [s]	110
Weight due to constant current offset	β	-	1.1679 [g]	-

$$W_b \geq \alpha_{\mu C} t_{\mu C} + \alpha_{CS} t_{CS} + \alpha_{Tx} t_{Tx} + \beta$$

FEASIBLE

With margin we have a buffer of 530 [g] for the rest of the drifter plus deployment mechanism

Power Budget: Model Limitations

- Does account for:
  - Batter discharge (falling voltage)
  - Voltage booster inefficiencies
  - Variability in transmission/receiver time

- Doesn’t account for:
  - Most component inefficiencies
  - Transient response of different components
  - Extraneous impedances
  - Battery self discharge

Electronics: Mass Budget

Component	Mass [g]
GNSS Receiver (Venus 638FLP)	45
Total	**45**

Leaves 405 [g] for Drogue Structures and Deployment

Deployment Mechanism Feasibility

Deployment Mechanism

FR 7.0

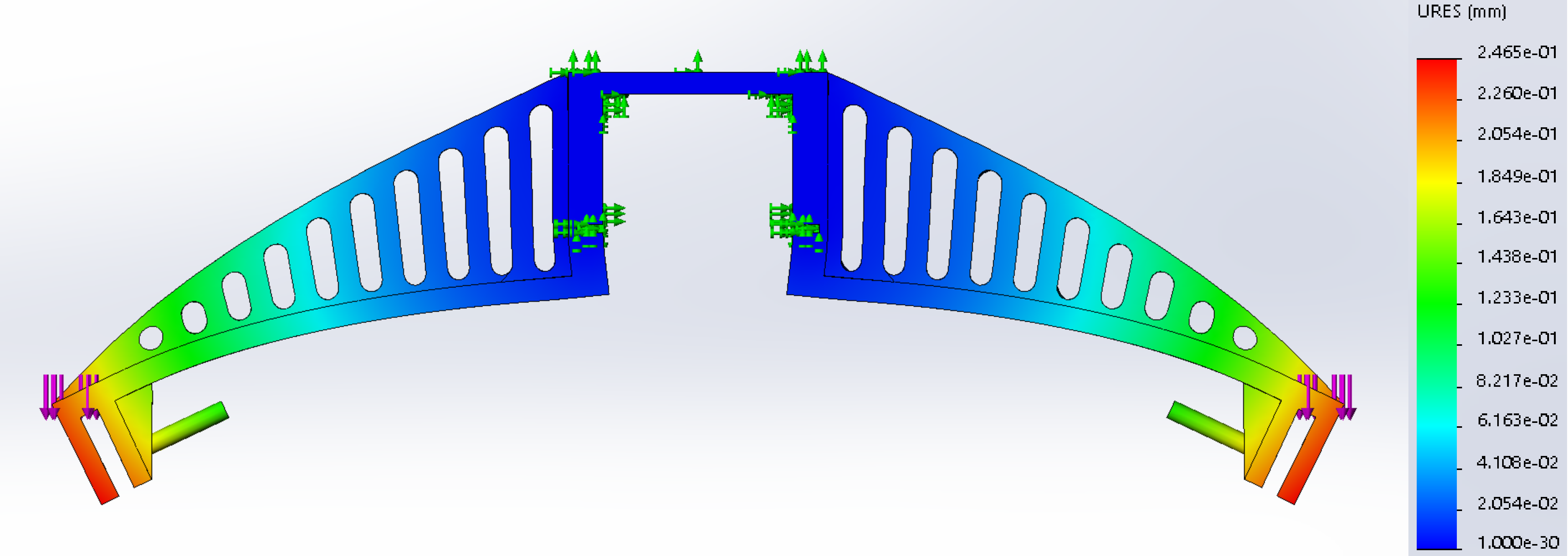
Each deployment system shall store 2 drifters and release each drifter individually

Problem: Deployment configuration needs to support 2 drifters, and the servo needs to produce enough torque to overcome friction.

Solution: Stress analysis and force analysis.

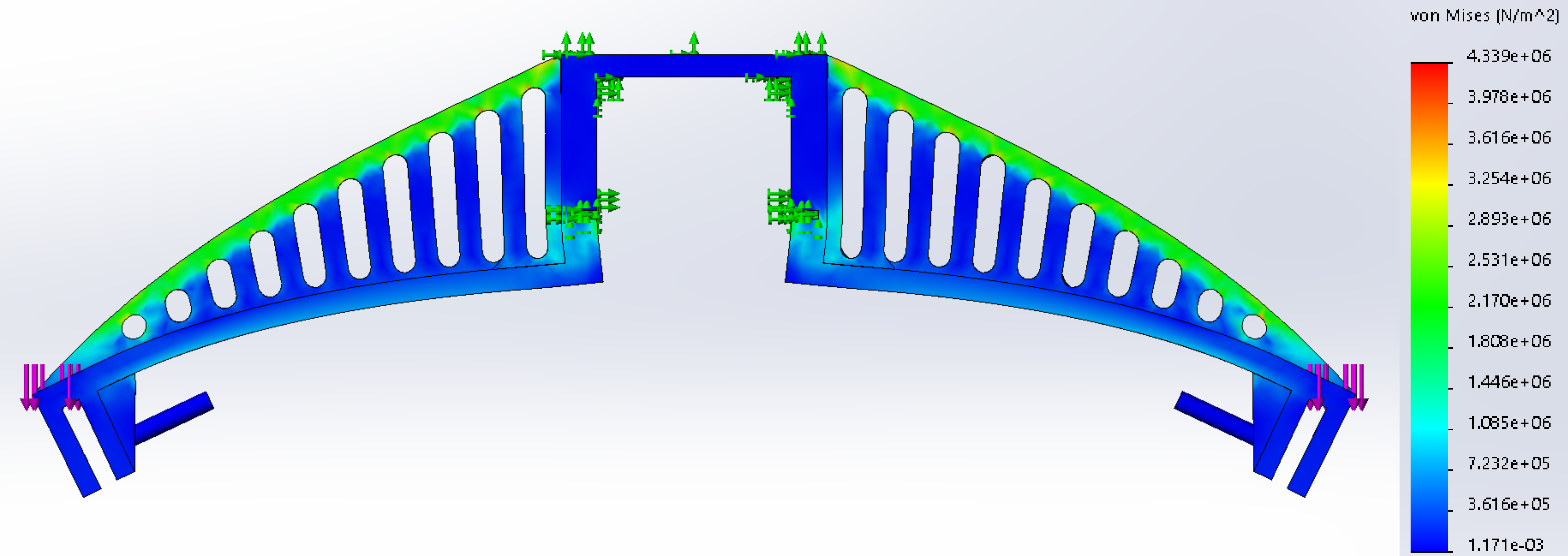
Deployment Mechanism: Displacement

- Maximum tip displacement: **0.25 [mm]**
- Note: displacement is greatly exaggerated



Deployment Mechanism: Stress

- Maximum yield stress of ABS: **68.9 [MPa]**
- Maximum occurring stress on model: **4.3 [MPa]**



Deployment Mechanism: Model

Known:
- Length of blade of servo: 23.2 [mm]
- Torque that servo can produce: 165.9 [N-mm]
- Mass of drifter: 0.62 [kg]
- Coefficient of friction of ABS: 0.46

Assumption: The pin is massless.

Result:
- Force of friction: 2.798 [N]
- Applied force: 14.306 [N]

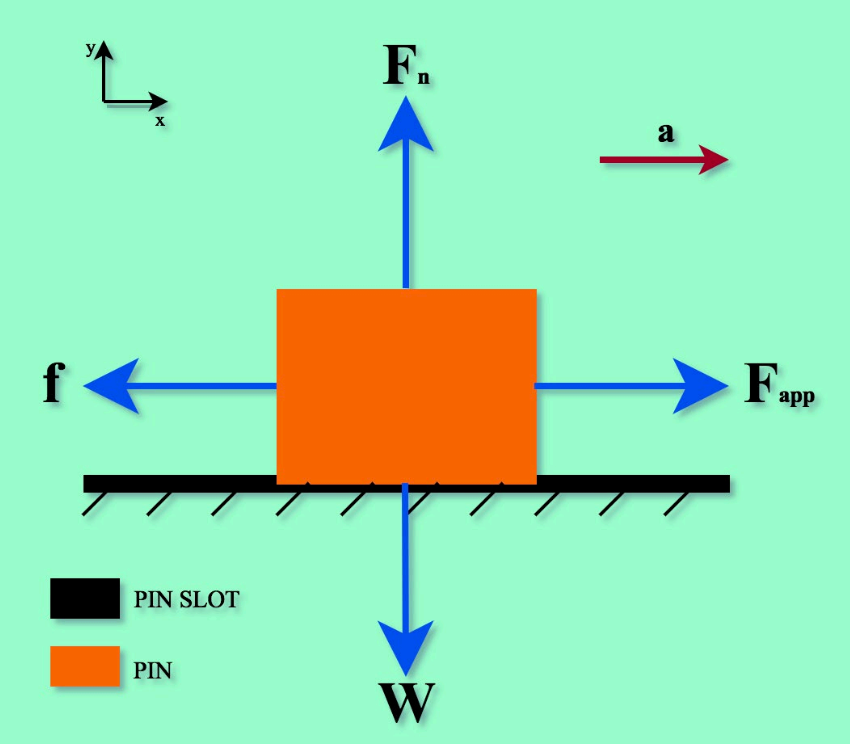
$$f < F_{APP}$$

Equation: Equations of motion are applied.

$$\sum F_y = 0 \qquad F_N - W = 0$$

$$f = \mu \cdot F_N \qquad f = \mu \cdot W$$

$$F_{APP} = \frac{\tau}{x}$$



Structure

Float Design

FR 1.0
The drifter shall follow currents in the Gulf of Mexico

Problem:
-The drifter needs to float with surface currents to collect positional data.
-Needs to be buoyant
-Needs to be large enough to house electronic and power components

Solution:
-Buoy shall be designed such that the buoyancy force is greater than the gravitational force of allocated mass of electronics and drifter structure design ~ 620 [g]

Float Design: Buoyancy Model

Assumptions:

- Total drifter mass (620 [g]) is housed in buoy
- k = fraction of buoy submerged = 0.75
- $\rho_{water} = 1027\ [\frac{kg}{m^3}]$
- Material is High Density Polyethylene (HDPE)

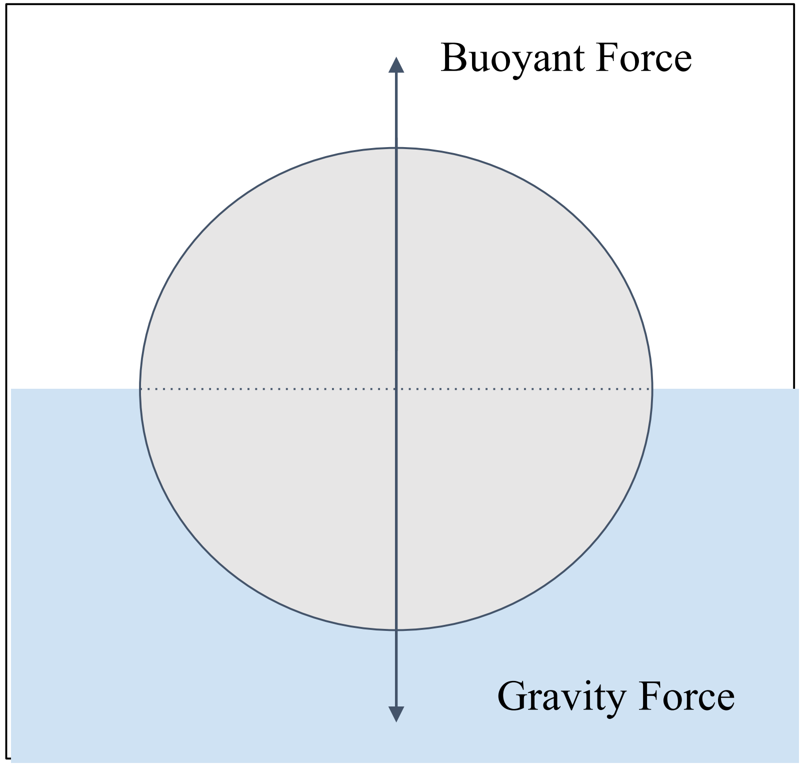
Governing Equations:

$$F_{bouyant} \geq F_{gravity}$$

$$\rho_{water} V_{disp} \geq m_{drifter}$$

$$V_{buoy} k = V_{disp}$$

$$V_{buoy} \geq \frac{m_{drifter}}{\rho_{fluid} k}$$



Results:

Radius: 5.77 [cm]
Thickness: 0.15 [cm]
Mass of float: 50 [g]
Displaced Volume: 603.7 [cm^3]

Float Design: Impact Analysis

FR 3.0

Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

Problem:

- Structural deformation could lead to loss of buoyancy
- Structural failure could expose electrical components to water
- Communication and electrical components could be damaged if impact force is transferred to them

Solution:

- House the communication and electrical components within a structure that is resistant to compression failure
- A hollow sphere made out of a material with a high compressive yield strength: HDPE

Float Design: Impact Assumptions

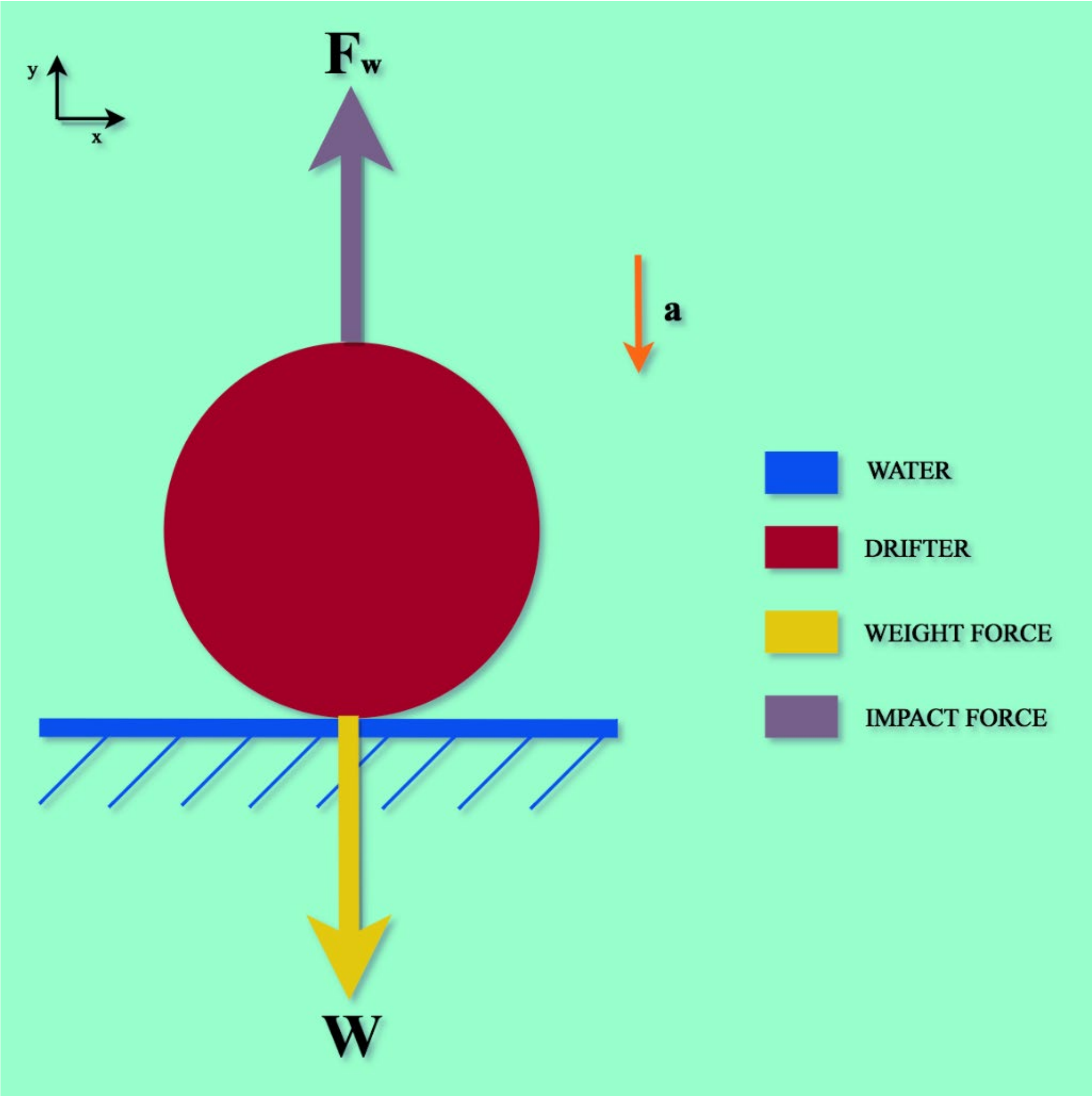
Knowns:

- The diameter of the float sphere is 11.43 [cm]
- Thickness of float walls are 0.15 [cm]
- The mass of the float structure is 50 [g]
- The mass of the float with electronics is 320 [g]

Assumptions:

- Impact well modeled by a sphere hitting water
- Impact occurs at terminal velocity only in vertical direction
- For worst case analysis, coefficient of force $(C_f) = 1$
- The net upward force experienced from impact is due to pressure forces
- Failure will occur due to compression
- The approximate mass of one drifter will be 620 [g]

Float Design: Impact Model



Governing Equations:

Summation of Forces in Y Direction

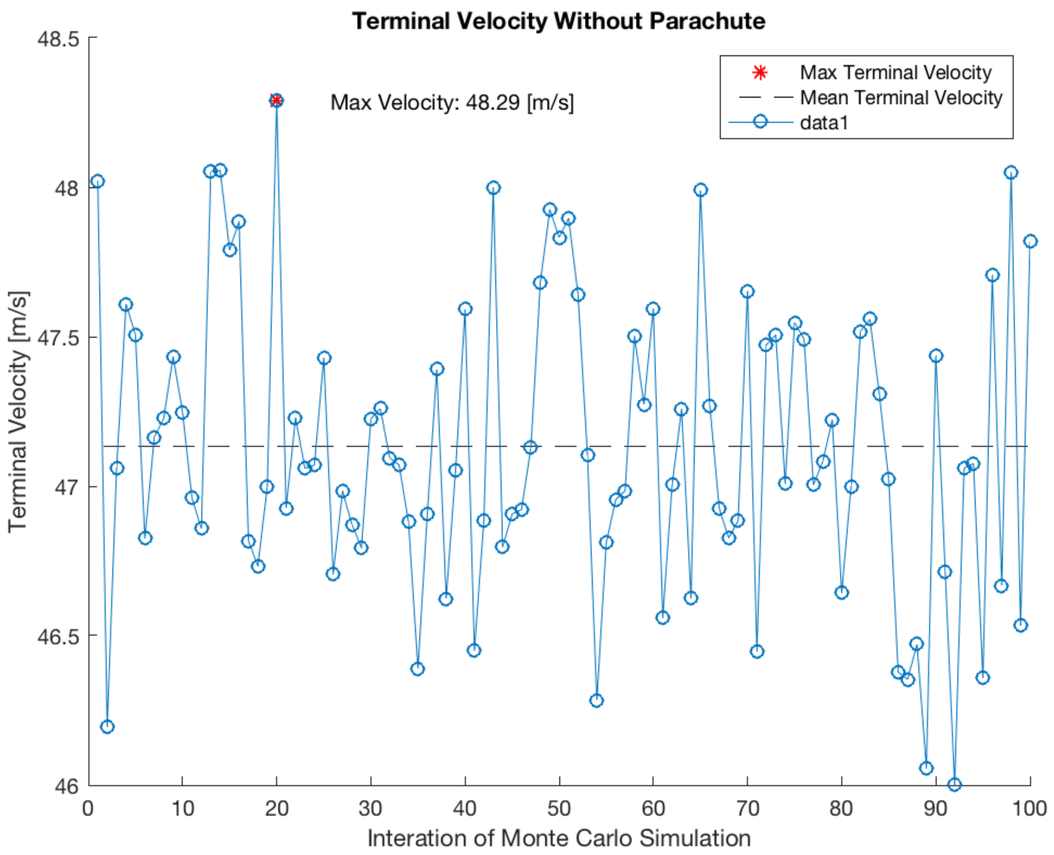
$$m\vec{a}(t) = Fw(t) - W$$

Impact Force

$$F_W(t) = \frac{\pi}{8}\rho_W D^2 U(t)^2 C_f$$

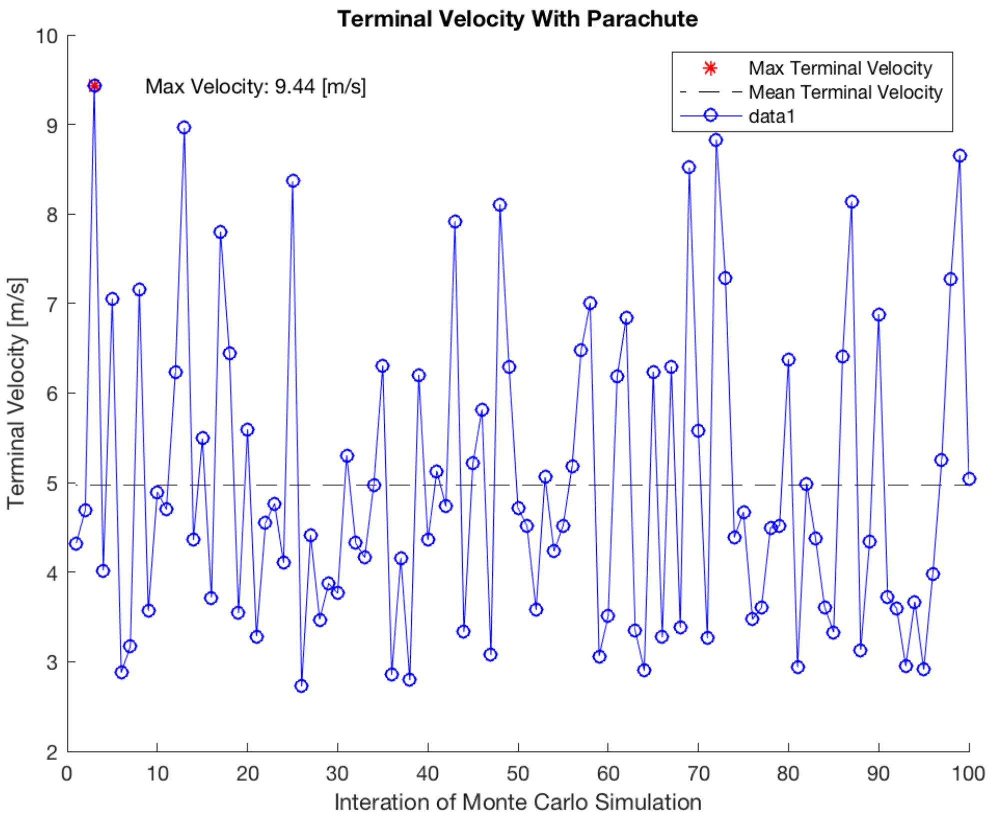
Float Design: Parachute Model Analysis

Without Parachute:



$$v_T = 48.29 \text{ [m/s]}$$

With Parachute:



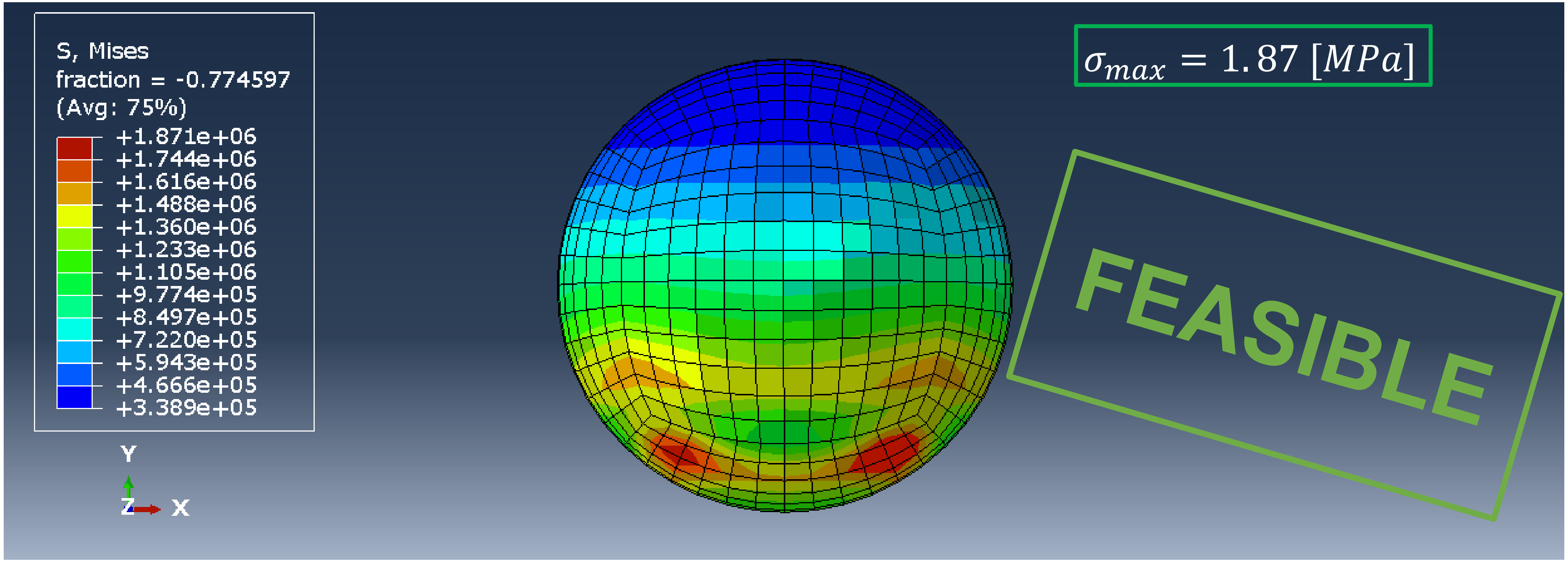
$$v_T = 9.44 \text{ [m/s]}$$

Float Design: Impact Stress Analysis

With Parachute:

Terminal Velocity = 9.44 [m/s]

Force of impact = 468 [N]



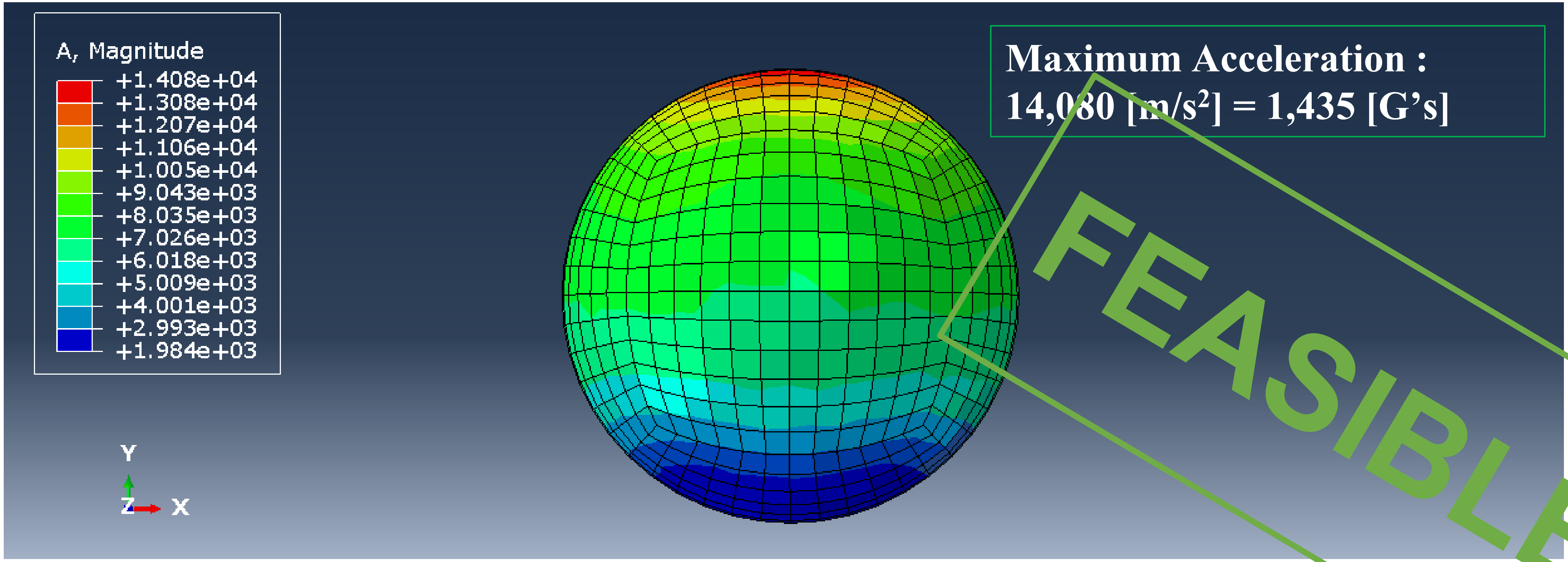
Compressive yield strength of HDPE is 12.6 [MPa]
Tensile yield strength of HDPE is 26.1 [MPa]

$$26.1\ [MPa] > 1.87\ [MPa] \Rightarrow \sigma_{yield} > \sigma_{max}$$

FR 3.0
Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

Float Design: Acceleration Analysis

With Parachute:



Electronics rated up to tens of thousands of G's

$$1{,}435\ [G] < 10{,}000[G] \Rightarrow \text{G-}force_{structure} < \text{G-}force_{limit}$$

FR 3.0

Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

Float Design: Model Limitations

- Does account for:
  - Mass of float and entire electronic and communication subsystem
  - Compression effects on structure
  - Worst case scenario of impact

- Doesn’t account for:
  - The drogue
    - Additional mass
    - Additional drag
  - Velocity components in the X and Y directions
  - Momentum transfer to water
  - Surface tension or viscous drag from water

Drogue Design

FR 1.0
Drifter shall follow currents in the Gulf of Mexico

Problem:

Winds and surface currents on float disturbs current tracking

Solution:

Drag forces on float must be minimal compared to drogue. Choice of intersecting flat plate design

- **Baseline:** CARTHE Drifter
  - Current drifter used to track gulf Currents
  - Drogue drag to float drag ratio of 40/1

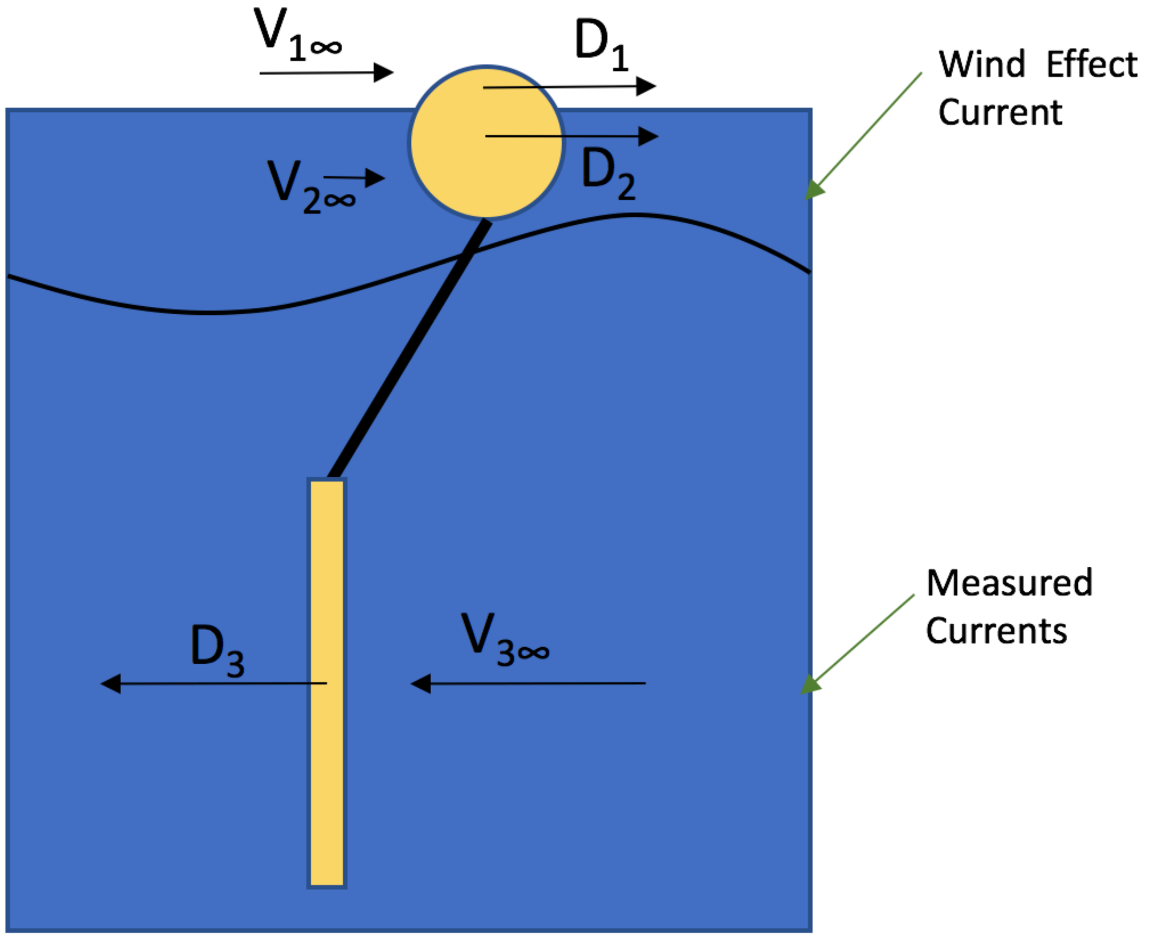
Drogue Design: Drag Model

Drag Analysis:

- Section 1 : Drag surface wind
- Section 2: Drag induced current
- Section 3: Drag tracked current

Assumptions:

- Spherical float
- Perpendicular flat plate drogue
- Density Air = 1.225 $[\frac{kg}{m^3}]$
- Density Water = 1027 $[\frac{kg}{m^3}]$
- Reynolds Number 1,2 = 2.1×10^4, 2.4×10^4
- Reynolds Number 3 = 7.7×10^4
- C_d of section 1 and 2 modeled by hemisphere



Drogue Design: Drag

Givens:

- $V_{\infty 1} = 3\ [\frac{m}{s}]$
- $V_{\infty 2} = 0.3\ [\frac{m}{s}]$
- $V_{\infty 3} = 0.7\ [\frac{m}{s}]$
- $C_{d1} \approx C_{d2} = 0.4$
- $C_{d3} = 1.3$

Solution:

- $D = \frac{1}{2}\rho V^2 C_d A$
- Drag Ratio = $\frac{D_3}{D_1 + D_2}$

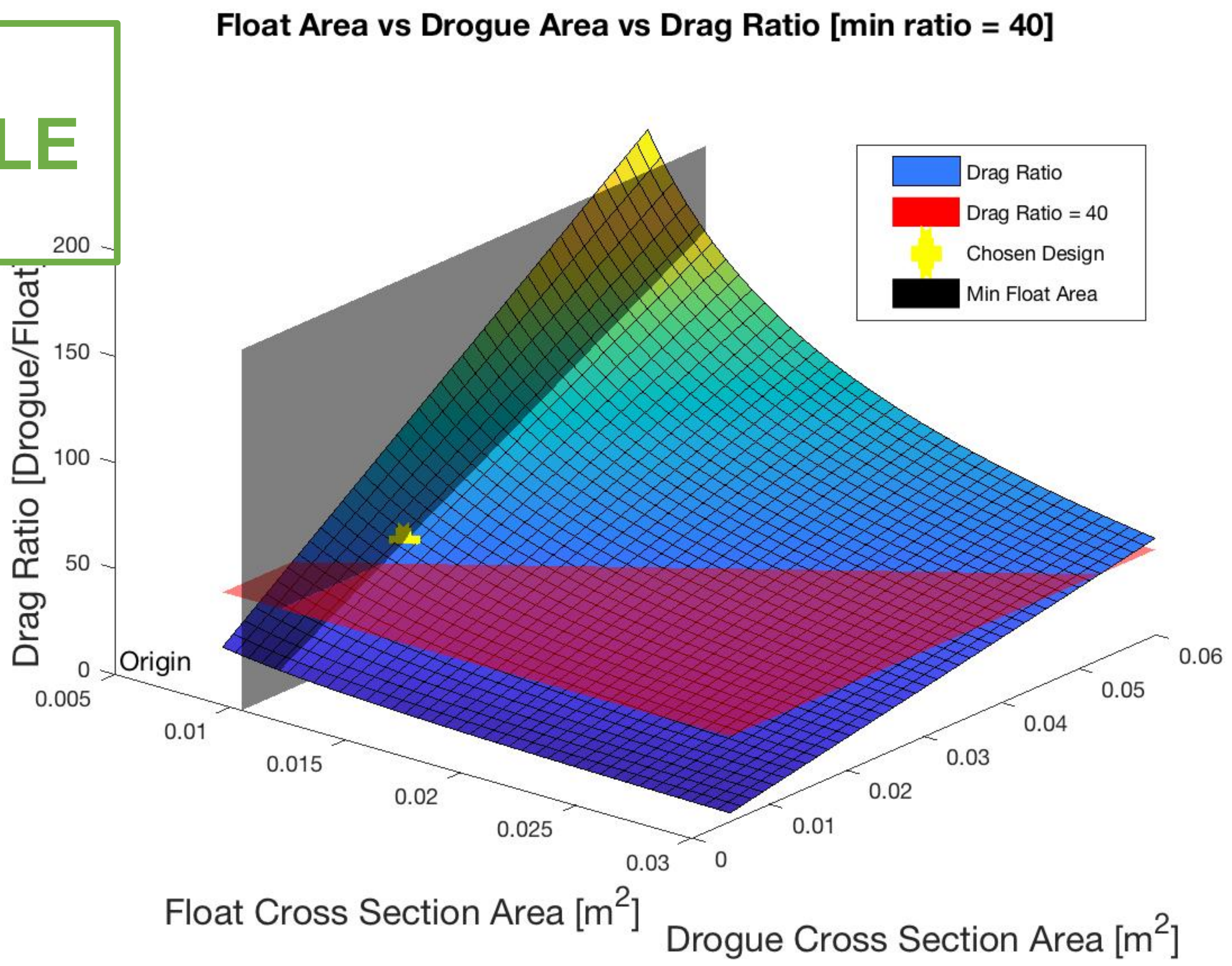
FEASIBLE

Design Point:

Drogue Cross Section Area = 210 [cm^2]

Float Cross Section Area = 105 [cm^2]

Drag Ratio = 45.44



FR 1.0

Drifter shall follow currents in the Gulf of Mexico

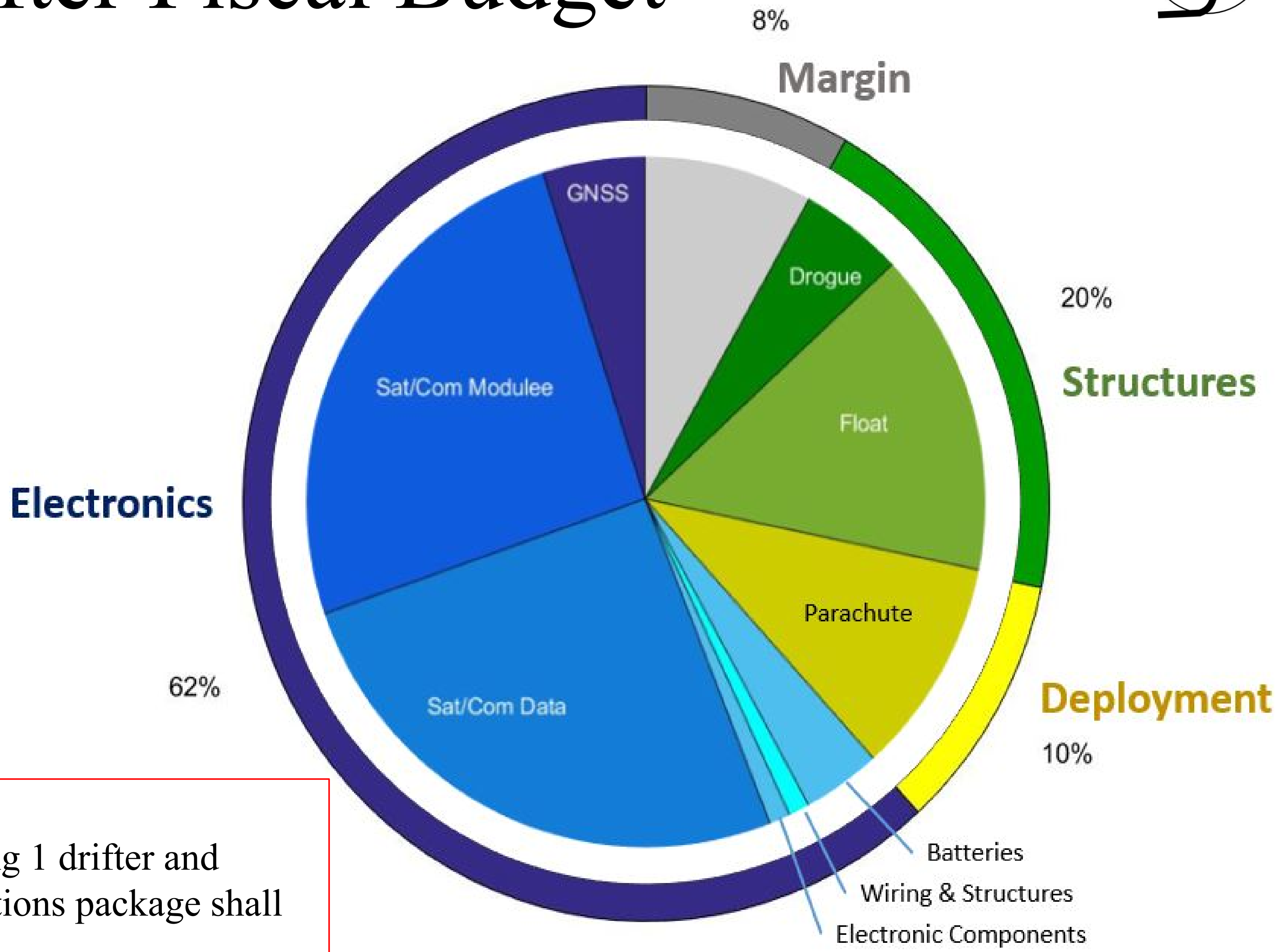
Drifter Fiscal Budget

FISCAL SUMMARY	
SUBSYSTEM	**TOTAL COST**
Electronics	$620.00
Deployment	$100.00
Structure	$200.00

Total Cost: $920 < $1000

FEASIBLE

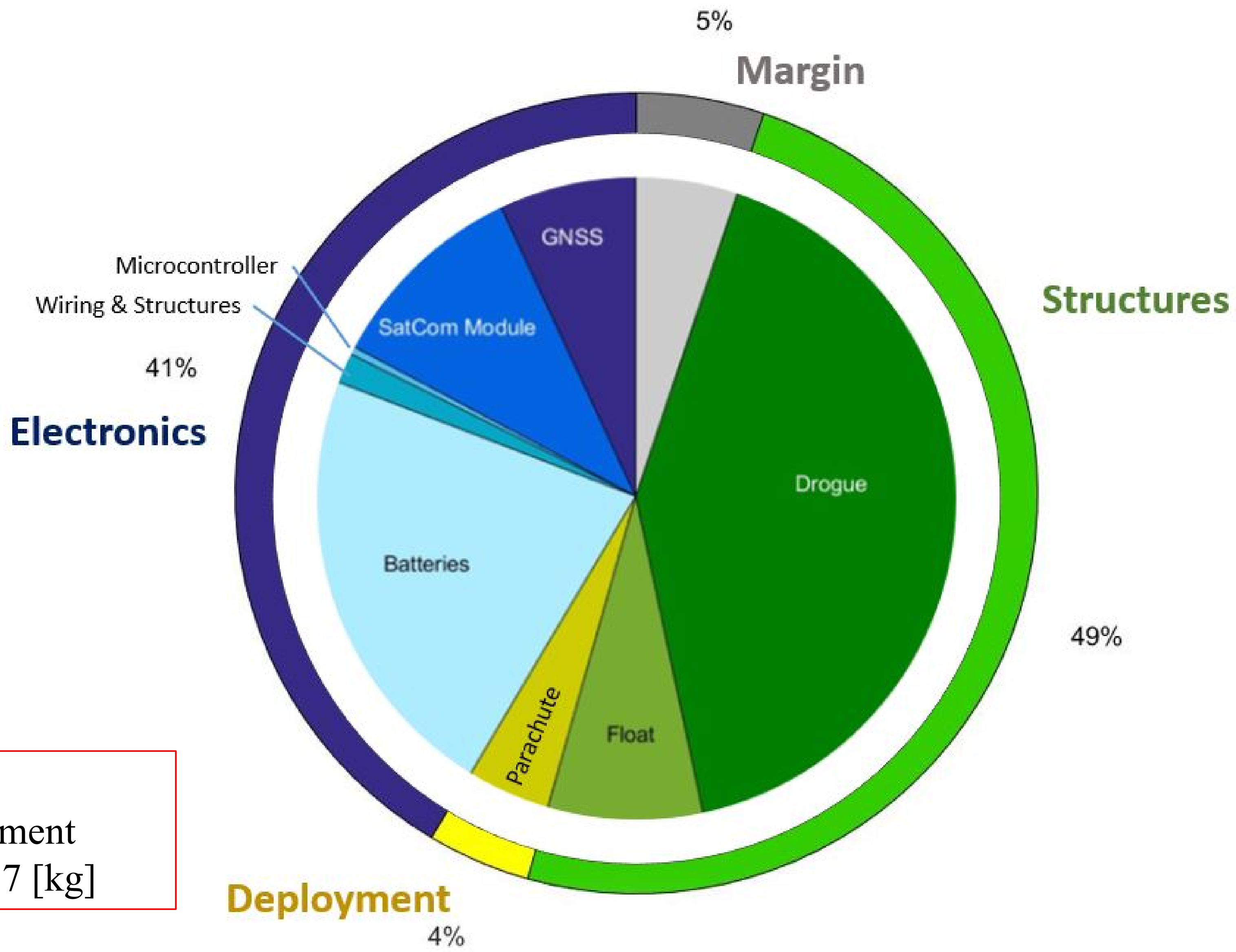
FR 8.0
Cost of manufacturing 1 drifter and required communications package shall not exceed $1000



Drifter Mass Budget

MASS SUMMARY	
SUBSYSTEM	**TOTAL MASS [g]**
Electronics	270.9
Deployment	26
Structure	320

FEASIBLE



FR 6.0
Mass of 4 drifters and 2 deployment mechanisms shall not exceed 2.7 [kg]

Recap – High Level Feasibility

Baseline Design	Feasibility Method	Feasible
Communications- Iridium RockBlock	Accuracy and Mass	✓
GPS- Venus 638FLP	Link Budget and Mass	✓
Power- Lithium Coin Battery	Power Budget and Mass	✓
Deployment Mechanism	Functionality and Mass	✓
Float Design	Buoyancy, Impact Strength, Total Volume, Mass	✓
Drogue Design	Drag Ratio and Mass	✓

Further Analysis

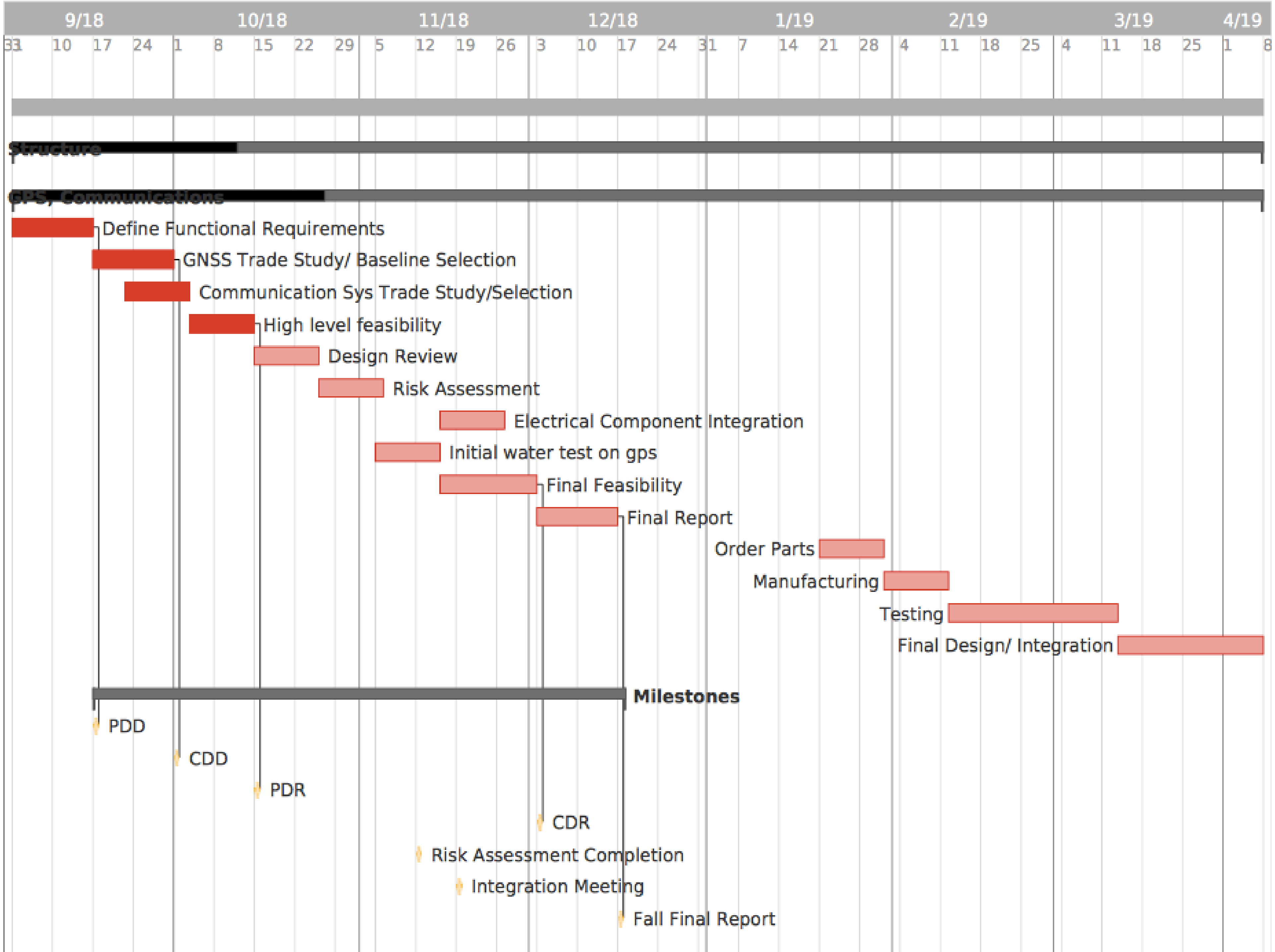
Structure:

- Impact: Will need further testing into impact analysis. Funding required.
- Integration: Further design into integration of parachute onto drifter and integration onto deployment mechanism.
- Thermal Management

Communications:

- Water Accuracy: Conduct a water test with a GPS unit. Assess potential accuracy loss issues.

Power Team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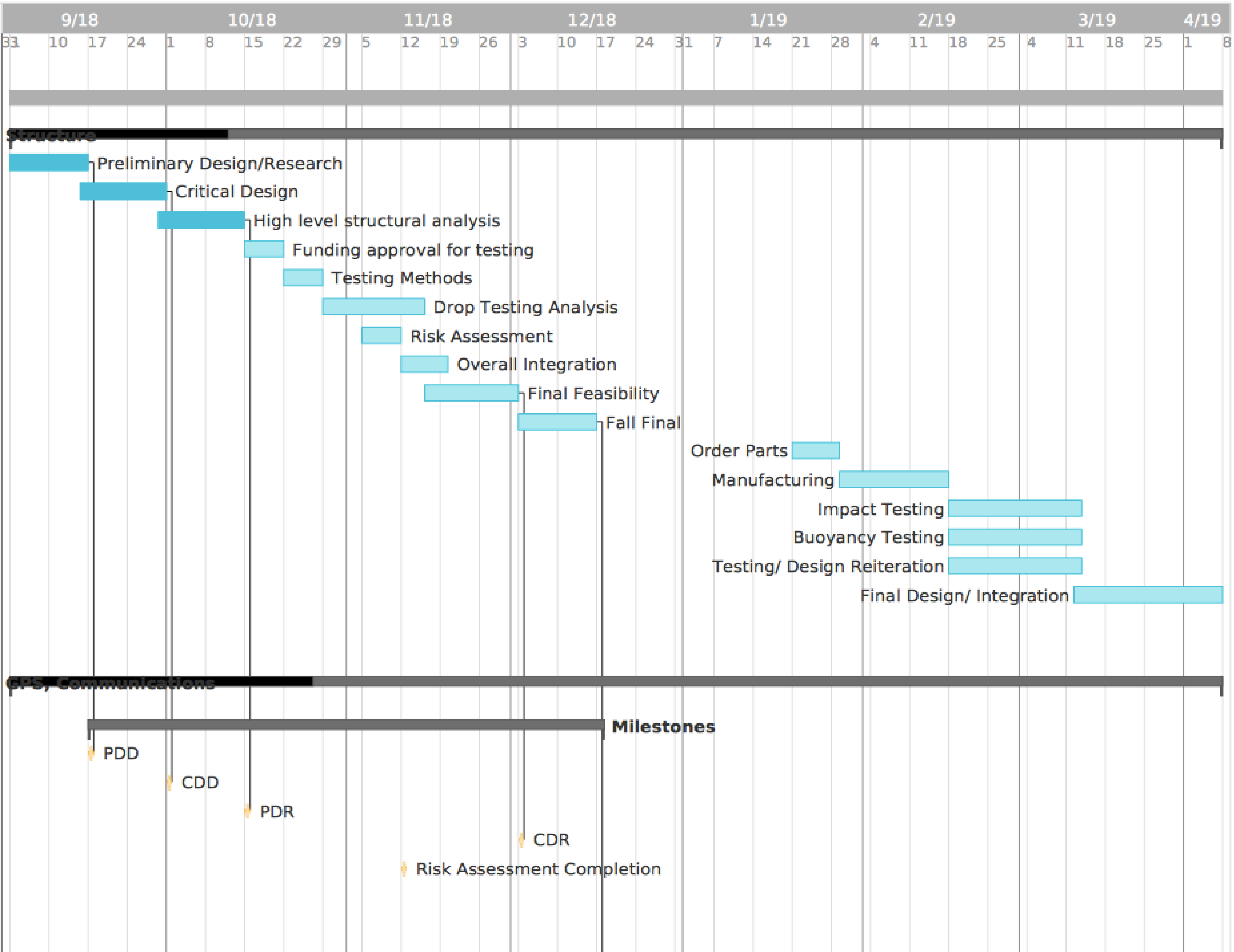
31 10 17 24 1 8 15 22 29 5 12 19 26 3 10 17 24 31 7 14 21 28 4 11 18 25 4 11 18 25 1 8
Structure
GPS, Communications
Define Functional Requirements
GNSS Trade Study/ Baseline Selection
Communication Sys Trade Study/Selection
High level feasibility
Design Review
Risk Assessment
Electrical Component Integration
Initial water test on gps
Final Feasibility
Final Report
Order Parts
Manufacturing
Testing
Final Design/ Integration
Milestones
PDD
CDD
PDR
CDR
Risk Assessment Completion
Integration Meeting
Fall Final Report

Structure Team



Questions?

Sources

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- “100 MA, Fixed Frequency PWM Step−Up Micropower Switching Regulator.” *Sparkfun*, Semiconductor Components Industries, LLC, Mar. 2006, www.sparkfun.com/datasheets/Prototyping/Batteries/Voltage_Switcher-NCP1400A-D.pdf.
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- https://www.google.com/search?q=carthe+drifters&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjvgLbvxvrdAhVCRa0KHZs3D2oQ_AUIDigB&biw=1680&bih=931#imgrc=h7Xs7pi1LTnf1M
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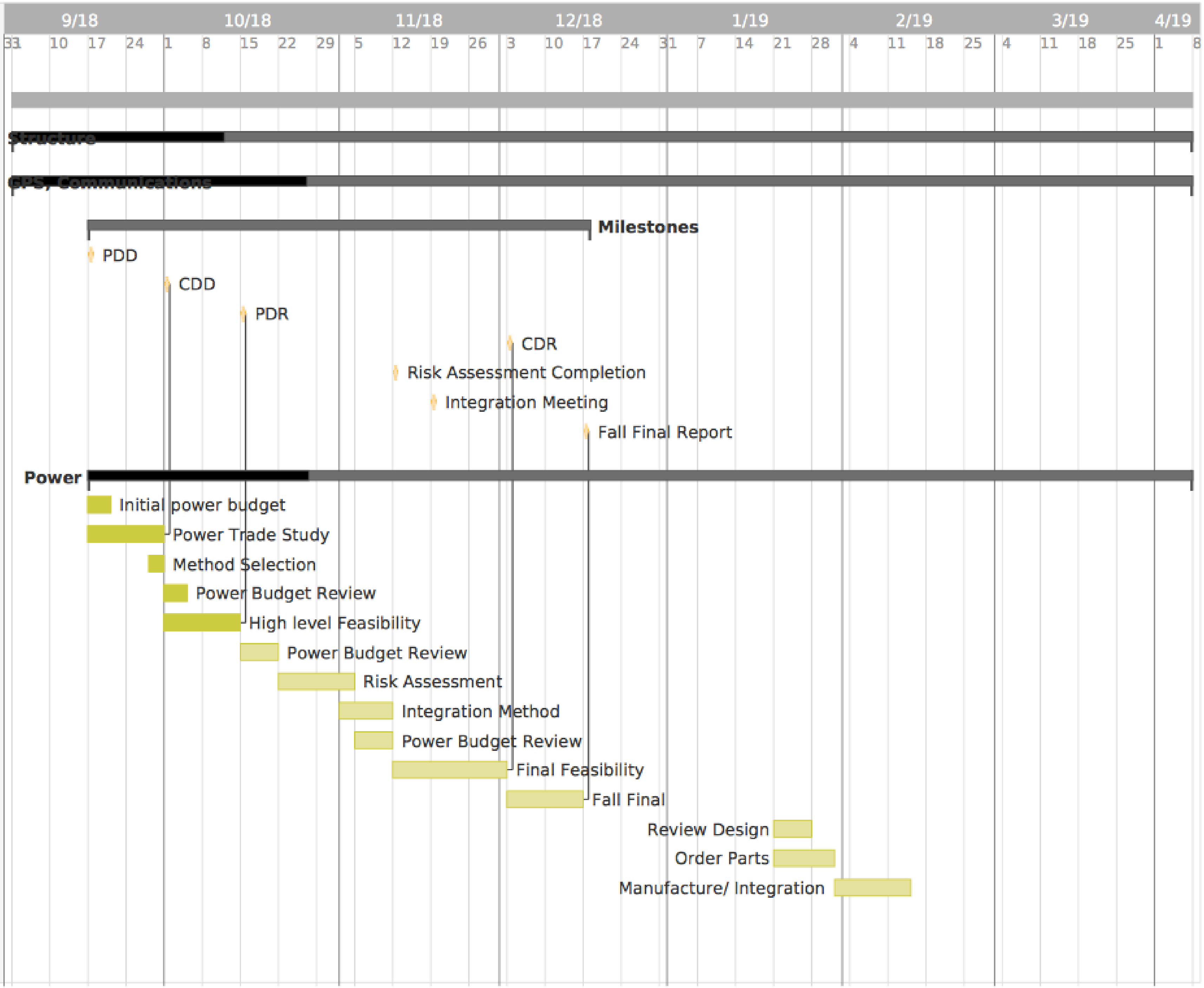
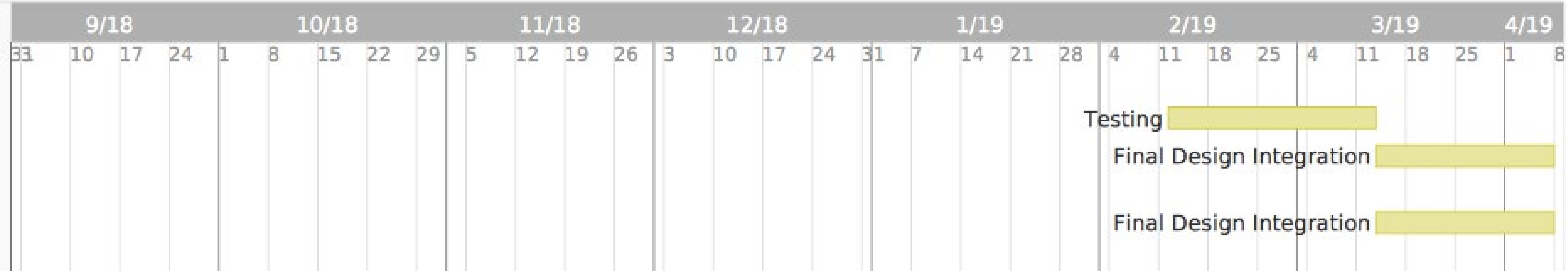
- http://bbaa6.mecc.polimi.it/uploads/validati/EB03.pdf
- https://www.scientificamerican.com/article/global-wind-speed-average/

Backup Slides

Members names (in order of presenting)

Electronics Team

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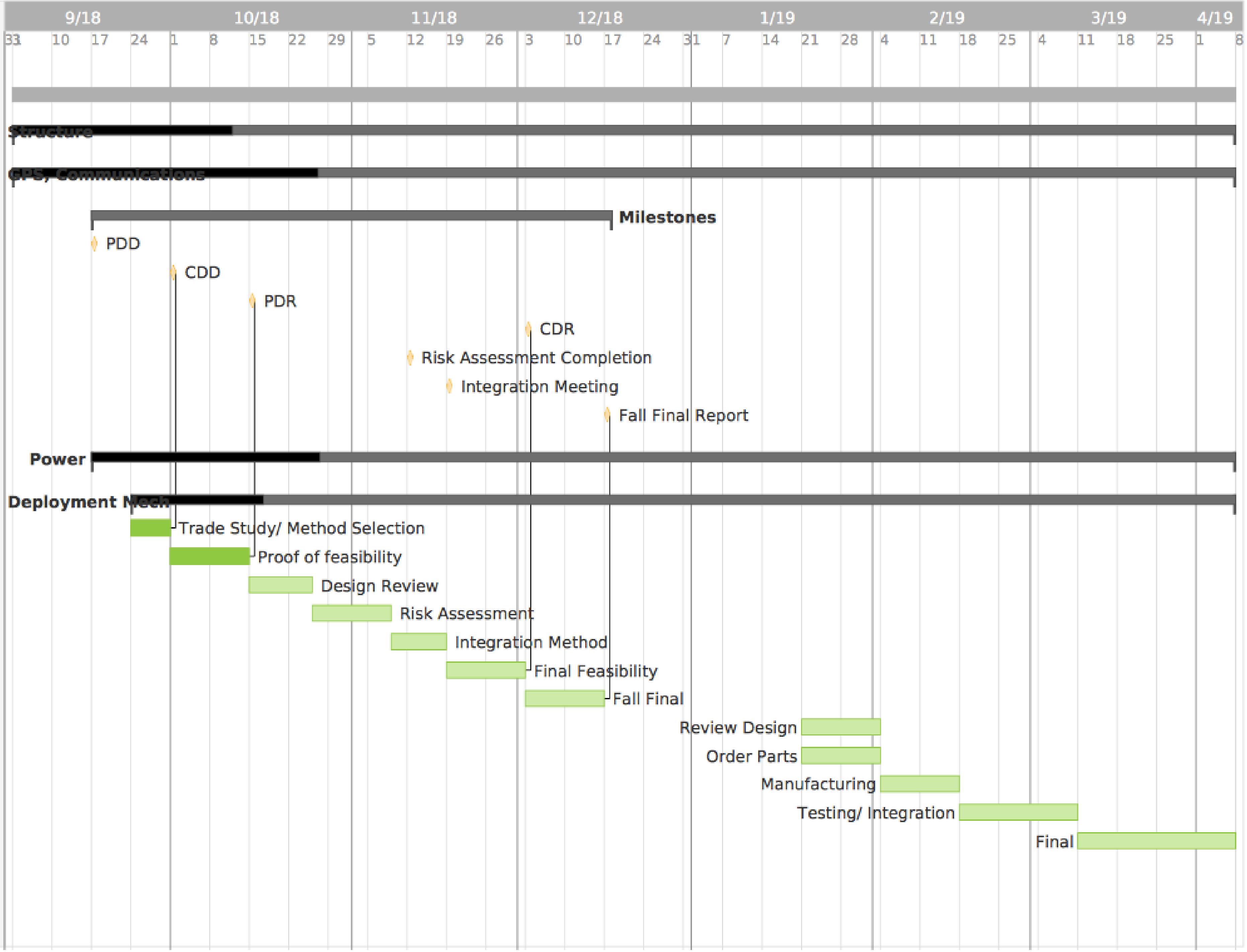
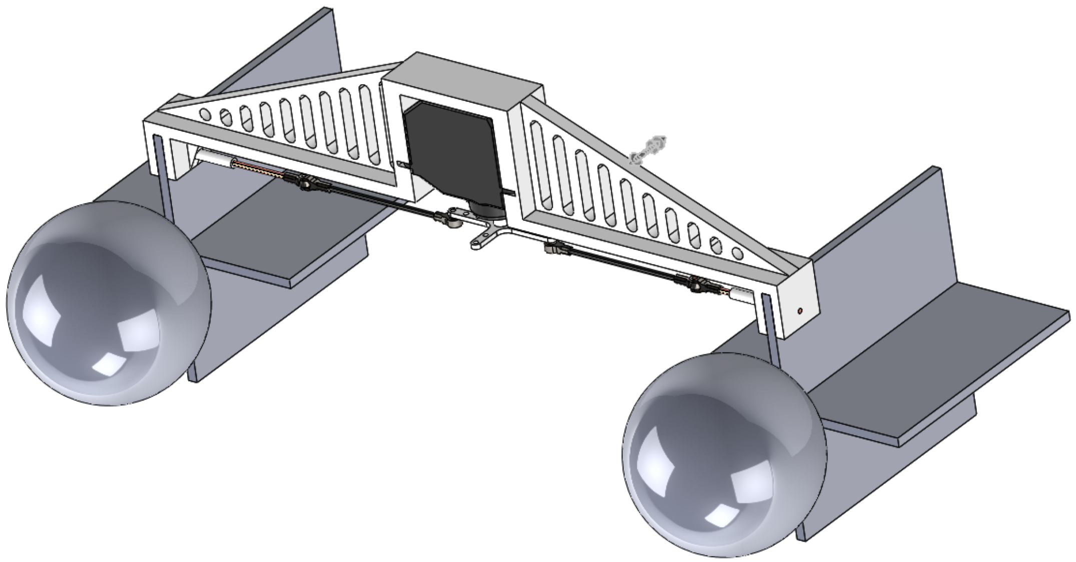
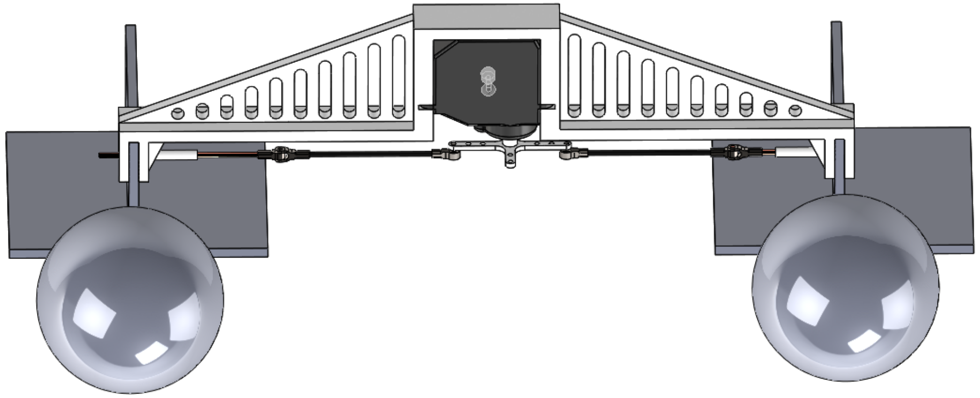
Testing
Final Design Integration
Final Design Integration

Deployment Team



Drifter on Deployment Mechanism





Material Selection

Members names (in order of presenting)

Material Selection

FR 2.0

Drifter shall maintain a 3 month lifespan

FR 3.0

Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

Problem:

- Float Material: Needs to withstand degradation in an aquatic environment, maintain structural integrity while subjected to impact forces, be lightweight, and have enough volume to encompass electrical and communication components
- Drogue Material: Needs to withstand degradation in an aquatic environment, maintain structural integrity while subjected to external forces, and be lightweight

Solution:

- Float Material: High-density polyethylene (HDPE) sphere
- Drogue Material: Polyvinyl chloride (PVC) sheets

Float Material: HDPE Sphere

Known:

Specification	Value
Diameter	11.43 [cm]
Wall Thickness	1.5 [mm]
Internal Volume	741.9 [cm^3]
Weight	50 [g]
Density	950 [kg/m^3]
Absorptivity	0.01 [%]
Compression Yield Strength	12.6 [MPa]

Assumptions:

- Low absorptivity correlates to aquatic survivability
- Compressive yield strength correlates to the ability of the structure to resist the forces felt at impact

Drogue Material: PVC Sheets

Known:

Specification	Value
Density	> 580 [kg/m^3]
Thickness	6 [mm]
Weight	270 [g]
Absorptivity	0.15 – 0.3 [%]
Bending Modulus	1,690 – 1,793 [MPa]

Assumptions:

- Low absorptivity correlates to aquatic survivability
- A high bending modulus corresponds to a stiff and rigid material

Material Limitations

Float:

- Modifications required
  - Electronics will need to be installed
  - Attachment point for drogue is required

Drogue:

- Modifications required
  - Sheets will need to be joined
  - Attachment point for float required
  - Attachment point for parachute required

Material Selection: Feasibility

FR 2.0

Drifter shall maintain a 3 month lifespan

FR 3.0

Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

FEASIBLE

Float:

	Absorptivity [%]	Compressive Yield Strength [MPa]	Overall Volume [cm^3]	Minimum Length [cm]
HDPE Sphere	0.01	12.6	741.9	11.43
Requirement	Water Resistant	> 2.00	93.59	7.6
Meets Requirement	✓	✓	✓	✓

Drogue:

	Absorptivity [%]	Bending Modulus [MPa]
PVC Sheets	0.15 – 0.30	1,690 – 1,793
Requirement	Water Resistant	> 328
Meets Requirement	✓	✓

Electronics

Overview of Electronic Components

Name	Voltage [V]	Active Current [mA]	Idle Current [μA]	Unit Cost	Unit Mass [g]	Dimensions [mm]	Symbol
Venus 638FLP	5	29	0.04	$49.95	45	10 x 10 x 1.3	Rx
Iridium RockBlock mk2	5	450	30	$253	67	76.0 x 51.5 x 19.0	Tx
Arduino Trinket Pro	5	150	0.03	$10	2.6	38.1 x 17.8 x 5.1	μC
TPL5110 ultra-low power timer	3.3	-	0.035	$4.95	1.3	19.3 x 18.0 x 4.5	ULPT
Venus638FLP VBAT pin	3.3	-	0.048	-	-	-	VBAT
MOSFET Transistor	-	-	-	$1.75	< 0.1	-	-
TLV61220 0 Low-Input Voltage Step-Up Converter	-	-	-	$0.40*	<0.1	-	-

Battery

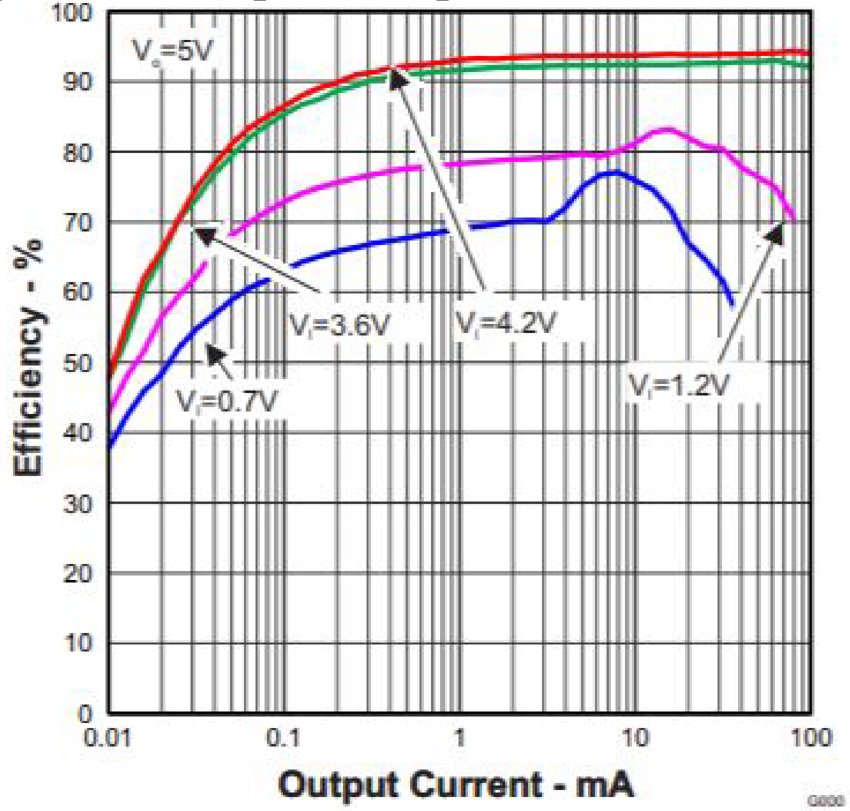
Name	Voltage (V)	Capacity (Ah)	Mass (g)	Self-Discharge Rate (λ_s)	Unit Cost	Unit Mass [g]
BR-2477A/HBN Lithium coin cell	3.3	1	8	0.3%/month	$1.96*	8

*Assuming bulk purchase

TLV61220 0 Low-Input Voltage Step-Up Converter

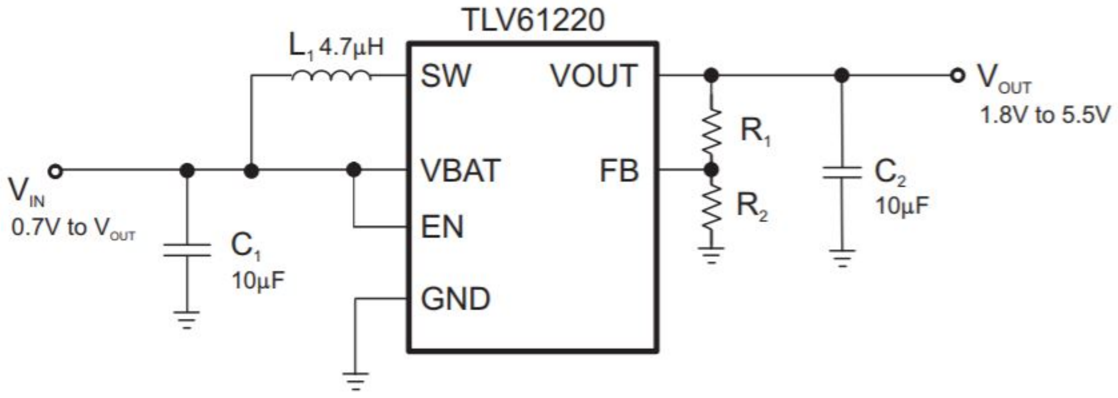
- Need to boost 3.3 V to 5V for μC, Tx and Rx
- Switching Converter
  - Efficient, lightweight, cheap

$$\longrightarrow I_{in}V_{in}\eta_C = I_{out}V_{out} \;\rightarrow\; I_{in} = \frac{I_{out}V_{out}}{V_{in}\eta_C}$$



- $\eta_C = f(I, V_{in}, V_{out})$

  - Low Current: $\eta_L = 0.75$
  - High Current: $\eta_H = 0.92$



Power Budget Model - Average Current

Average Current

$$I_{Av} = I_{ULPT} + I_{VBAT} + \frac{5V}{3.3V}\left[\frac{1}{\eta_H}\left(I_{Rx}\tau_{Rx} + I_{\mu C}\tau_{\mu C} + I_{Tx}\tau_{Tx}\right) + \frac{1}{\eta_L}\left(I_{RxL}(1-\tau_{Rx}) + I_{\mu CL}(1-\tau_{\mu C}) + I_{TxL}(1-\tau_{Tx})\right)\right]$$

3.3 V

5 V

$$= \frac{5V}{3.3V}\left(\frac{I_{\mu C}}{\eta_H} - \frac{I_{\mu CL}}{\eta_L}\right)\tau_{\mu C} + \frac{5V}{3.3V}\left(\frac{I_{Rx}}{\eta_H} - \frac{I_{RxL}}{\eta_L}\right)\tau_{Rx} + \frac{5V}{3.3V}\left(\frac{I_{Tx}}{\eta_H} - \frac{I_{TxL}}{\eta_L}\right)\tau_{Tx} + I_{ULPT} + I_{VBAT} + \frac{5V}{3.3V}\frac{I_{RxL} + I_{TxL} + I_{\mu CL}}{\eta_L}$$

$\tau_{Rx} = \tau_{\mu C}$

$$= \frac{5V}{3.3V}\left(\frac{I_{\mu C} + I_{Rx}}{\eta_H} - \frac{I_{\mu CL} + I_{RxL}}{\eta_L}\right)\tau_{\mu C} + \frac{5V}{3.3V}\left(\frac{I_{Tx}}{\eta_H} - \frac{I_{TxL}}{\eta_L}\right)\tau_{Tx} + I_{ULPT} + I_{VBAT} + \frac{5V}{3.3V}\frac{I_{RxL} + I_{TxL} + I_{\mu CL}}{\eta_L}$$

- where: τ_X is the proportion of one day that component *X* is powered on

Power Budget Model - Average Current

- Introduce Design Parameters:

  $t_{\mu C}$: time in seconds the microcontroller is on during each 5 min period

  t_{Tx}: time in seconds the Iridium transmitter is on during each 24 hour period

  t_{CS}: time in seconds for GNSS cold start

$$\tau_{Tx} = \frac{t_{Tx}}{86400} \qquad \tau_{\mu C} = \frac{281 t_{\mu C} + 6 t_{CS} + t_{Tx}}{86400}$$

- Back to the current

$$I_{Av} = \frac{5V}{3.3V}\left(\frac{I_{\mu C} + I_{Rx}}{\eta_H} - \frac{I_{\mu CL} + I_{RxL}}{\eta_L}\right)\frac{281 t_{\mu C} + 6 t_{CS}}{86400} + \frac{5V}{3.3V}\left(\frac{I_{Tx} + I_{Rx} + I_{\mu C}}{\eta_H} - \frac{I_{TxL} + I_{RxL} + I_{\mu CL}}{\eta_L}\right)\frac{t_{Tx}}{86400}$$

$$+ 2I_{ULPT} + I_{VBAT} + \frac{5V}{3.3V}\frac{I_{RxL} + I_{TxL} + I_{\mu CL}}{\eta_L}$$

Power Budget Model - Weight

- Bringing it back to weight

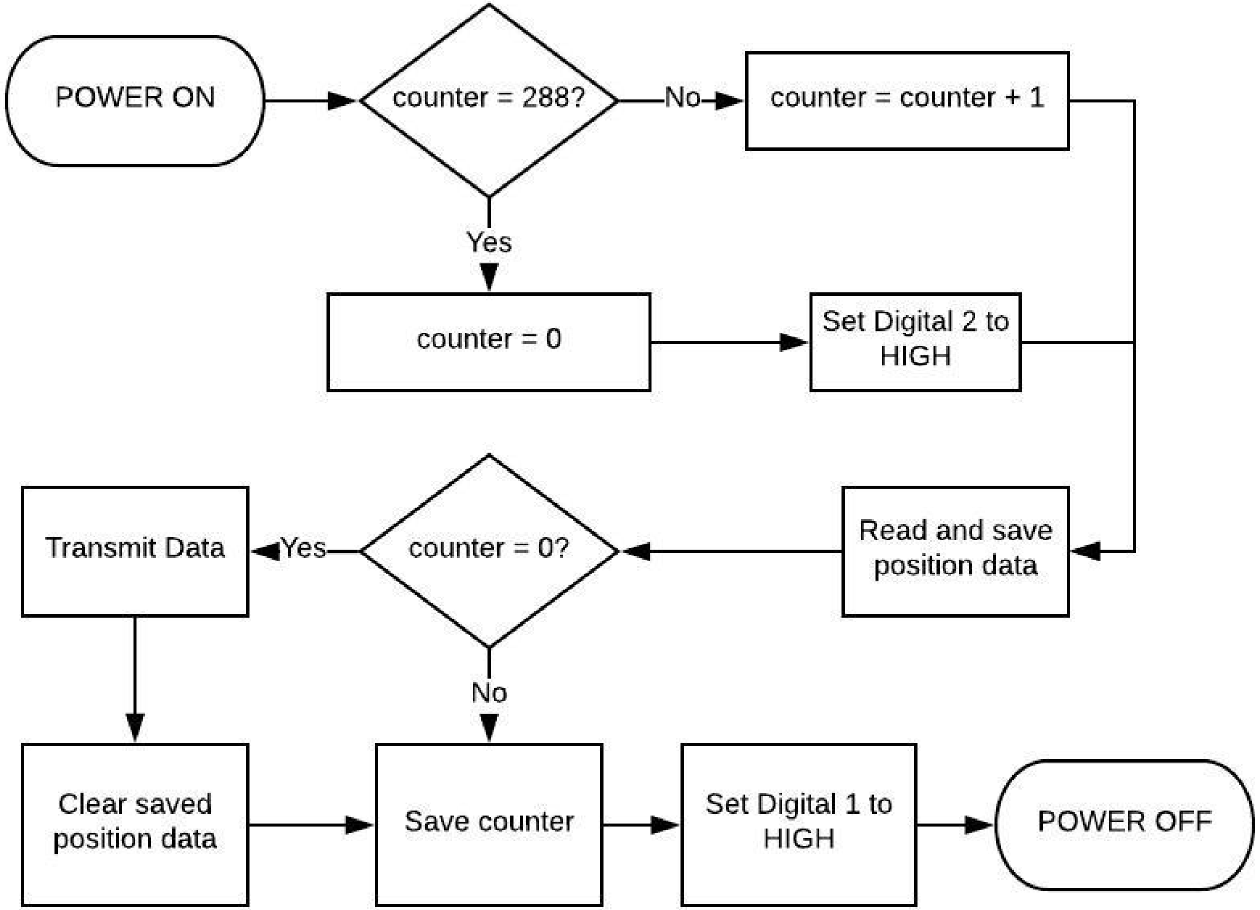
$$\begin{cases} W_b\left(\frac{1Ah}{8g}\right) = \frac{W_b}{w_i} \geq Q_0 \\ \eta_B Q_0 = Q_0 - I_{Av}T \end{cases} \quad \Rightarrow \quad W_b \geq \frac{w_i I_{Av} T}{1-\eta_B}$$

$$W_b \geq \overbrace{\left(\frac{Tw_i}{1-\eta_B}\right)\left(\frac{5V}{3.3V}\right)\left(\frac{281}{86400}\right)\left(\frac{I_{Rx}+I_{\mu C}}{\eta_H} - \frac{I_{RxL}+I_{\mu CL}}{\eta_L}\right)}^{\alpha_{\mu C}} t_{\mu C} + \overbrace{\left(\frac{Tw_i}{1-\eta_B}\right)\left(\frac{5V}{3.3V}\right)\left(\frac{6}{86400}\right)\left(\frac{I_{Rx}+I_{\mu C}}{\eta_H} - \frac{I_{RxL}+I_{\mu CL}}{\eta_L}\right)}^{\alpha_{CS}} t_{CS}$$

$$+ \overbrace{\left(\frac{Tw_i}{1-\eta_B}\right)\left(\frac{5V}{3.3V}\right)\left(\frac{1}{86400}\right)\left(\frac{I_{Rx}+I_{\mu C}+I_{Tx}}{\eta_H} - \frac{I_{RxL}+I_{\mu CL}+I_{TxL}}{\eta_L}\right)}^{\alpha_{Tx}} t_{\mu C}$$

$$+ \overbrace{\left(\frac{Tw_i}{1-\eta_B}\right)\left(I_{VBAT} + I_{ULPT} + \left(\frac{5V}{3.3V}\right)\left(\frac{I_{RxL}+I_{\mu CL}+I_{TxL}}{\eta_L}\right)\right)}^{\beta}$$

Software Flowchart



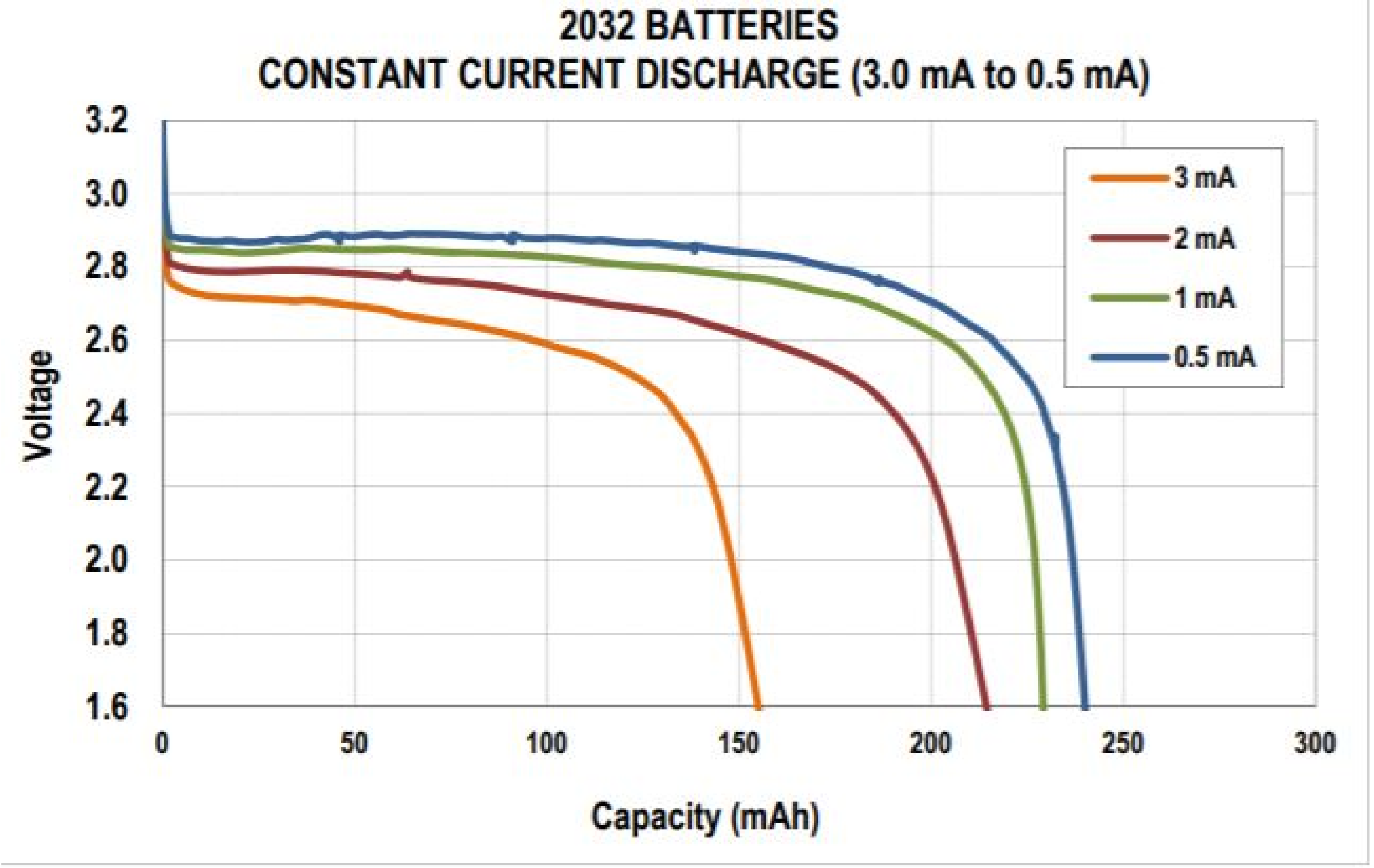
GPS Hot Start - Venus 638 FLPx

- 29 [s] cold start TTFL (Time to first lock)
- 1 [s] hot start TTFL
- Venus has a Vbat pin to keep clock and SRAM only powered (1.5-6[V])

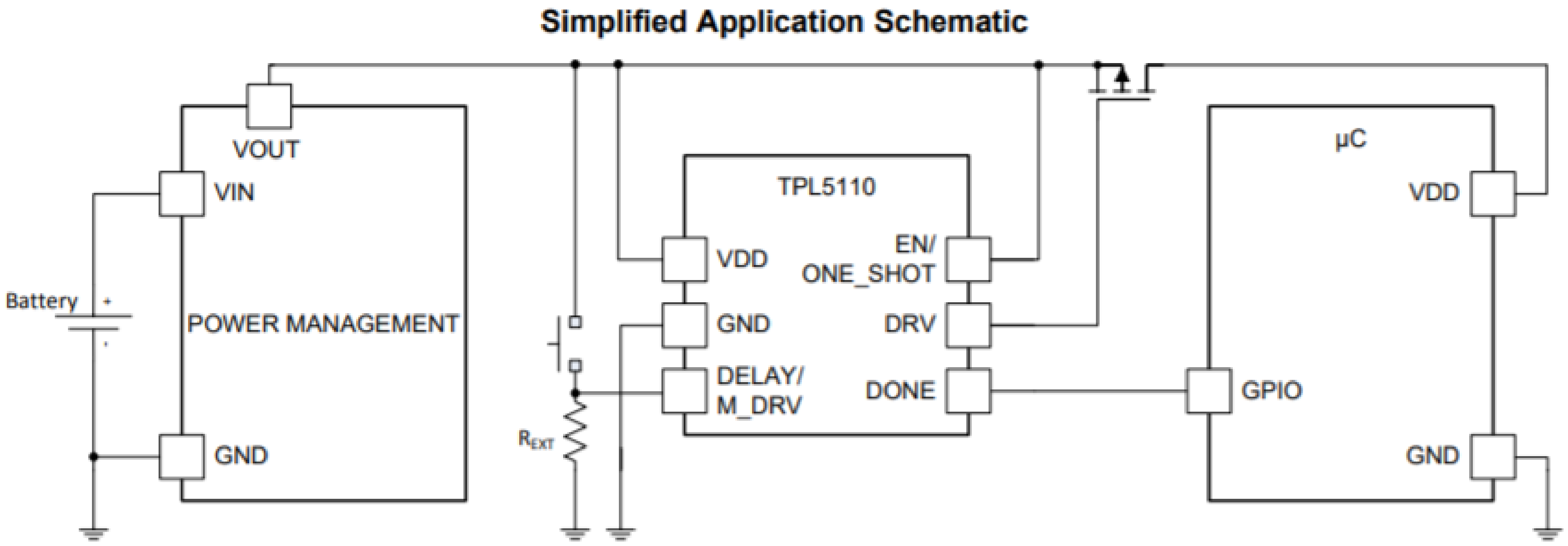
4. Pin-18 VBAT supplies backup power to the real-time clock and backup SRAM for fast startup. For portable applications where there is battery with voltage in range of 1.5V ~ 6.0V as the main source, the VBAT pin can be directly connected to it. If VBAT is connected to main power as pin-2, no supply voltage as Venus638FLPx is powered off, then it'll cold start every time and GPS performance will not be optimal.

- Battery mode power usage is about 48nA
- Cuts GPS power usage by 29x and total power budget by 1/3!

Lithium Coin Discharge



TPL5110 Ultra-Low Power Timer



- selectable timing intervals from 100 ms to 7200 s
- designed for power gating applications
- Consumes only 35 nA!

GNSS Link Budget Parameters

Parameter	
Speed of sound c	3 x 10^8 [m/s]
Frequency f	1575.42 [MHz]
Range R	20200 [km]
Wave length	0.19 [m]
Receiver Gain Gr	20 [dB]

Propagation Parameter	
Pointing loss L	-3 [dB]
Space Loss Ls	-182.48 [dB]
Atmospheric loss La	-2.6 [dB]

GNSS Strategy

Define Problem Statement

- *How often we turn power on/off (process data) the module*
- *How much data we receive per message/whole day*
- *Where are we going to store the data*

Provide Solution

- *Power Budget Calculation*
- *How many bytes of data does a lock-on take*
- *SD Card or Arduino μc*

Proof: Explain Methodology and Execution Plan

SD Card	23616 [Bytes]
Data usage per location	82 Bytes
Often?	$\frac{1440\ mins/day}{5\ mins/day} = 288$
Cold Start	32 Secs

SAT COM Baseline Design

SAT COM Module : Iridium Rockblock mk2

Specification	
Power	Run mode : 5V @ 100 mA Transmission mode : 5V @ 450 mA
Communication	UART AT command
Antenna	Built in 25 mm square patch ceramic Antenna
Antenna Gain	2.5 dBi

CDD SAT COM choices

	Iridium RockBlock mk2	**Globalstar GSP-1720**	**Iridium 9603N SBD Transceiver**	**STX3 Globalstars**
Power	(Run) 5V @ 100 mA (Transmission) 5V @ 450 mA (Sleep mode) 5V @ 20 uA	(Run) 5V @ 100 mA (Transmission) 5V @ 730 mA (Sleep) 5V @ 130 uA	(Run) 5V @ 100mA (Transmission) 5V @ 145 mA (Sleep) 5V @ 39 mA	(Run) 3.3V @ 2.25mA (Transmission) 5V @ 390 mA (Sleep) 5V @ 60 uA
Data	0.272 kbps	9.6 kbps	0.272 kbps	72 bits every 30 minutes
Cost	$250	$400	$195	$82
Size	76 mm x 51.5 mm x 19 mm	119 mm x 65 mm x 15 mm	31.5 mm x 29.6 mm x 8.1 mm	28.70 mm x 20.57 mm x 4.13 mm
Weight	0.065 kg	0.060 kg	0.0114 kg	[redacted]
Communi-cation	UART, AT command	USB-B	AT Command	Requires a circuit board setup
Available Antenna	Built-in Antenna	Built-in Antenna	Need External Antenna	Need External Antenna
Antenna Gain	18 dB	31 dB	Need External Antenna	Need External Antenna

Communication Link feasibility

- Iridium Rockblock mk2 link budget
  - Objective :
    - Establishing a successful communication link between drifter and satellite
    - Transmitting 3.94 kB to a server with less than 1 hour of latency

Parameter	Iridium rockblock mk2
Speed of light	3* 10^8 [m/s]
Frequency	1621 [MHz]
Range	783 [km]
Wave length	0.185 [m]
Receiver Gain	18 [dB]

Transmitter parameter	
Antenna Diameter	0.025 [m]
Antenna Area	0.625 [m ^2]
Antenna Efficiency	75 %
Transmitter Gain	2.5 [dBi]
Beam width	116.18 [degree]
Power	3.521 [dBW]
EIPR	6.021 [dBW]
Link Budget	
EIPR	6.021 [dBW]
Total Propagation losses	-155 [dB]
Receiver Power	-130.97[dB]
System noise power	-203.97 [dB]
Minimum Carrier to Noise ratio	67.35[dB]
Actual Signal to Noise Ratio	73 [dB]
Link budget	5.65 [dB]

Data Feasibility : Accuracy Requirements

$$\theta = \frac{d}{R} = \frac{60}{6371 * 10^2} = 9.4176 * 10^{-6}\ rad$$

$$\theta = 9.4176 * 10^{-6} * \frac{180}{\pi} = 5.3959 * 10^{-4}\ deg * 3600 = 1.94\ seconds$$

Data Feasibility : Accuracy Requirements

Type	Size	Contains
Byte	8 bits	Signed Integer
Short	16 bits	Signed Integer
Int	32 bits	Signed Integer
Long	64 bits	Signed Integer
Float	32 bits	Floating number
Double	64 bits	Floating number
Char	16 bits	Unicode Character

Data Feasibility : Compress Data

Number	Sign in Binary	Exponent	Mantissa	Size
092204.999	0	**10001111**	**01101000001011010 000000**	32 bits
04250.5589	0	**10001011**	**00001001101010001 111001**	32 bits
14718.5084	**0**	**10001100**	**11001011111101000 001001**	32 bits

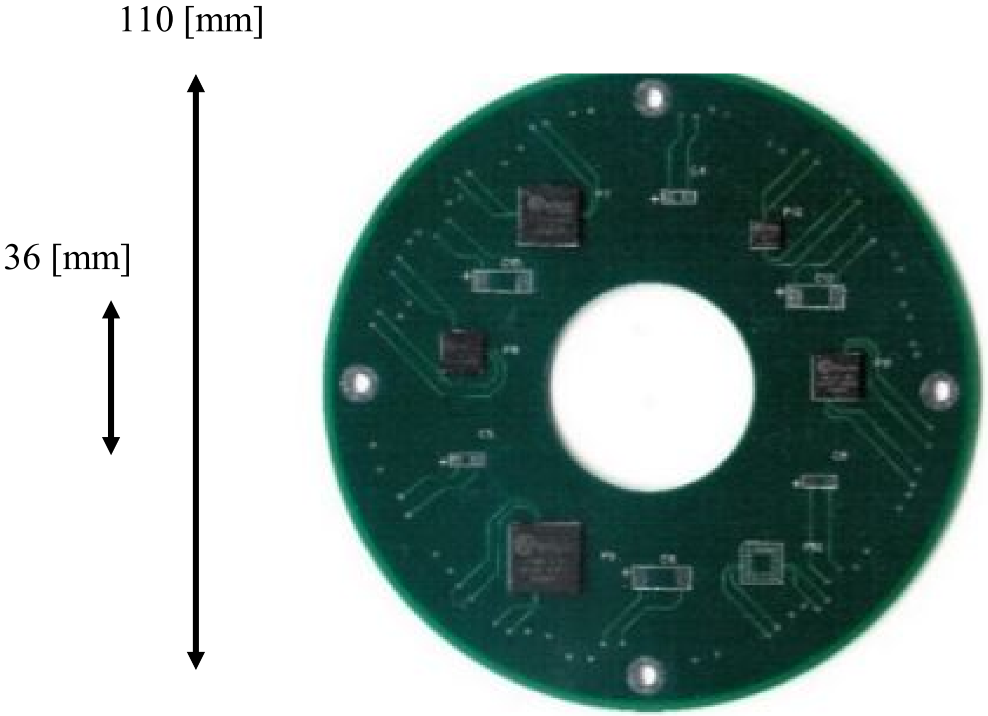
Interface Board Processor - CDD

	Raspberry Pi Zero	Arduino Trinket Pro	ADSP-21065L DSP
Power	5 V @ 1A	5 V @ 150 mA	5 V @ 3.6 A
Data rate	1 GHz processor chip	16 MHz	450 MHz
Memory Size	512 MB of RAM	28kB flash, 2 kB of RAM	1 MB of RAM
Ports	- Two micro USB	Two USB - FTDI	UART
Costs	$5	$ 9.95	$388
Weight	9 grams	2.6 grams	
Size	65 mm x 31 mm x 5.0 mm	38 mm x 18 mm x 2.0 mm	

GNSS choices - CDD

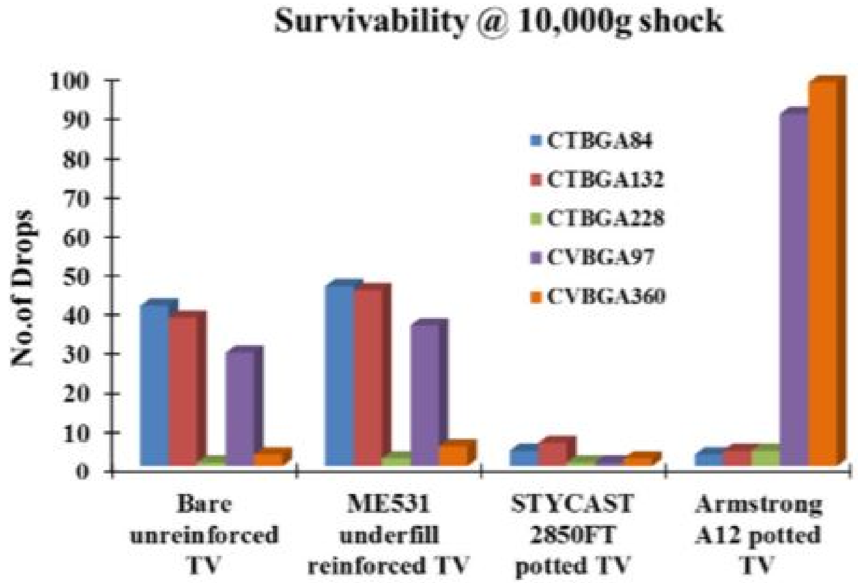
	Adafruit Ultimate	WI-GNSS-XX	Venus638FLP	Copernicus II
Power	3.0-5.5V @ 25mA (Tracking) @ 20mA (Navigation)	5V @ 220mA (Single Power Mode)	2.8-3.6V @ 29mA (Tracking) @ 20mA (Navigation)	2.7V @ 48mA (Single Power Mode)
Weight	0.0085 kg	0.025 kg	0.0045 kg	0.0017 kg
Cost	$39.95	$86.00	$49.95	$74.95
Cold Start	34 s	38 s	29 s	38 s
Dimension	25.4 x 34 x 0.25 mm	63.5 x 63.5 x 0.21 mm	10 x 10 x 1.3 mm	26.5 x 35 x 0.21 mm
Antenna Gain	28 dB	28	30 dB	36 dB
Position Accuracy	+/- 1.8 m	+/- 2.5 m	+/- 2.5 m	+/- 3 m
Port	UART	USB	UART, SPI	UART, USB

Electronics Survivability



CTBGA228

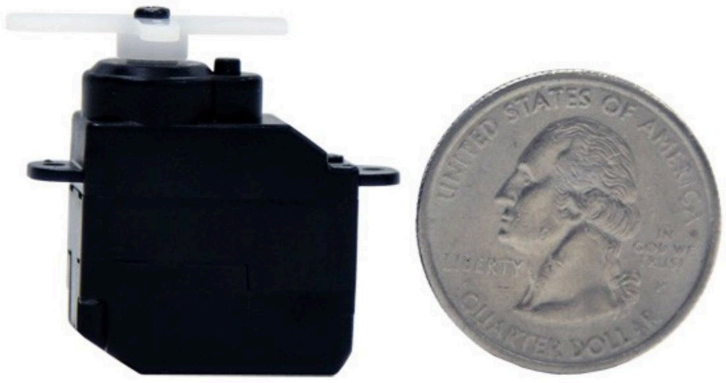
Package Attributes			
Package	CVBGA360	CTBGA84	CTBGA228
Location on board	P7	P8	P9
Body Size	10mm	7mm	12mm
I/O Count	360	84	228
Ball Pitch	0.4mm	0.5mm	0.5mm
Matrix	23 x 23 Perimeter	12 x 12 Perimeter	22 x 22 Perimeter
Ball Diameter	0.25mm	0.3mm	0.3mm
Substrate Pad	NSMD (Board) SMD (Package)	NSMD (Board) SMD (Package)	NSMD (Board) SMD (Package)



Deployment Mechanism

Deployment Mechanism: S3114 SERVO

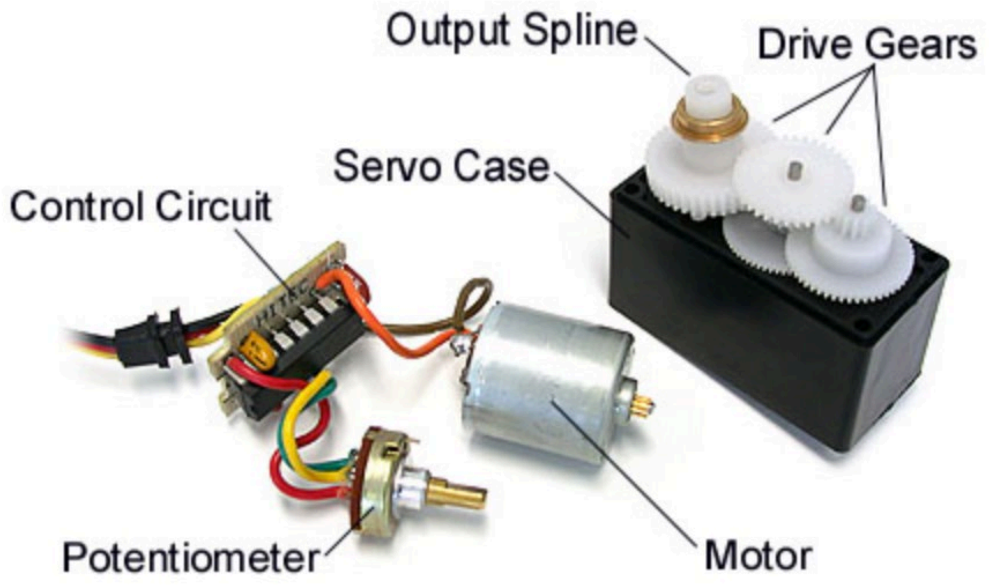
Dimensions	21.8 x 11 x 19.8 [mm^3]
Weight	7.8 [g]
Voltage Range	4.8-6.0 [V]
No-Load Speed at 4.8 [V]	0.10 sec/60˚
No-Load Speed at 6.0 [V]	0.09 sec/60˚
Stall Torque at 4.8 [V]	146.9 [N-mm]
Stall Torque at 6.0 [V]	165.9 [N-mm]
Operating Temperature	-20° to 60°
Gear Material	Nylon
Wire Length	304.8 [mm]



Deployment Mechanism: S3114 SERVO

How does it work?

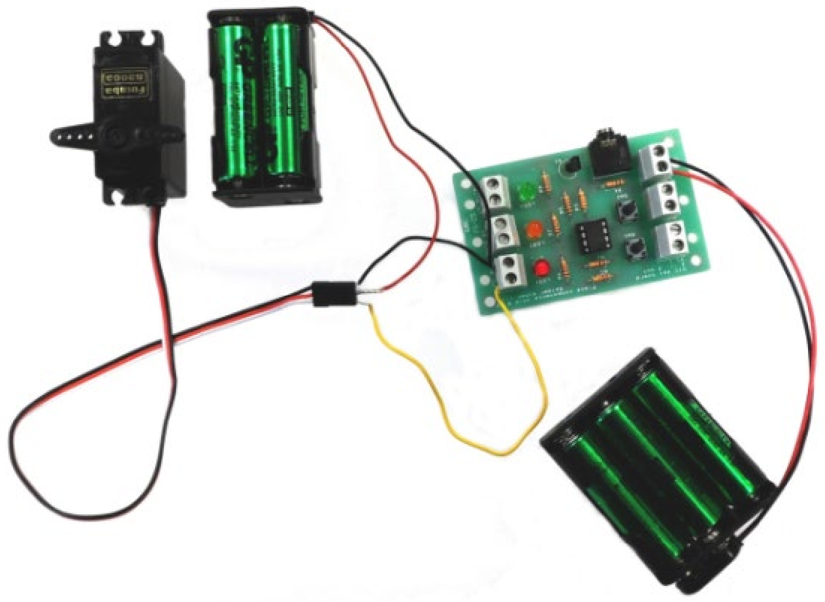
- The motor inside the servo runs by electricity and produces shaft work.
- This work can be translated into torque in order to produce a linear motion.
- The servo can be commanded by a microcontroller.



Deployment Mechanism: Electronics

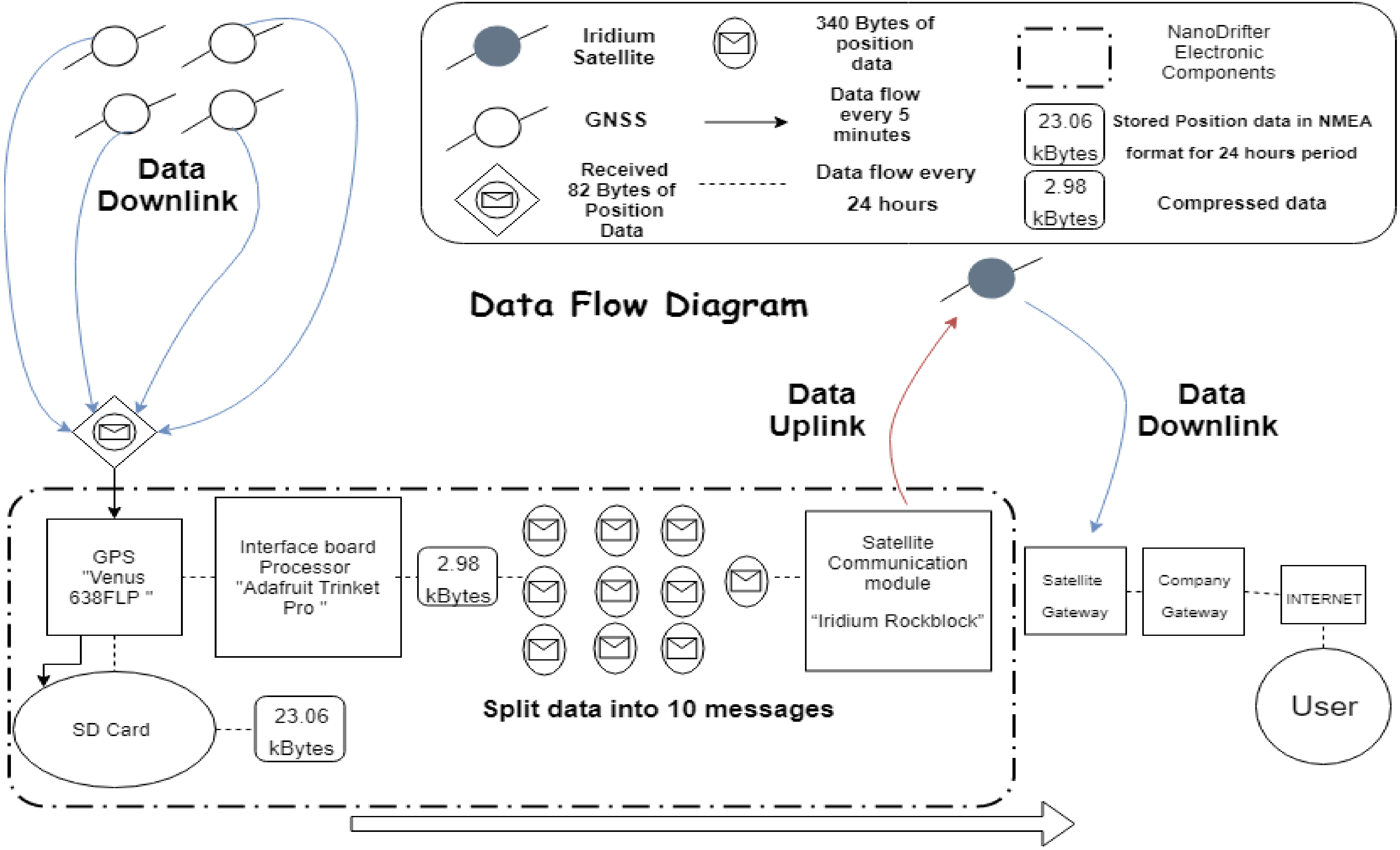
- Servo motors rotates based on pulse waves
- Pulse waves are supplied through signal wire from controller to servo

Controller	ATtiny13a Microcontroller
Circuit Board	Custom printed
Power Supply	On-board UAV voltage source (11.2 V)



Deployment Mechanism: Mass Budget

Component	Quantity	Component Mass [g]	Total Mass [g]
Servo	2	8	16
Housing	2	15	30
Electronics	2	~10	~20
Connections	2	~15	~30
		Total:	**96 [g]**



Iridium Satellite
340 Bytes of position data
NanoDrifter Electronic Components
GNSS
Data flow every 5 minutes
23.06 kBytes
Stored Position data in NMEA format for 24 hours period
Received 82 Bytes of Position Data
Data flow every 24 hours
2.98 kBytes
Compressed data
Data Downlink
Data Flow Diagram
Data Uplink
Data Downlink
GPS "Venus 638FLP "
Interface board Processor "Adafruit Trinket Pro "
2.98 kBytes
Satellite Communication module
"Iridium Rockblock"
Satellite Gateway
Company Gateway
INTERNET
SD Card
23.06 kBytes
Split data into 10 messages
User

Relation to Volume of Sphere Shell

Using the analysis from buoyancy, we can find a relation for the outer radius with relation to different values of K:

$$R_o = \sqrt[3]{\frac{3*m_T}{4*\rho_W*K}}$$

Relating this to the volume of the shell:

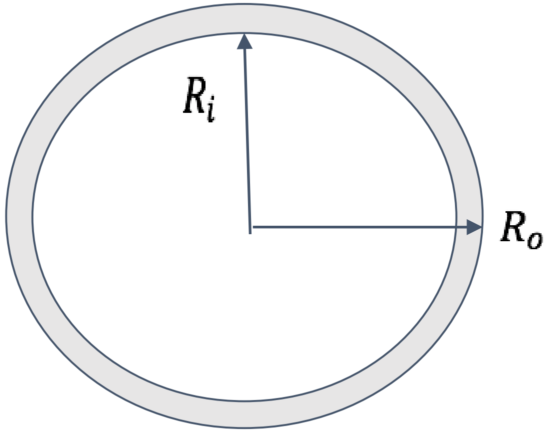
$$V_{shell} = \frac{4\pi}{3}\left({R_o}^3 - {R_i}^3\right)$$

$$V_{shell} = \frac{m_T}{\rho_W}$$

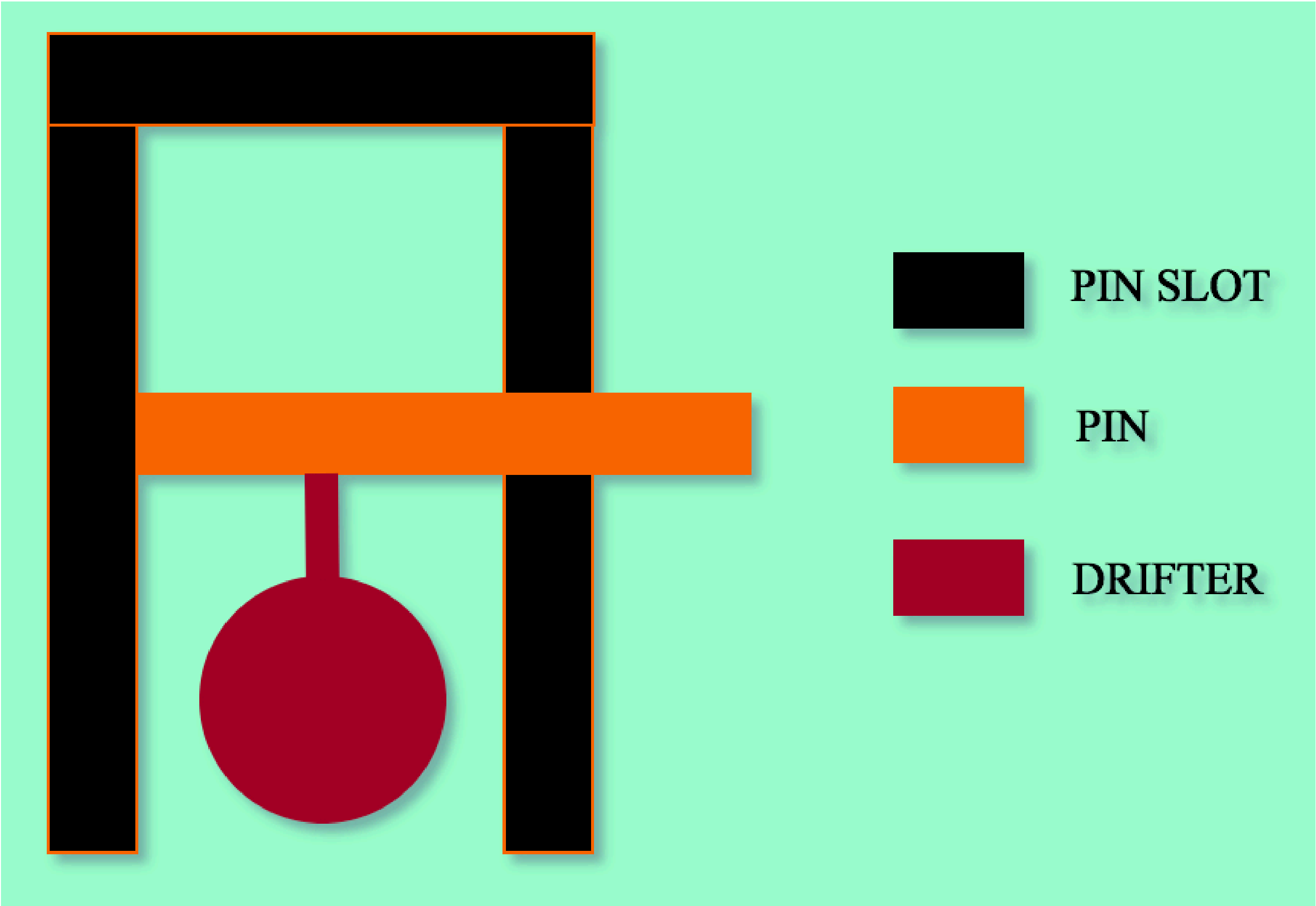
This gives a relationship between thickness and density of the material based on K

$$t = R_0 - R_i$$

$$t = R_0 - \sqrt[3]{{R_o}^3 - \frac{3*m_T}{4*\rho_{Shell}}}$$



Deployment Mechanism: Model

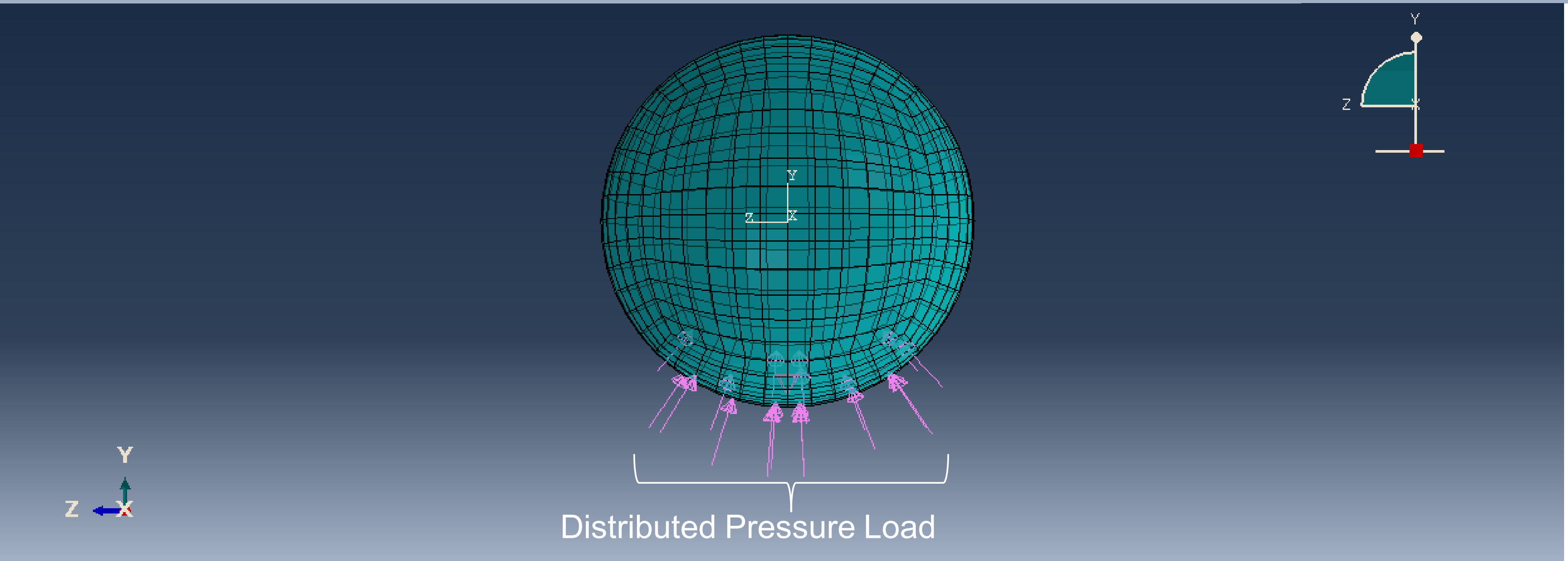


Main Idea: As the servo moves the pin towards the center, the drifter attached to the pin drops.

Main Question: Does the servo produce enough torque to overcome friction?

Impact Analysis – Model, Mesh, Load and Boundary Conditions

- Thin shell
- Pressure applied at bottom four octants

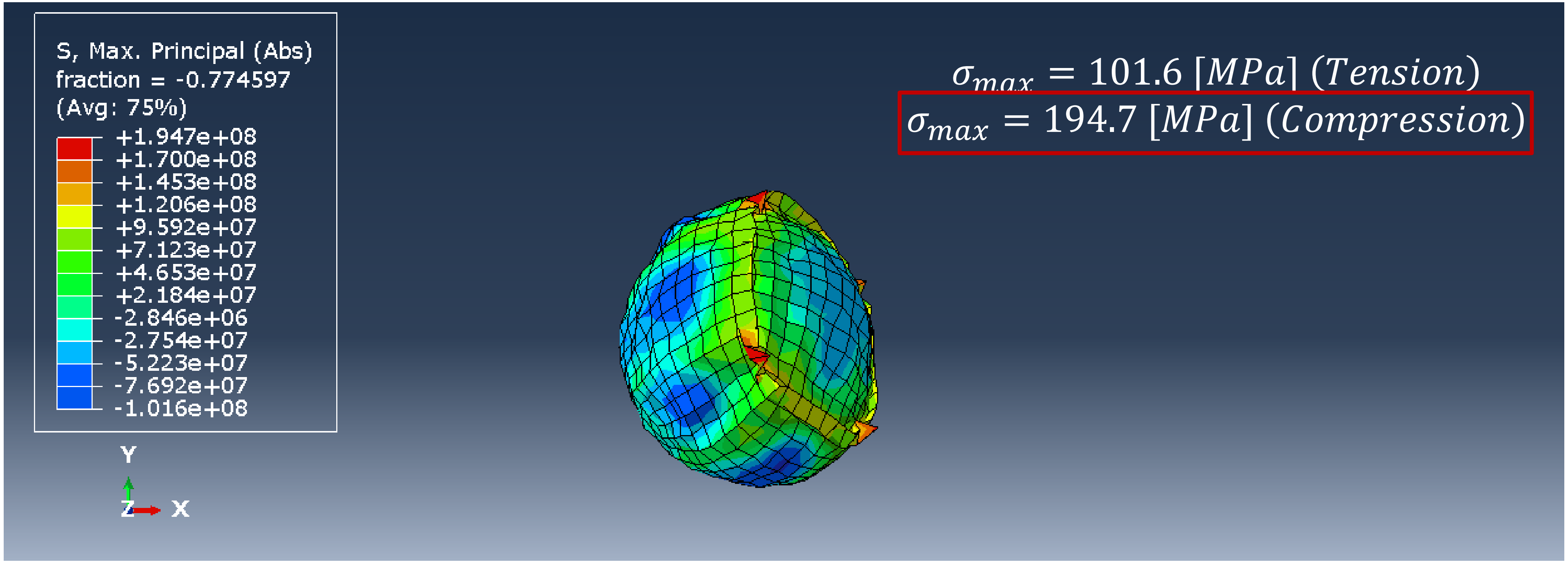


- Surface area of applied loading is 68.3 $[cm^2]$
- Magnitude of pressure $P = \frac{F}{A}\ [Pa]$

Compression Analysis – Simulation

No Parachute

- Larger terminal velocity (48.2 [m/s]) results in larger force of impact (10,168 [N])



Compressive yield strength of HDPE is 12.6 [MPa]

Tensile yield strength of HDPE is 26.1 [MPa]

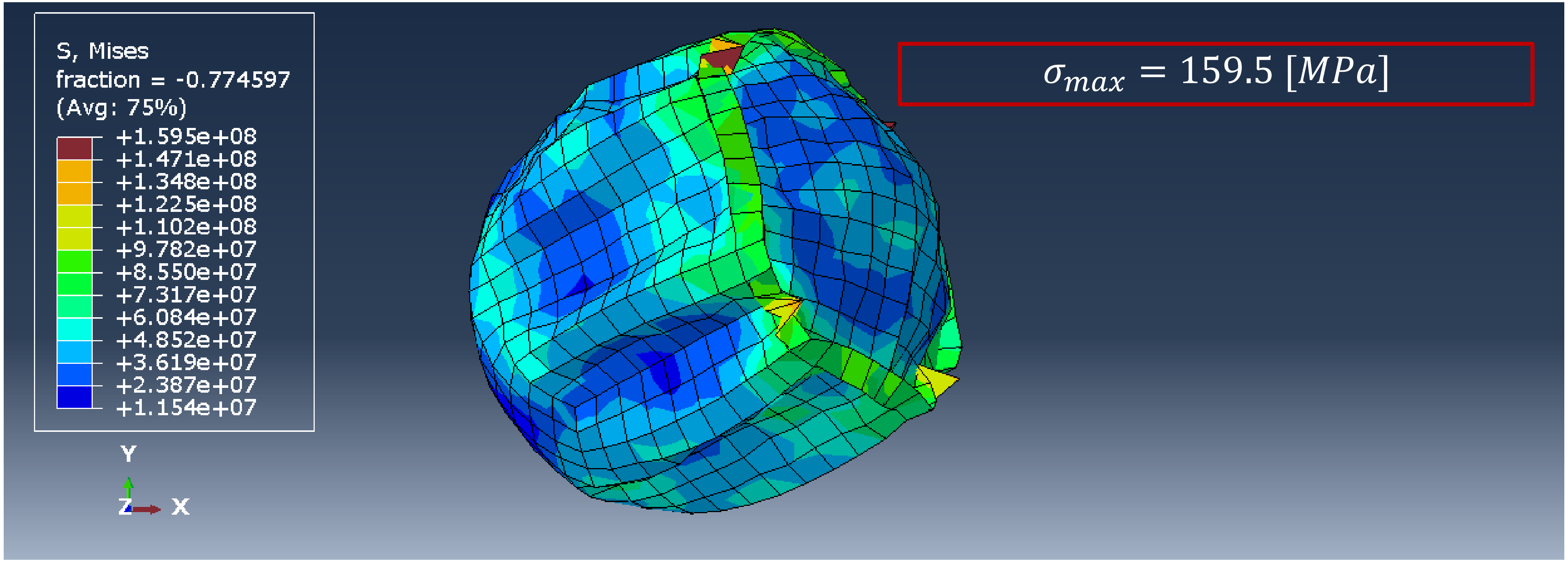
$$12.6\ [MPa] \ll 194.7[MPa] \Rightarrow \sigma_{yield} \ll \sigma_{max}$$

Fails

Compression Analysis – Simulation

No Parachute

- Larger terminal velocity (48.2 [m/s]) results in larger force of impact (10,168 [N])



Compressive yield strength of HDPE is 12.6 [MPa]
Tensile yield strength of HDPE is 26.1 [MPa]

$$26.1[MPa] \ll 159.5[MPa] \Rightarrow \sigma_{yield} \ll \sigma_{max}$$

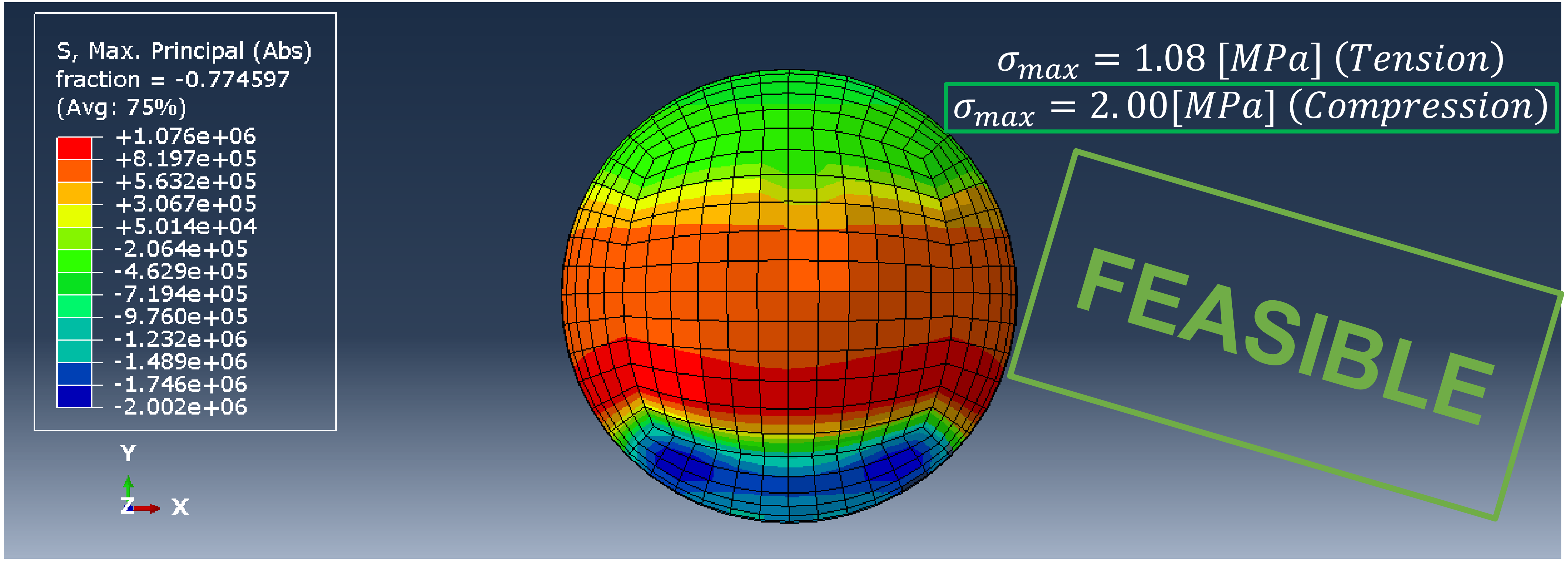
Fails

Compression Analysis – Simulation

Impact With Parachute:

Terminal Velocity = 9.44 [m/s]

Force of impact (468 [N])



Compressive yield strength of HDPE is 12.6 [MPa]

Tensile yield strength of HDPE is 26.1 [MPa]

$12.6\ [MPa] > 2.00[MPa] \Rightarrow \sigma_{yield} > \sigma_{max}$

FR 3.0
Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

Impact Analysis: Feasibility

Summary:

- A parachute **IS** required to prevent compression failure of the structure at impact
- Average compressive yield strength of HDPE =12.6 [MPa] > Maximum predicted impact = 2.00 [MPa]
    - Resultant factor of safety = 6.3
- Maximum predicted g-force of structure at impact = 1,435 [g's] < Minimum g-force of functional BGA electronics = 10,000-25,000 [g's]

FR 3.0
Drifter shall maintain full structural and component functionality after ocean impact from being deployed from UAV at altitudes of 300 [m]

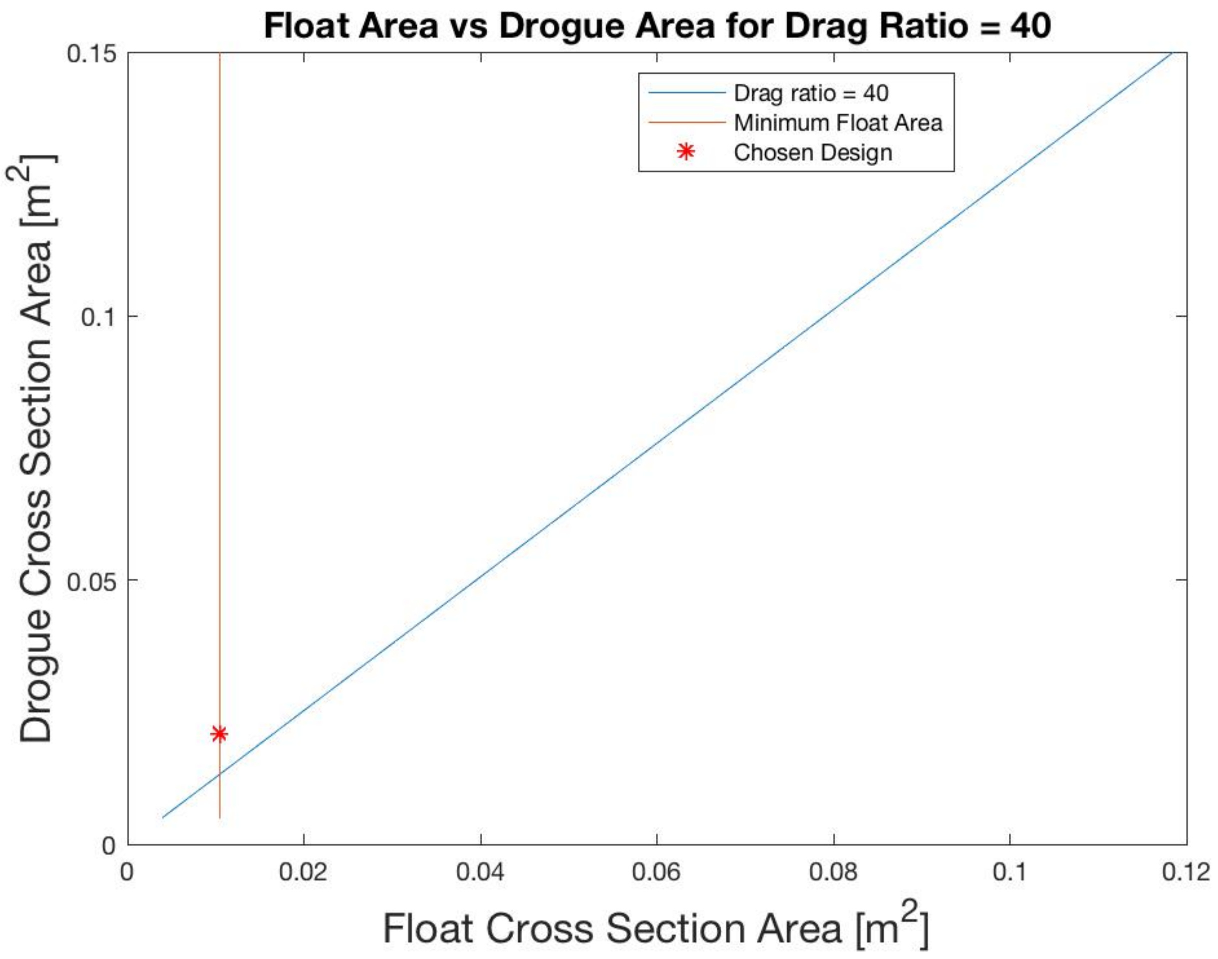
FEASIBLE

Drogue: Float Drag Ratio

Constraints

- Drag ratio of 40
- Minimum cross sectional area of float to house electronics and float

- Large Design Space
  - Chose cross sectional areas
    - Float Area = 0.0105 m^2
    - Drogue Area = 0.0210 m^2
- **Feasible** Drag Ratio = 45.44



Deployment Accuracy

- Problem: The accuracy and precision of the nano drifter's decent post deployment relies largely on its configuration

- Solution: To get a better understanding of the accuracy and descent of the nano drifter, test the best and worst case scenario in order to see the precision differences

- Best Case: Modeling the nano drifter as a sphere

- Worst Case: Modeling the nano drifter with a parachute configuration

Monte Carlo Simulation

Monte Carlo Variations:

- Wind and direction varied based on a normal distribution with a standard deviation set about average conditions for wind in the Gulf of Mexico for each iteration over 300 iterations
  - X-direction: σ = 3 (m/s)
  - Y-direction: σ = 3 (m/s)
  - Z-direction: σ = 0.5 (m/s)

Case 1 - No Parachute:

- Modeling nano drifter as a sphere:
  - cD ~ 0.5
  - Diameter ~ 0.1 [m]
  - Mass: 500 [g] (Drifter)

Case 2 - Parachute:

- Parachute used: 30” diameter Iris Ultra Zero Light Weight with spectra lines
  - cD ~ 2.20
  - Reference Diameter ~ 0.762 [m]
  - Mass: 527.78 [g] (Drifter + Parachute)

Differential Equation Solver Model

Governing Equations:

$$F_{drag} = \frac{1}{2}\rho|V_{rel}|^2 * (C_{d_{drifter}} * A_{drifter} + C_{d_{parachute}} * A_{parachute})\check{v}$$

$$V_{rel} = [\, V_x - W_x, V_y - W_y, V_z - W_z]$$

$$\check{v} = \frac{V_{rel}}{|V_{rel}|}$$

$$\frac{\delta \dot{x}}{\delta t} = -F_{drag,x}$$

$$\frac{\delta \dot{z}}{\delta t} = -F_{drag,z} - (m_{drifter} + m_{parachute}) * g$$

$$\frac{\delta \dot{y}}{\delta t} = -F_{drag,y}$$

Initial Conditions:

$$x_0 = 0\ (m/s)$$

$$y_0 = 0\ (m/s)$$

$$z_0 = 0\ (m/s)$$

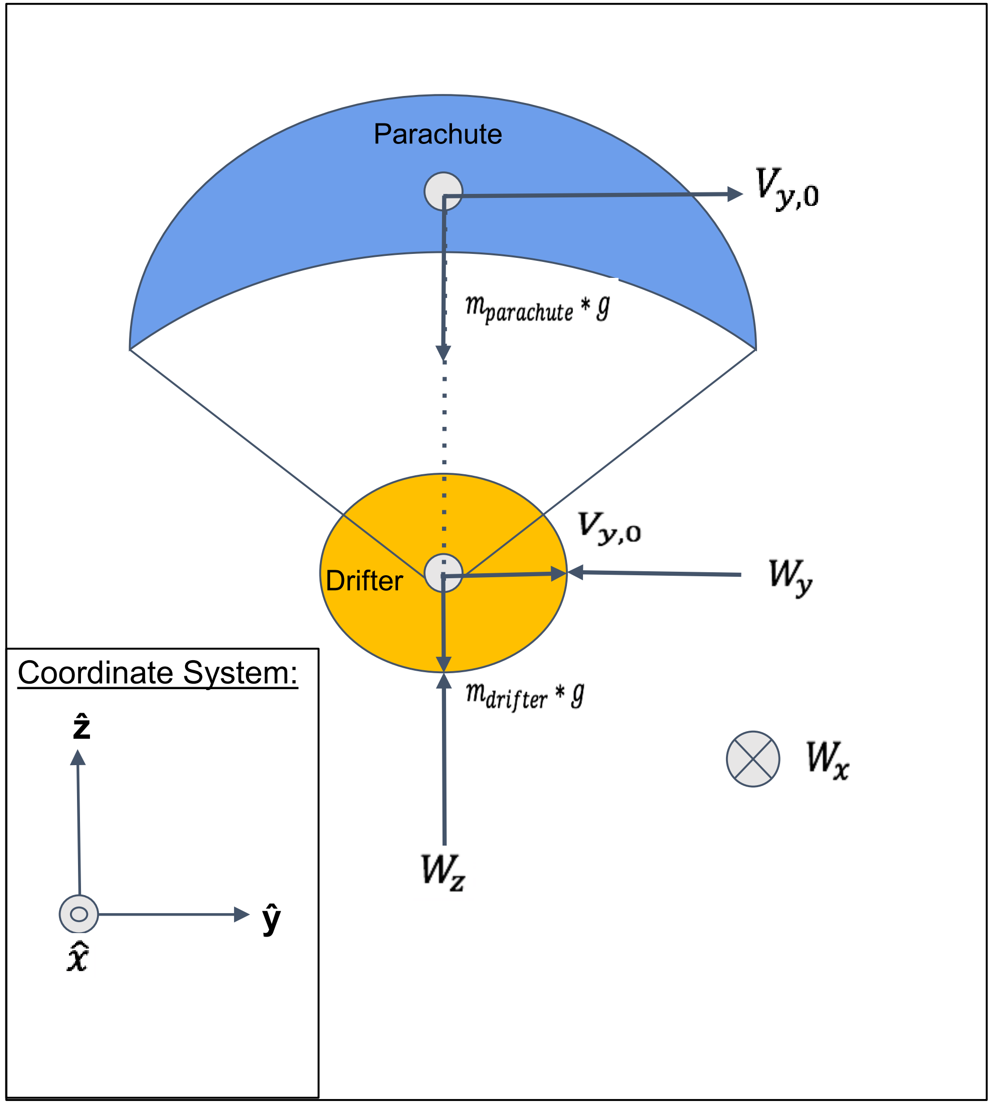
$$V_{x,0} = 0\ (m/s)$$

$$V_{x,0} = 20\ (m/s)$$

$$V_{z,0} = 0\ (m/s)$$

Assumptions:

$\Delta\rho = \sim 4\% \approx 0$ $\frac{dW_x}{dz} = 0$ $\frac{dW_y}{dz} = 0$ $\frac{dW_z}{dz} = 0$



Simulation Results

- Required accuracy is 1000 [m]
- Required accuracy is just within 3σ
    - ~ 99% of simulated cases landed within required zone