RAMROD

REMOTE AUTONOMOUS MAPPING OF RADIO FREQUENCY OBSTRUCTION DEVICES

Team: Jorgen Baertsch, Ian Cooke, Kennedy Harrmann, Mary Landis, Sarah Larson, Harrision Mast, Ethan Morgan, Selby Stout, Jake Ursetta, Justin Williams, Samantha Williams

Sponsor: Dennis Akos

Advisor: Jade Morton

MISSION STATEMENT

RAMROD will utilize an autonomous **UAS** and self-contained **sensor payload** to **localize** Radio Frequency Interference and Emerging Threat sources in a **GPS-denied environment** to allow civilian and military GNSS endeavors to continue without disruption.

AGENDA

1. Project Description
   a. Critical Project Elements
   b. Functional Requirements
   c. Concept of Operations (CONOPS)
   d. Functional Block Diagram
2. Baseline Design
   a. UAS Baseline Design
   b. Localization and Flight Algorithm Baseline Design
   c. Operational Payload Baseline Design
3. Evidence of Feasibility
   a. UAS Endurance, weight, and power
   b. Localization
   c. Inertial Navigation System
4. Status Summary
   a. Schedule
   b. Budget
5. Future Studies

ACRONYMS

Acronym:	Meaning:
AGC	Automatic Gain Control
ET	**Emerging Threat**
FAA	Federal Aviation Administration
GNC	Guidance Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	**Inertial Measurement Unit**
INS	**Inertial Navigation System**
MCU	Microcontroller
PDOA	**Power Difference of Arrival**
PPD	**Personal Privacy Device**
RFI	**Radio Frequency Interference**
UAS	Unmanned Aerial System

Project Description

Baseline Design

Evidence of Feasibility

Status Summary

Future Studies

BACKGROUND

- Personal Privacy Devices and Emerging Threat Devices (spoofers) are becoming a more common issue in military and commercial settings
- Utilizing a UAS is the most efficient method for localizing these RFI sources
- Flying a UAS in GPS denied conditions is problematic due to most autopilots reliance on GPS

Project Description

Baseline Design

Evidence of Feasibility

Status Summary

Future Studies

CRITICAL PROJECT ELEMENTS

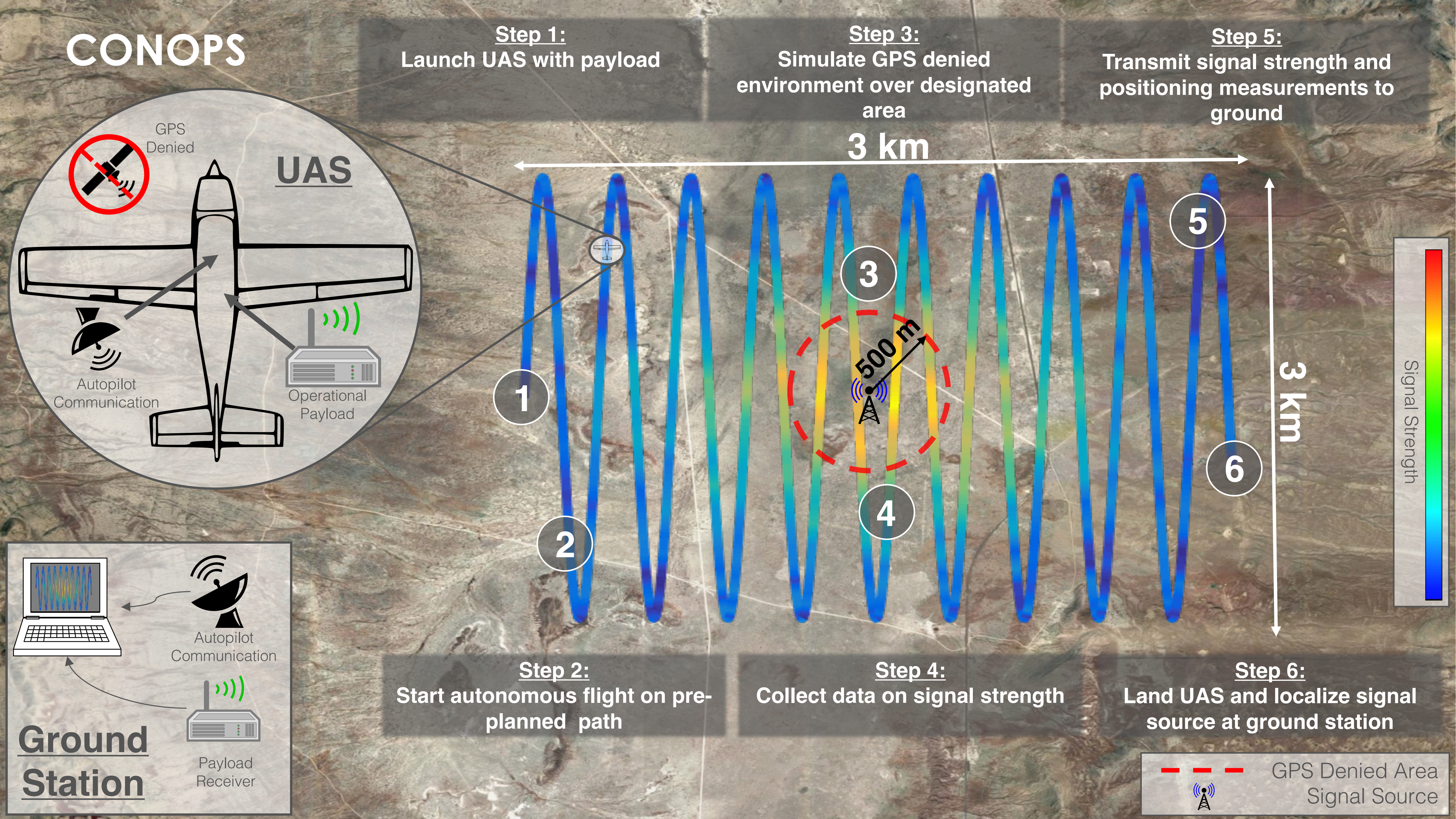
CPE	Description	Solution
Algorithm	Maintain autonomous flight while in a simulated GPS denied environment for an extended period of time	Use PDOA to determine GPS denied conditions and use an Inertial Navigation System to estimate UAS location and orientation
UAS	Develop a UAS platform capable of maintaining flight in a GPS denied environment while supporting all RFI measuring equipment	Choose and modify a UAS platform that can maintain flight for at least 60 minutes
Payload	Self-powered sensor payload that can monitor, store and transmit RFI signal data while interfaced with the UAS platform	Rigid structure containing RFI measuring equipment that will fit inside the payload bay of the UAS

FUNCTIONAL REQUIREMENTS – PT. 1

Functional Requirement	Description
FR 1.0	**The UAS shall have a flight time of 60 minutes**
FR 2.0	**The UAS shall fly in maximum winds of 30km/hr**
FR 3.0	**The UAS shall fly in a GPS denied environment for a distance of up to 2 km and a time of 200 seconds**
FR 4.0	**The UAS shall support all flight hardware and instrumentation**
FR 5.0	The UAS and its testing shall adhere to FAA and CU Boulder regulations
FR 6.0	**The UAS shall be capable of flying the operational payload**
FR 7.0	The system shall fly autonomously given a pre-programmed flight plan

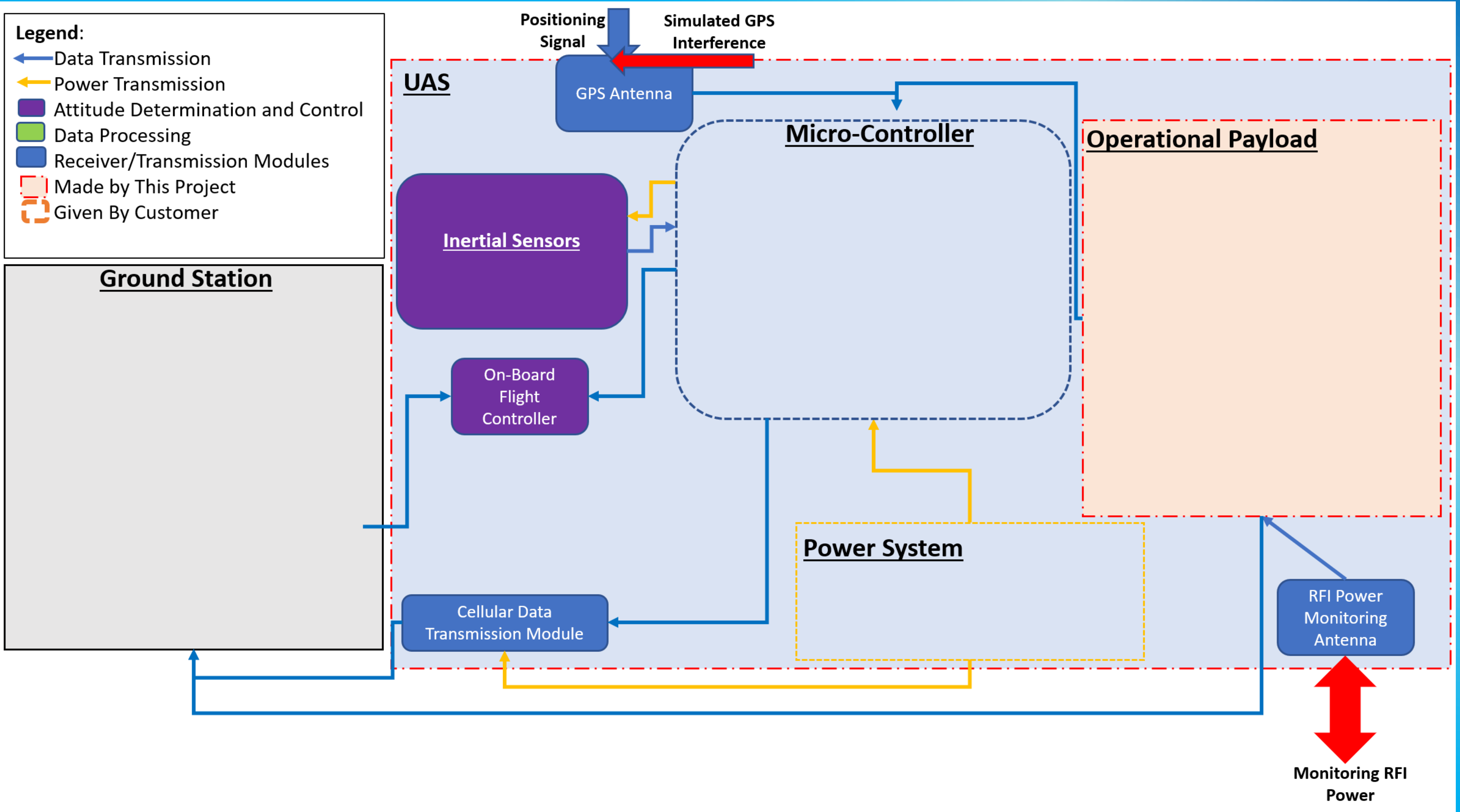
FUNCTIONAL REQUIREMENTS – PT. 2

Functional Requirement	Description
FR 8.0	The system shall have the ability to switch between the GPS and GPS-denied flight modes within 1 second of RFI detection
FR 9.0	The system shall transmit data for all six degrees of freedom
FR 10.0	**The system shall create a profile of RF signal power**
FR 11.0	The payload components shall be in a stable self-contained structure
FR 12.0	**The payload shall have the ability to measure and localize an RFI source in GPS denied environments**

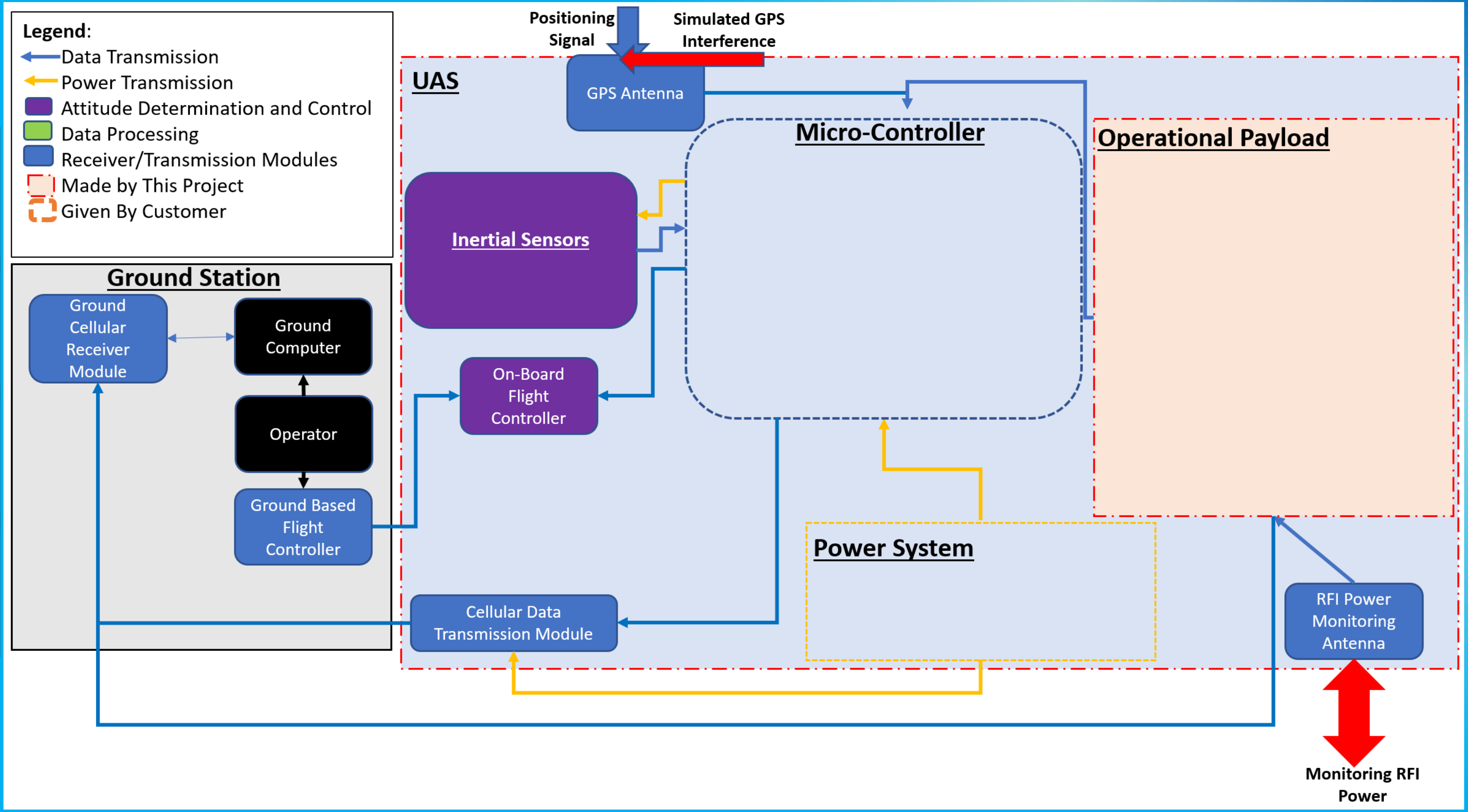


CONOPS
Step 1:
Launch UAS with payload
Step 3:
Simulate GPS denied environment over designated area
Step 5:
Transmit signal strength and positioning measurements to ground
GPS Denied
UAS
Autopilot Communication
Operational Payload
3 km
3 km
500 m
1
2
3
4
5
6
Signal Strength
Autopilot Communication
Payload Receiver
Ground Station
Step 2:
Start autonomous flight on pre-planned path
Step 4:
Collect data on signal strength
Step 6:
Land UAS and localize signal source at ground station
GPS Denied Area
Signal Source

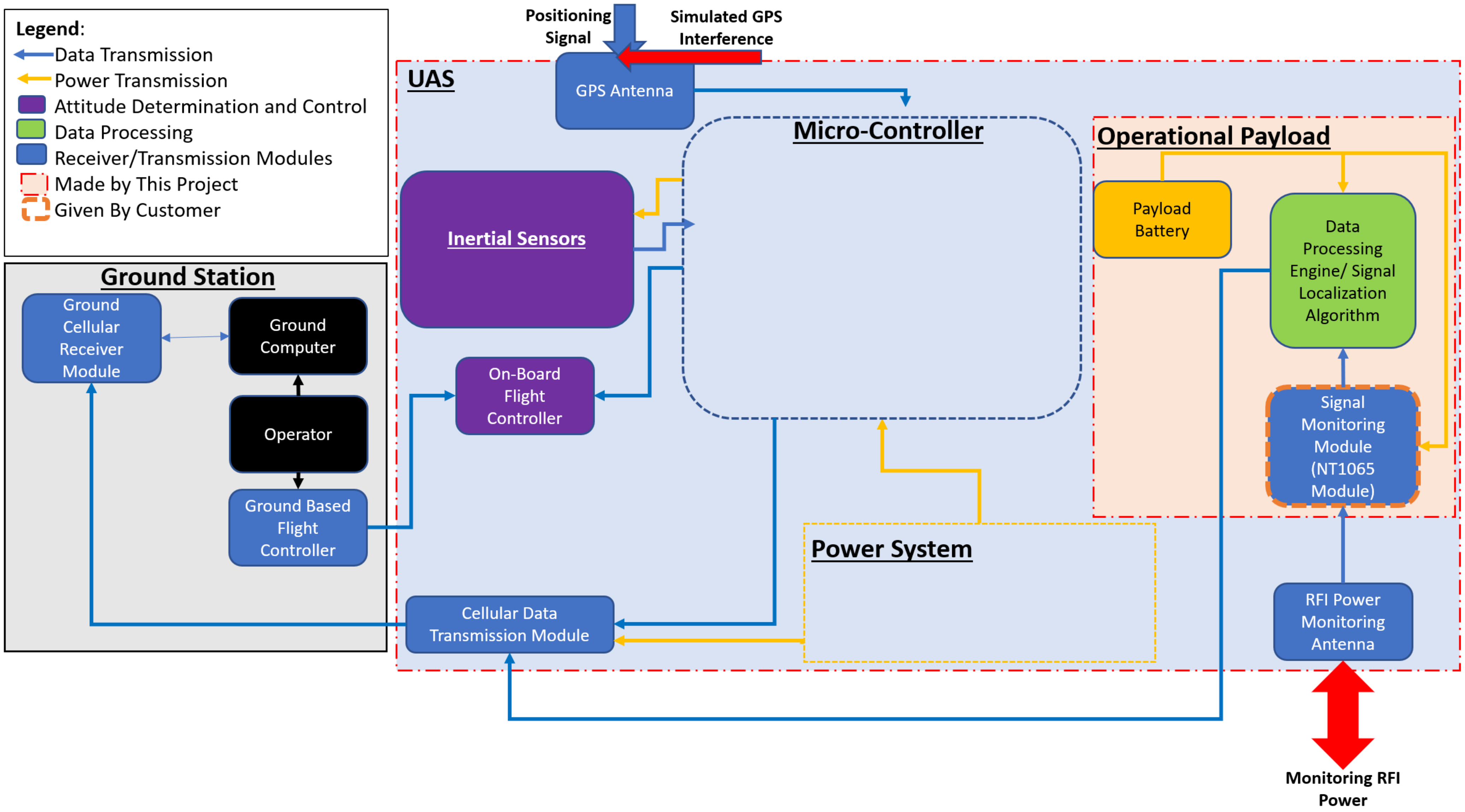
FUNCTIONAL BLOCK DIAGRAM



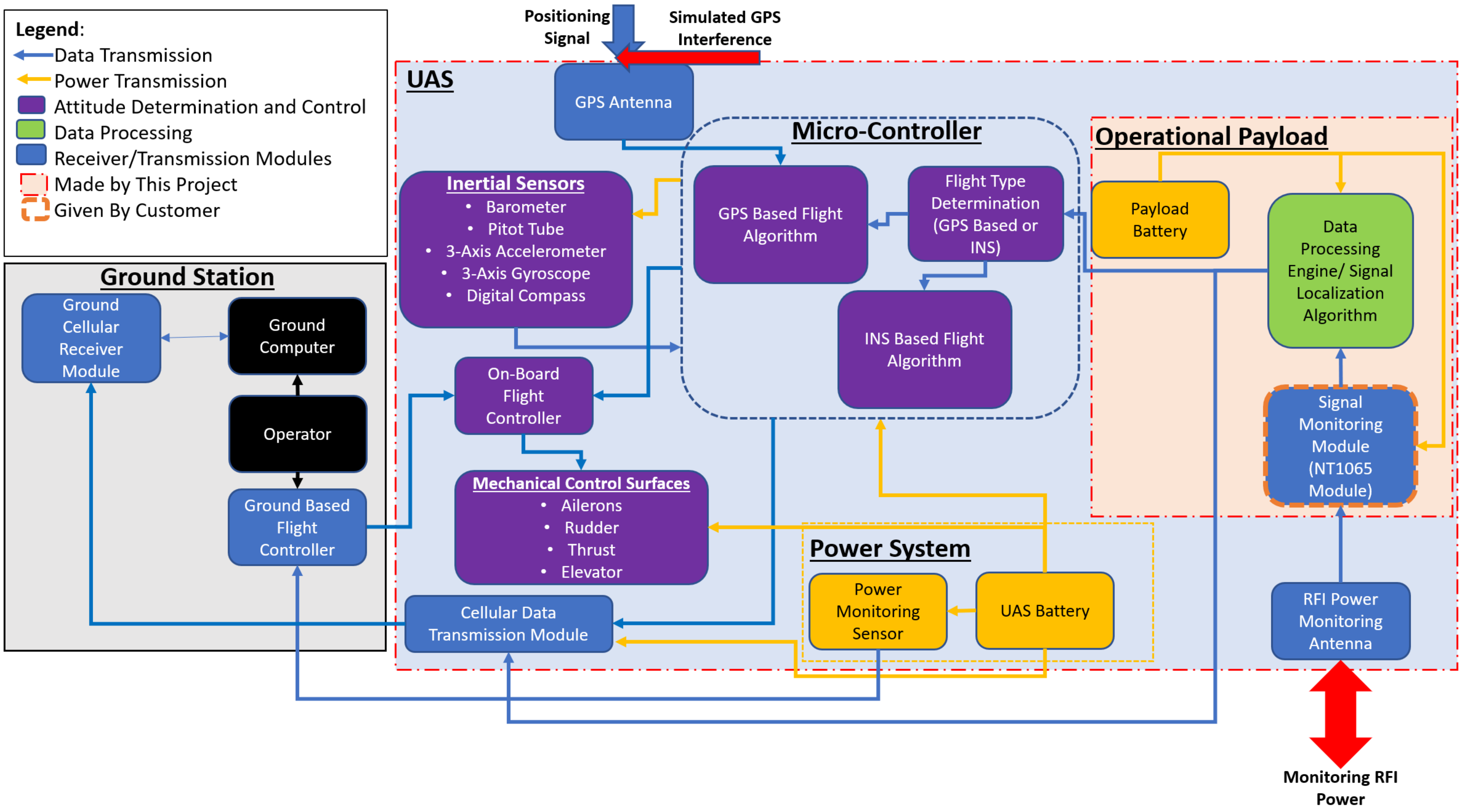
FUNCTIONAL BLOCK DIAGRAM



FUNCTIONAL BLOCK DIAGRAM



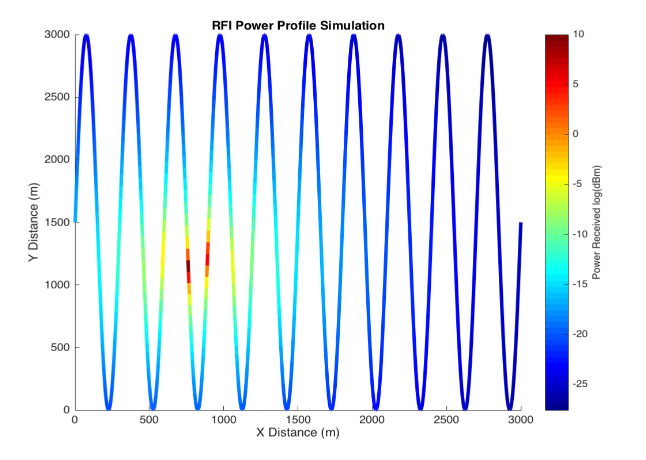
FUNCTIONAL BLOCK DIAGRAM



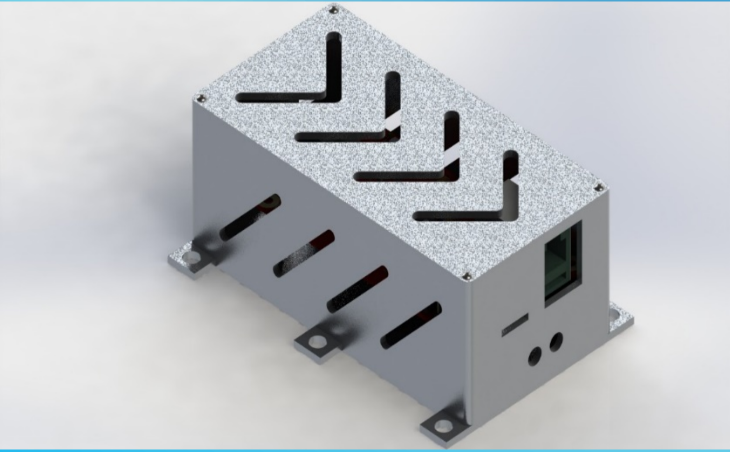
BASELINE DESIGN

UAS Platform

Algorithm



Payload



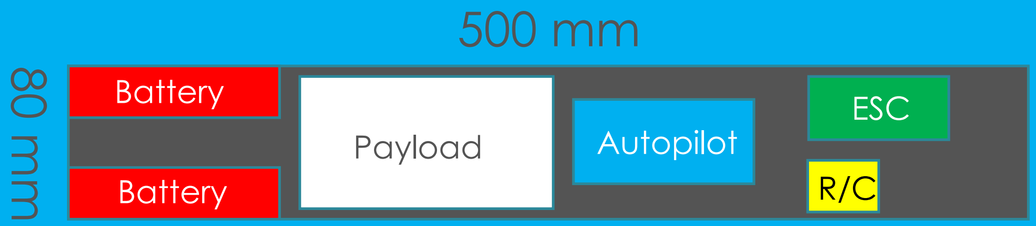
UAS PLATFORM

X-UAV Talon

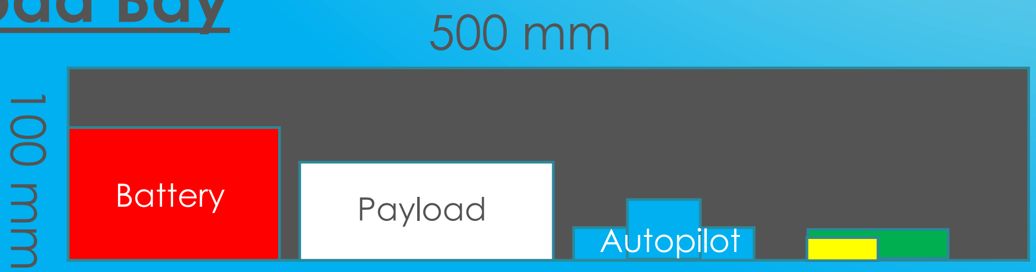
Key Features

- Long Flight Times (1+ hr)
- Stable Flight (Tri-tail)
- Large Payload Bay
- Native Autopilot Compatibility
- Affordable
- IRISS Supported

Talon Payload Bay



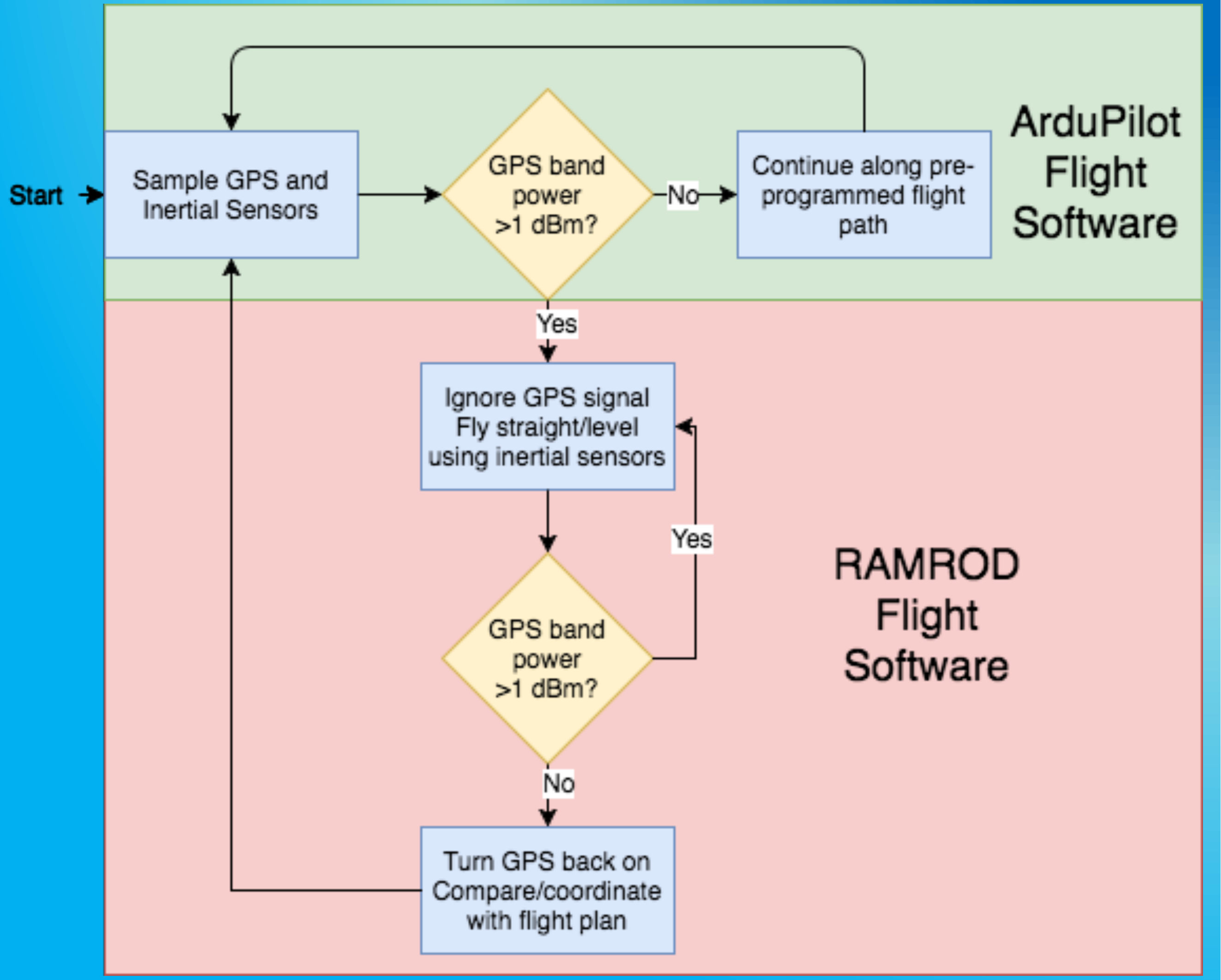
Top View



Side View

FLIGHT ALGORITHM BREAKDOWN

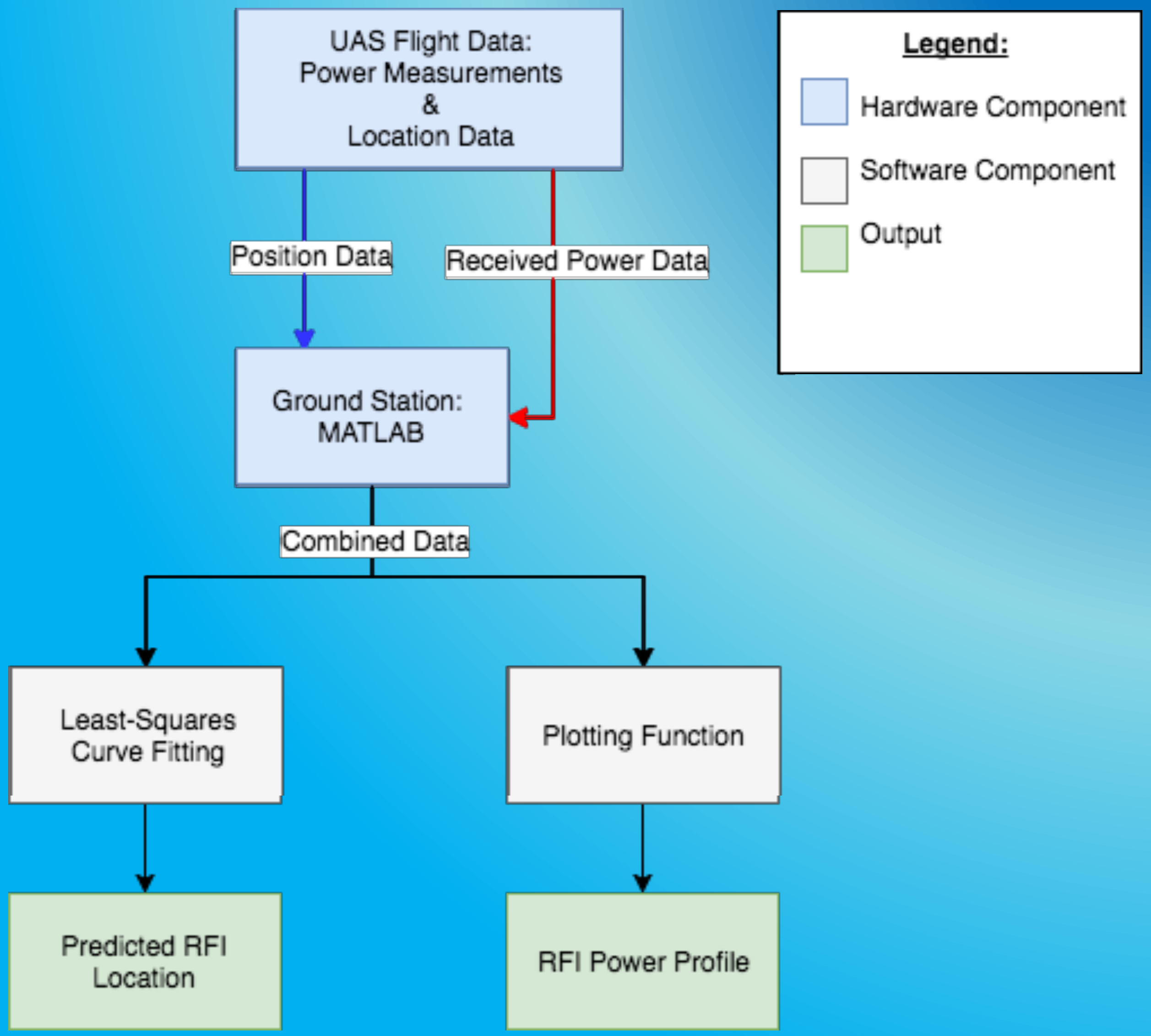
- The flight algorithm will use the ArduPilot code base for flight with access to GPS signal
- When GPS band power increases above threshold, switch to RAMROD INS-assisted flight mode



RAMROD

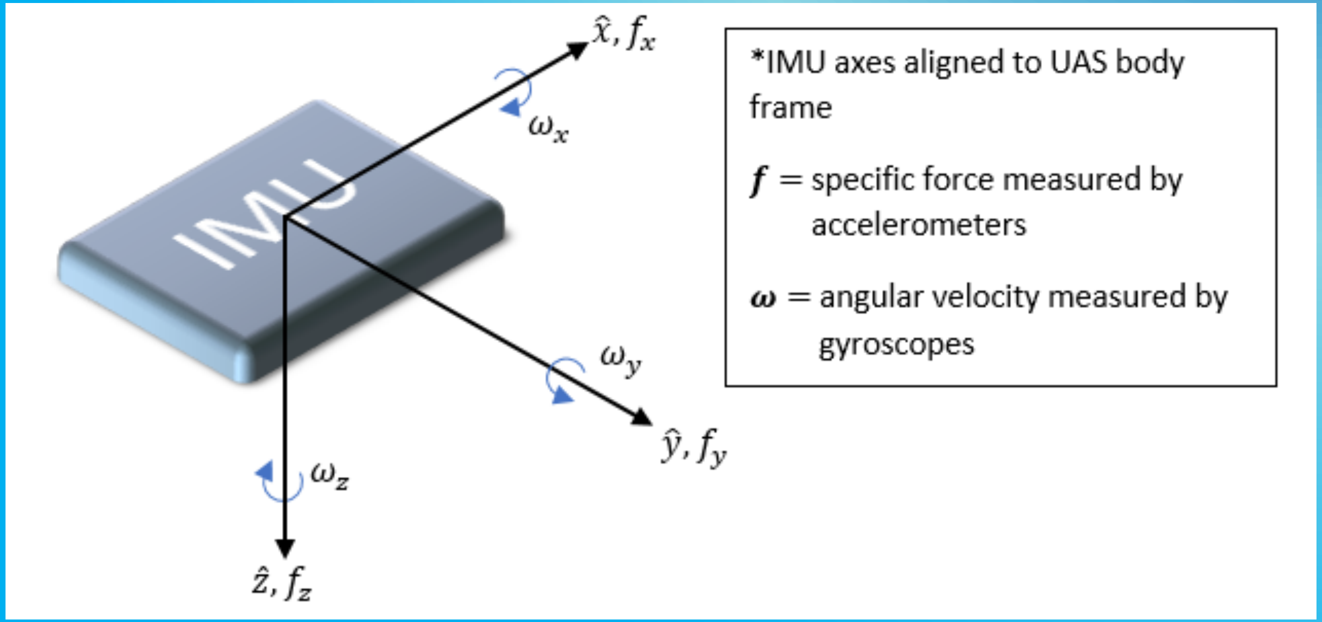
LOCALIZATION BREAKDOWN

- Position and RFI power data will be combined for post processing
- RFI source will be located using a least-squares method of curve-fitting



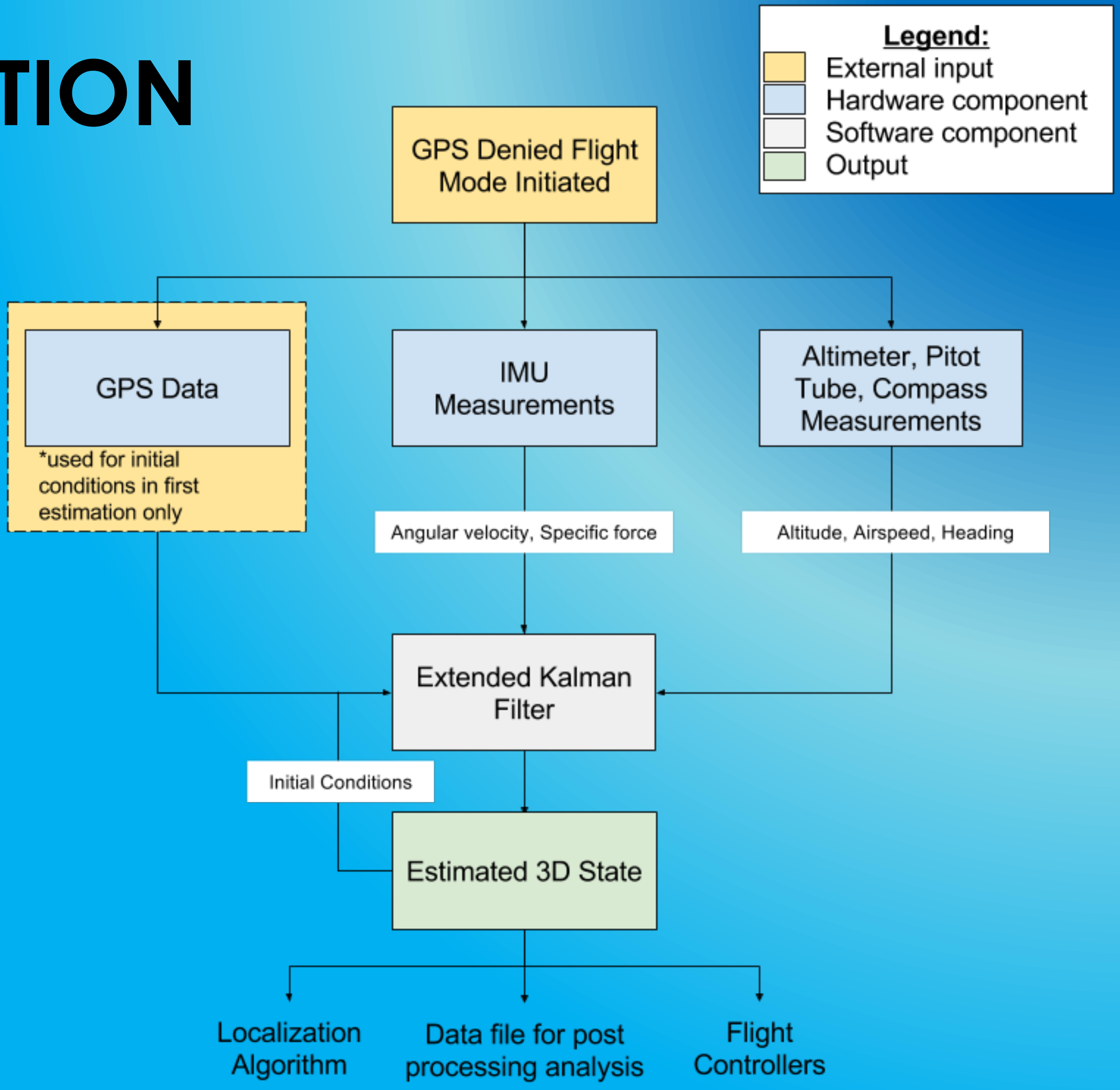
INERTIAL NAVIGATION SYSTEM

- Results of the GPS denied navigation trade study indicate INS as the most feasible for this project
- Key Features:
  - Three dimensional state estimations
  - Output data rates $\geq 100\ Hz$
  - Can increase accuracy with additional sensor inputs
  - Small size and weight
  - Detailed documentation



INERTIAL NAVIGATION SYSTEM

- Unaided INS: IMU only
  - IMU: six degrees of freedom
    - 3 accelerometers
    - 3 gyroscopes
- Aided INS: integration with additional sensors
  - Altimeter (barometric)
  - Pitot tube
  - Digital compass



Project Description
Baseline Design
Evidence of Feasibility
Status Summary
Future Studies

OPERATIONAL PAYLOAD

NT1065

Design Drivers

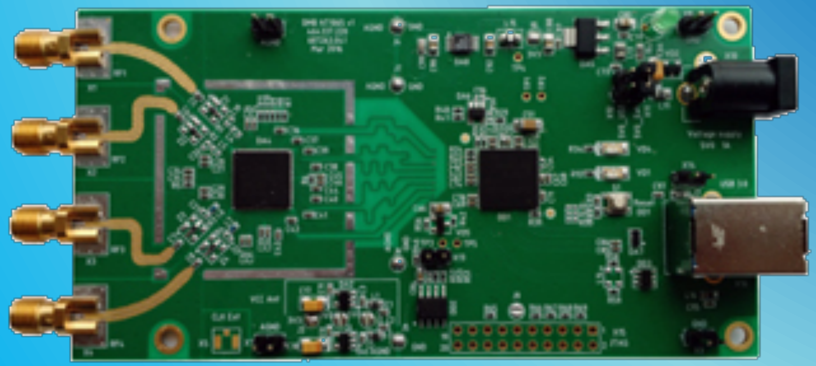
- Measures an RFI power source on multiple GPS bands

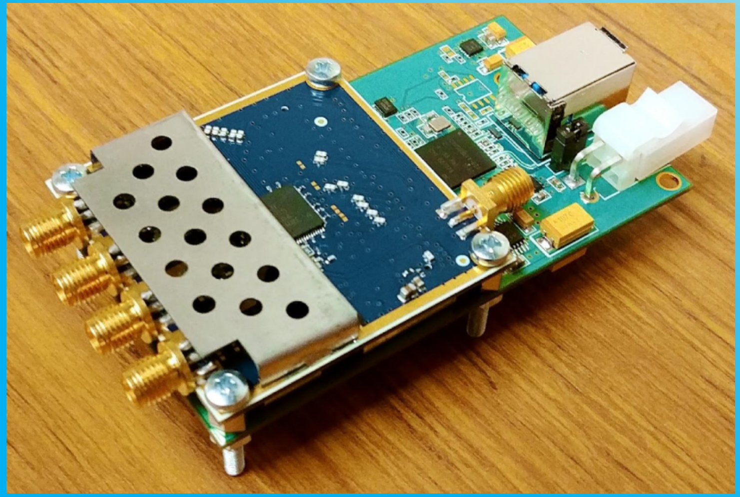
What can it do?

- NT1065 takes RF power readings
- Interface for external antenna
- Filters raw data
- Sends data to a processor

What must be done:

- Board must be redesigned to have internal splitting.





Project Description

Baseline Design

Evidence of Feasibility

Status Summary

Future Studies

OPERATIONAL PAYLOAD

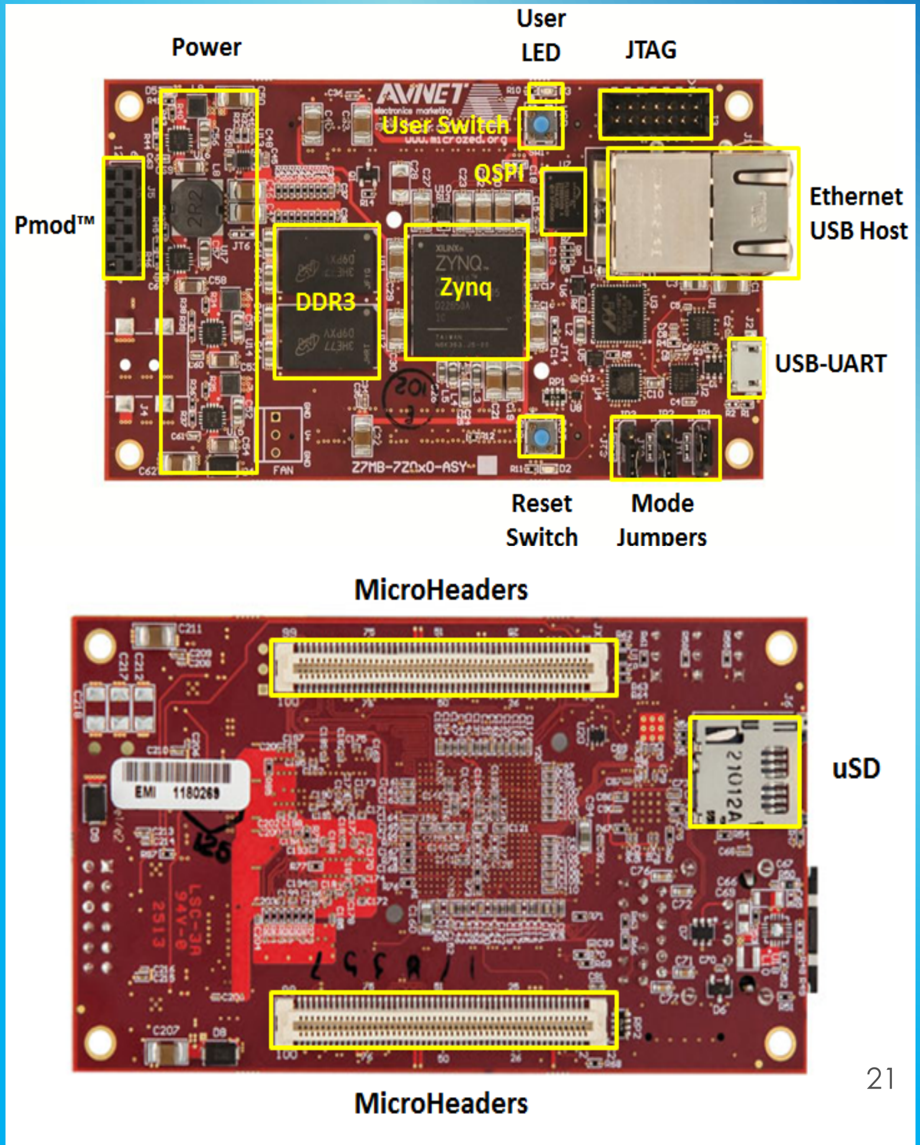
MICROZED

Design Drivers

- RFI source data must be stored
- RFI data must modified and downlinked

Why this board?

- Stores data from NT1065 on microSD card
- Interface for cellular modem for data downlink
- Proven to interface with NT1065
- Sufficient processing power



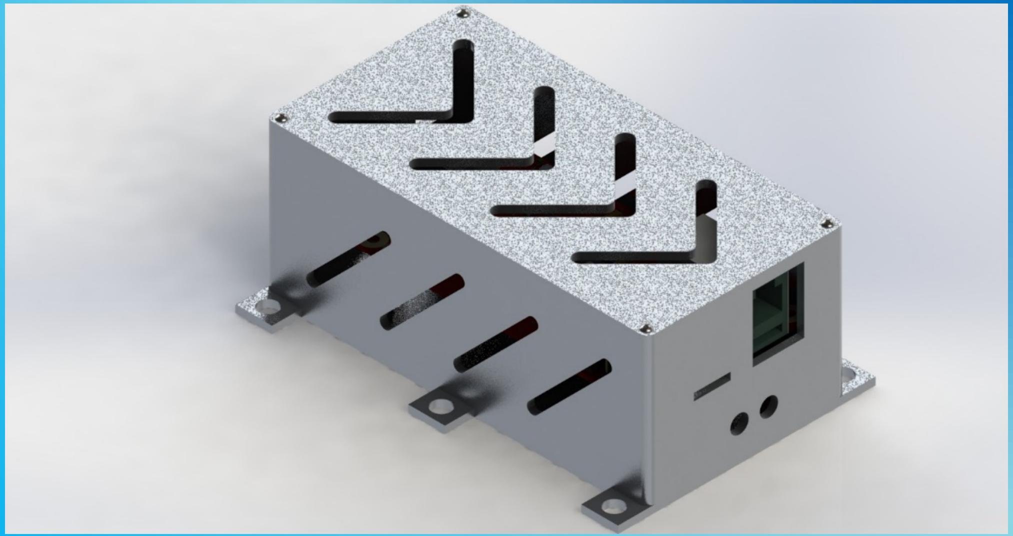
OPERATIONAL PAYLOAD

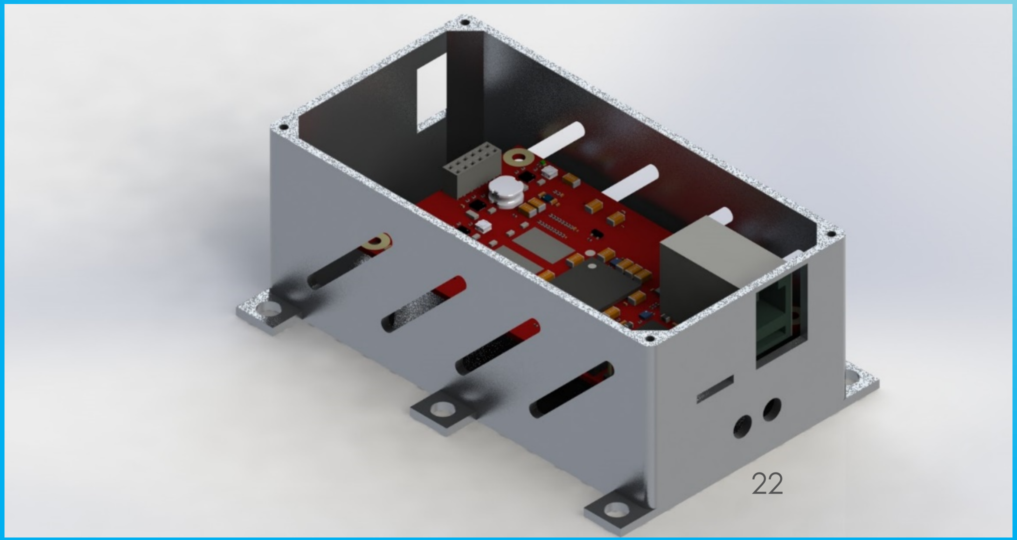
Design Drivers:

- Must fit inside UAS Payload Bay
- Must weigh below 1 kg
- Temperature must remain below electrical components' operating temperature

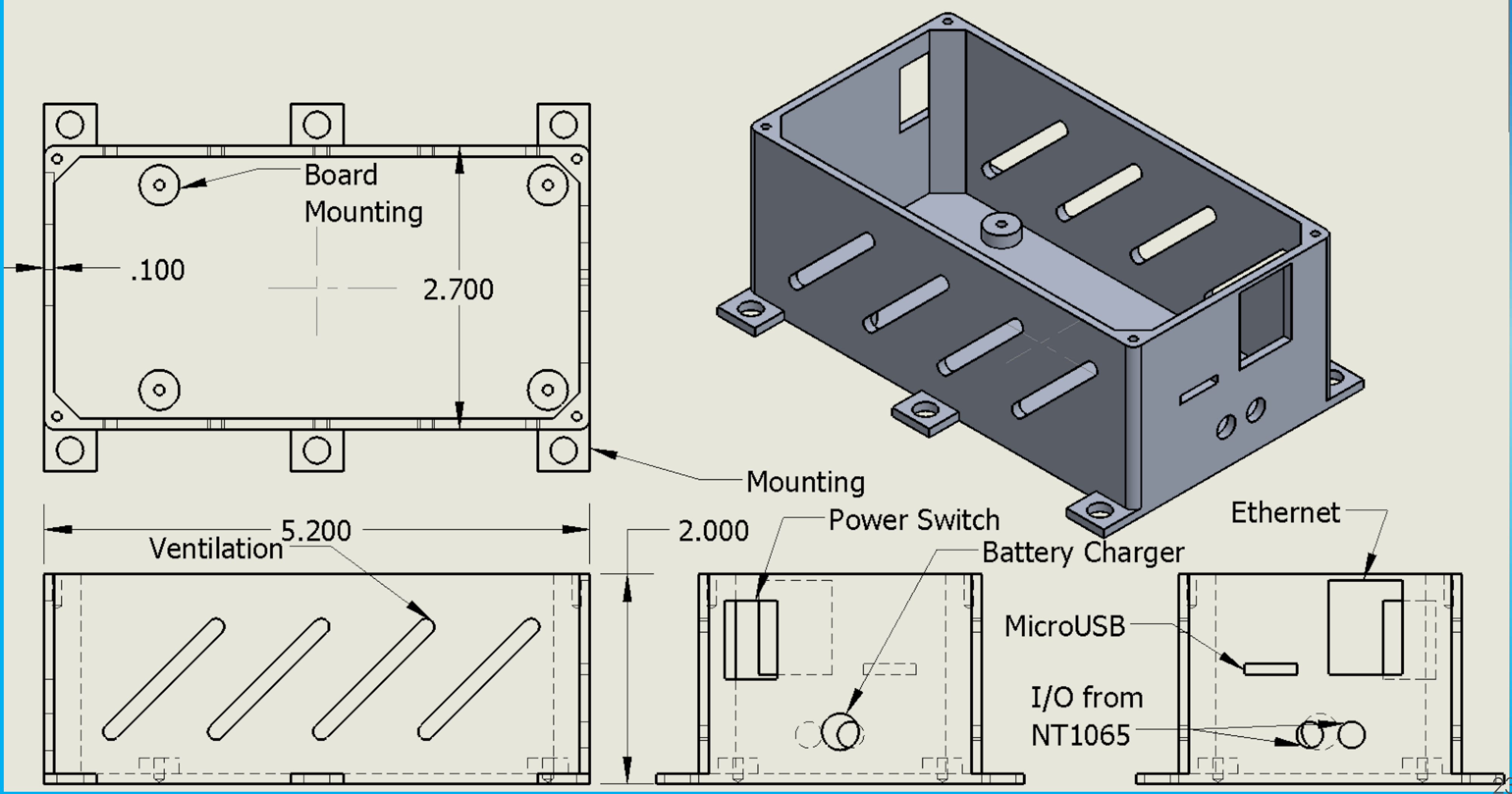
Included Components:

- Redesigned NT1065 signal filter
- MicroZed micro-processing unit
- Power Supply
- Power Switch and additional wiring





OPERATIONAL PAYLOAD



Project Description

Baseline Design

Evidence of Feasibility

Status Summary

Future Studies

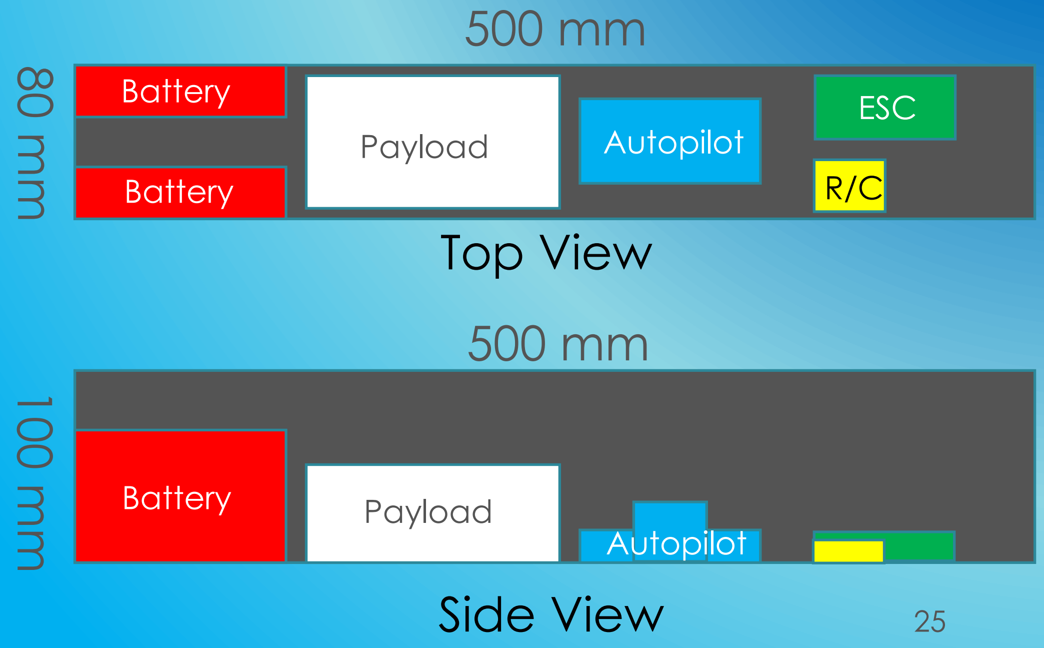
EVIDENCE OF FEASIBILITY

UAS ENDURANCE

UAS PLATFORM

X-UAV Talon

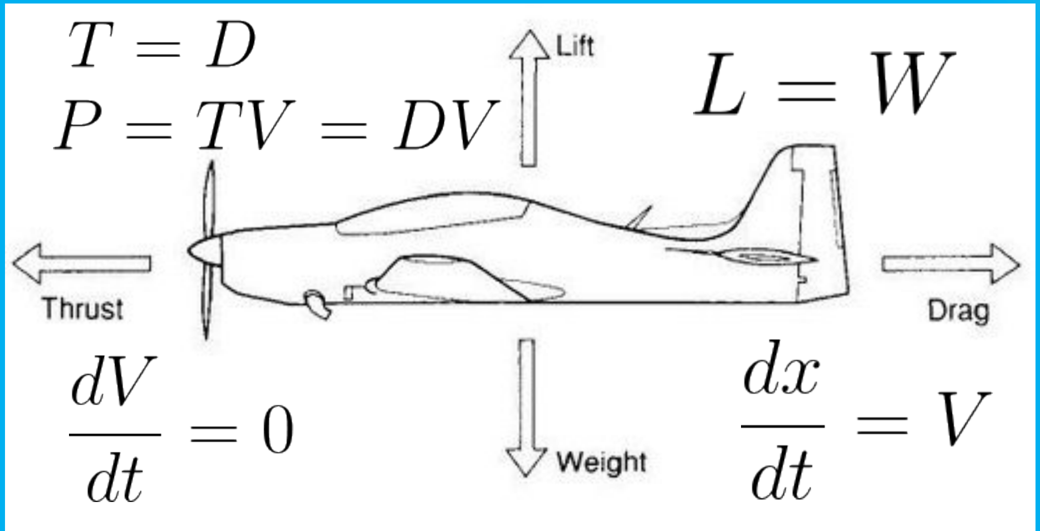
Talon Payload Bay



Requirement	Feasibility
FR 4: The UAS shall support all flight hardware and instrumentation	**feasible** ✓
FR 6: The UAS shall be capable of storing the operational payload	**feasible** ✓

UAS ENDURANCE MODEL

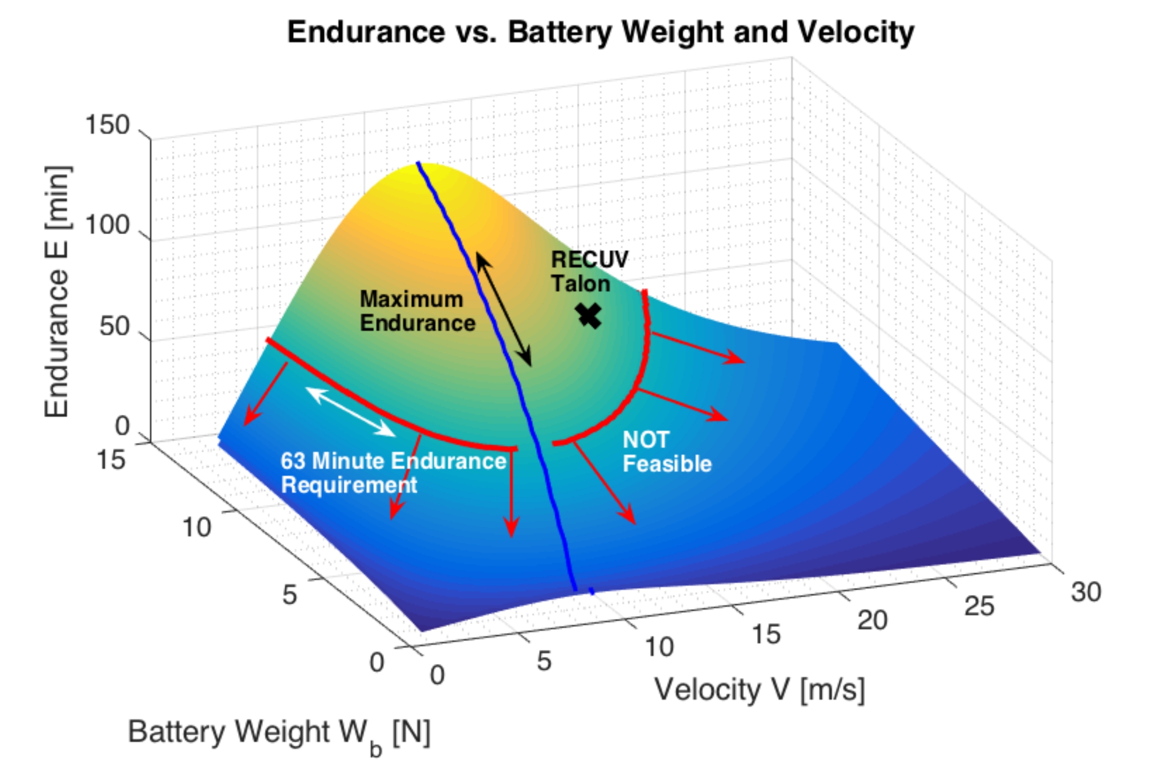
1. Can the selected UAS platform achieve a 63-minute flight time?
2. How do we optimize for minimum power?
3. How much will the UAS weigh?

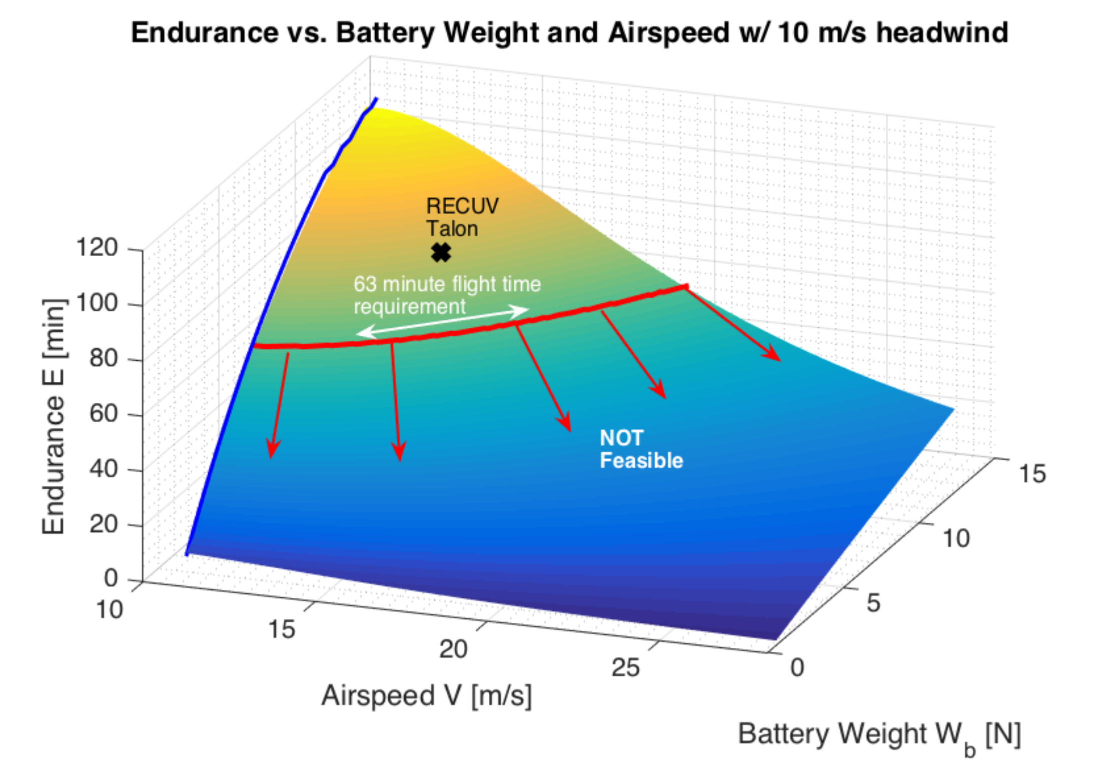


Assumptions
E = 63 min (inc. 5% buffer)
Worst-case headwind is 10 m/s
Steady, level flight throughout
Battery discharge depth is 80%
Overall system efficiency is 85%

Project Description
Baseline Design
Evidence of Feasibility
Status Summary
Future Studies

UAS ENDURANCE ESTIMATION



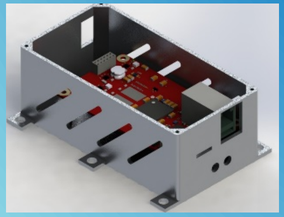


- Endurance as a function of battery weight and velocity
- Max Endurance :~ 109 mins @ 11.4 m/s (21000 mAh battery)
- 14000 mAh battery yields 84 min endurance @ 10.2 m/s

$$E = \frac{3600 W_b \sigma V_b D_b}{\left(\frac{1}{2}\rho V^3 S C_{D,0} + \frac{W}{\frac{1}{2}\rho V S}\frac{1}{\pi e b^2}\right)\eta_{system} g}$$

UAS WEIGHT – RAMROD TALON

Component	Mass [g]
Talon Airframe	1050
Battery	845
Payload	900
Additional Hardware	537
TOTAL	**3,332**



RECUV Talon Mass	3,343 g
RAMROD Talon Mass w/ Same Battery	3,332 g

Requirement	**Feasibility**
FR 1: The UAS shall support all flight hardware and instrumentation	**feasible** ✓
FR 2: The UAS shall fly in maximum winds of 30 km/hr (8 m/s)	**feasible** ✓

Project Description

Baseline Design

Evidence of Feasibility

Status Summary

Future Studies

EVIDENCE OF FEASIBILITY

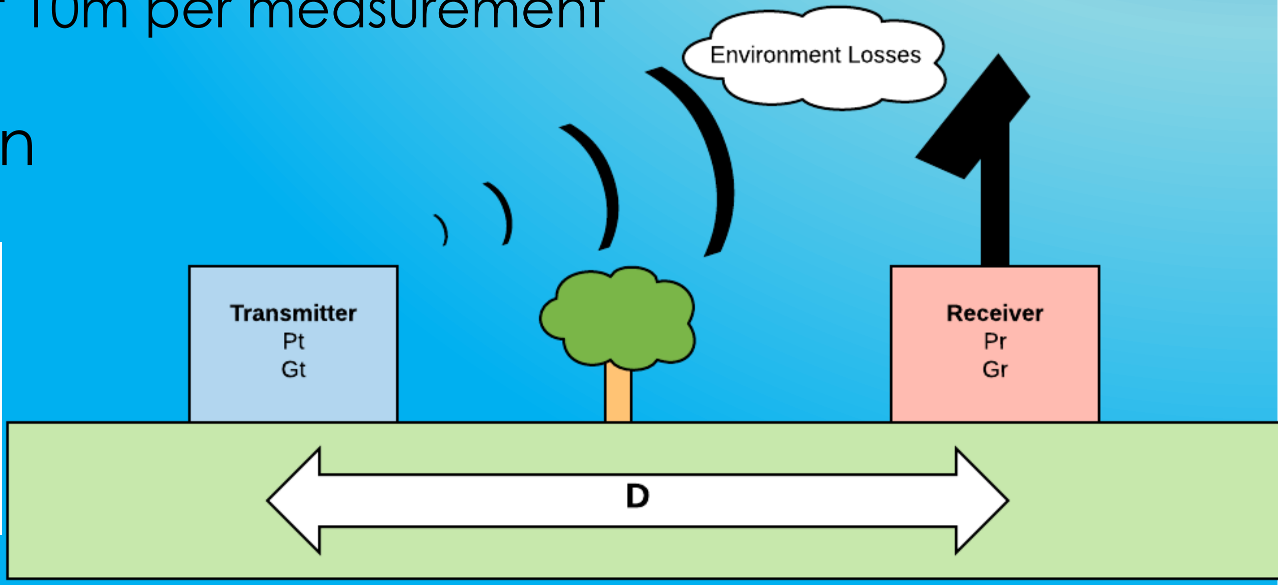
ALGORITHM

FEASIBILITY STUDY: ALGORITHM

- **Feasibility Study**: The algorithm shall create an RFI Power Profile and the algorithm shall localize the RFI source within a 40 meter radius
- **Assumptions:**
  - Signal decays with free-space attenuation
  - Transmitter and receiver antenna gains are 0.80
  - There is an average position error of 10m per measurement
  - All other losses are ignored
- **Theory:** free space loss equation

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi)^2 R^2}$$

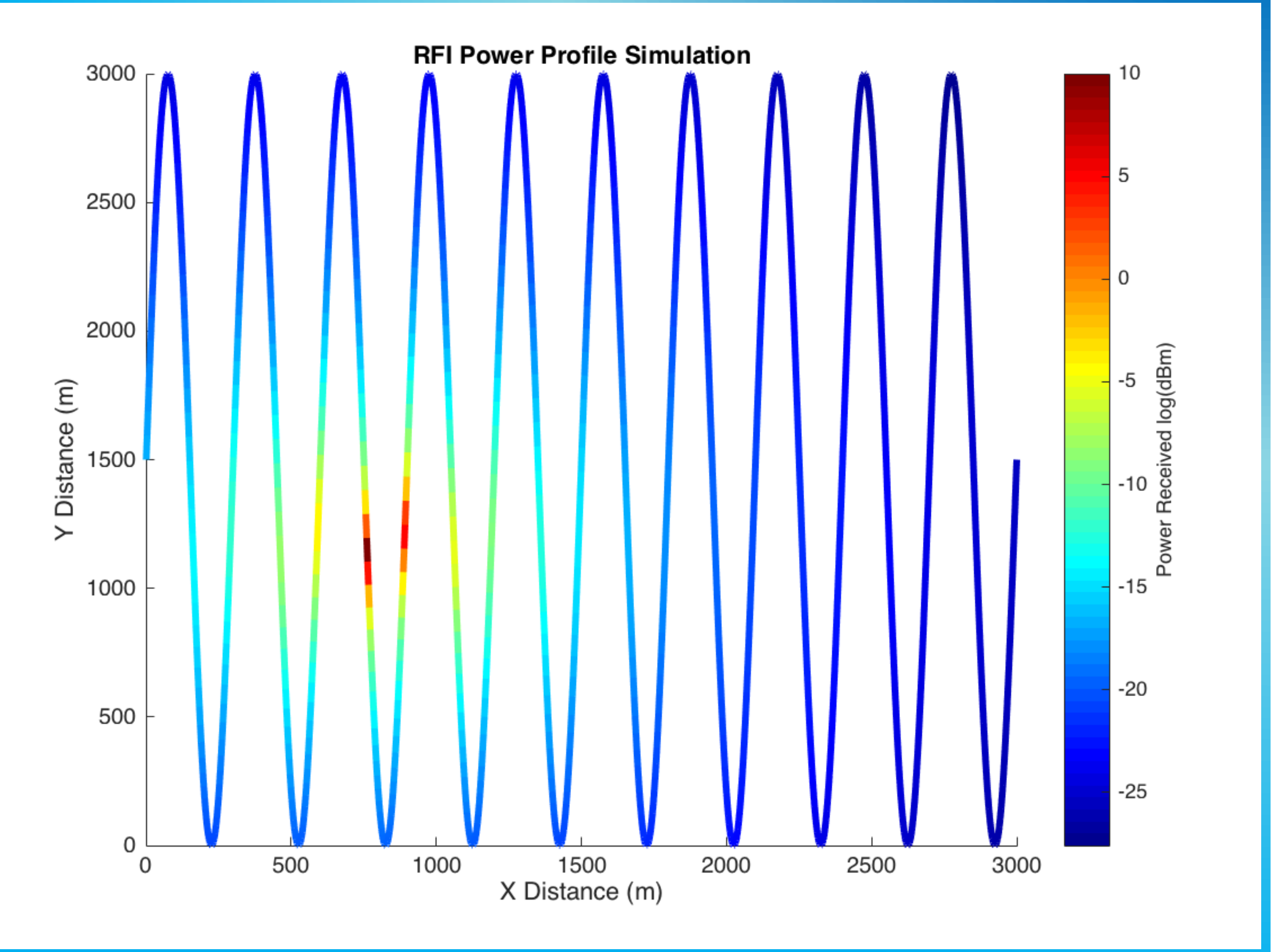
R: Distance from transmitter to receiver
Pr: Power Received
Pt: Power Transmitted
Gt: Transmitter Antenna Gain
Gr: Receiver Antenna Gain
λ : Signal Wavelength



ALGORITHM
RFI POWER PROFILE

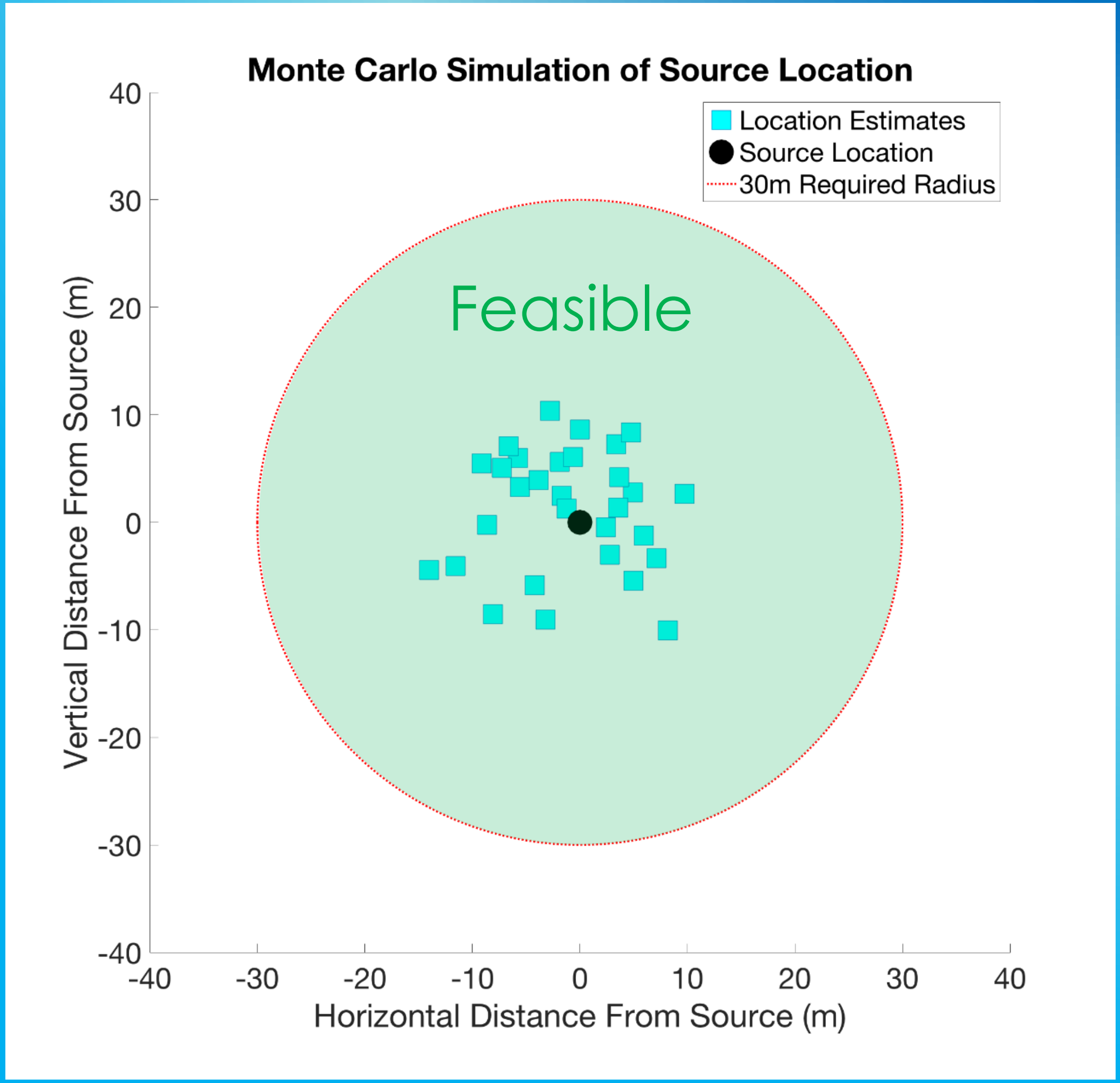
Project Description
Baseline Design
Evidence of Feasibility
Status Summary
Future Studies

- The power profile will show measured position and power data
- The power profile will be created in MATLAB during post-processing
- Based on simulated flight data using free-space loss theory and simulated position data, the profile is **feasible** ✓



LOCALIZATION USING OF PDOA

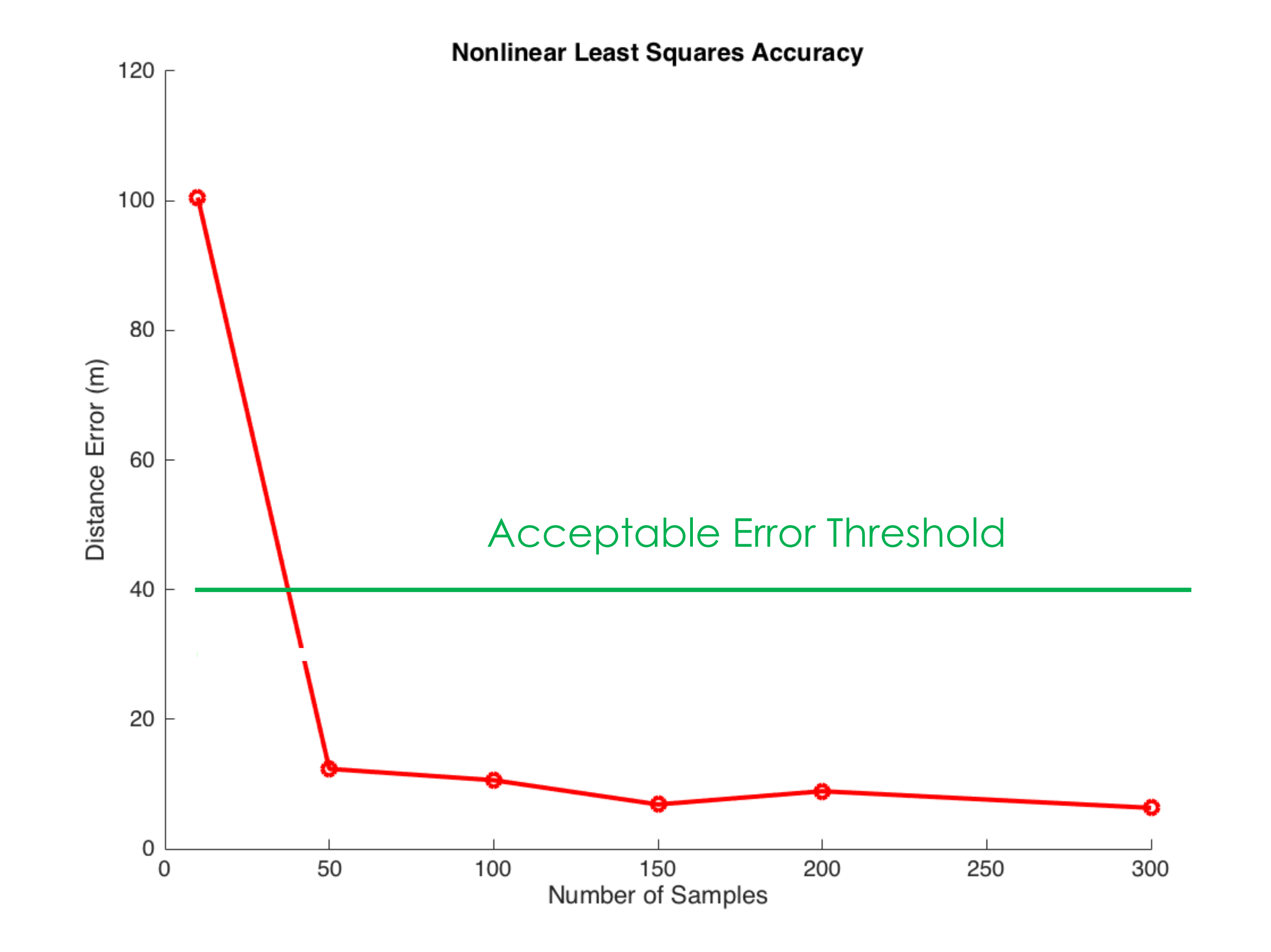
- Monte Carlo simulation with 30 trials
- +/- 40m error in each x and y coordinate
- Average distance error: 8 m
- Based on simulation, the localization is **feasible** ✓



LOCALIZATION USING OF PDOA

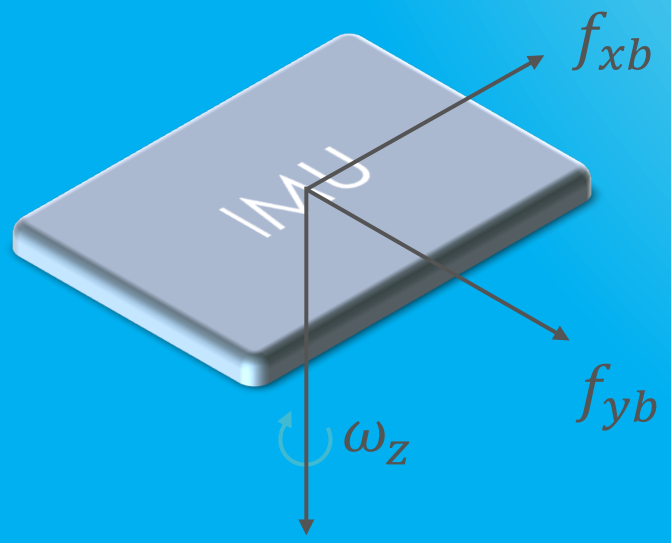
- Non-linear least squares method repeated for 10-300 samples with 5 trials .
- Each trial had a randomly placed RFI source within the search grid
- Sampling at 1 Hz over the GPS denied area is sufficient

feasible ✔



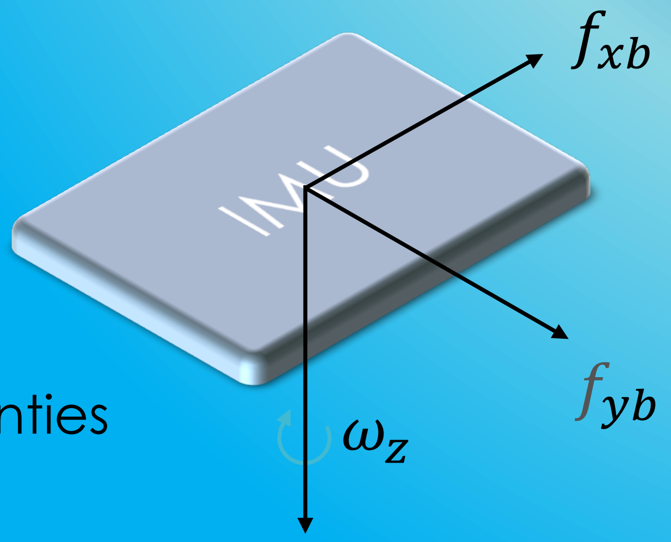
EVIDENCE OF FEASIBILITY

GPS DENIED FLIGHT

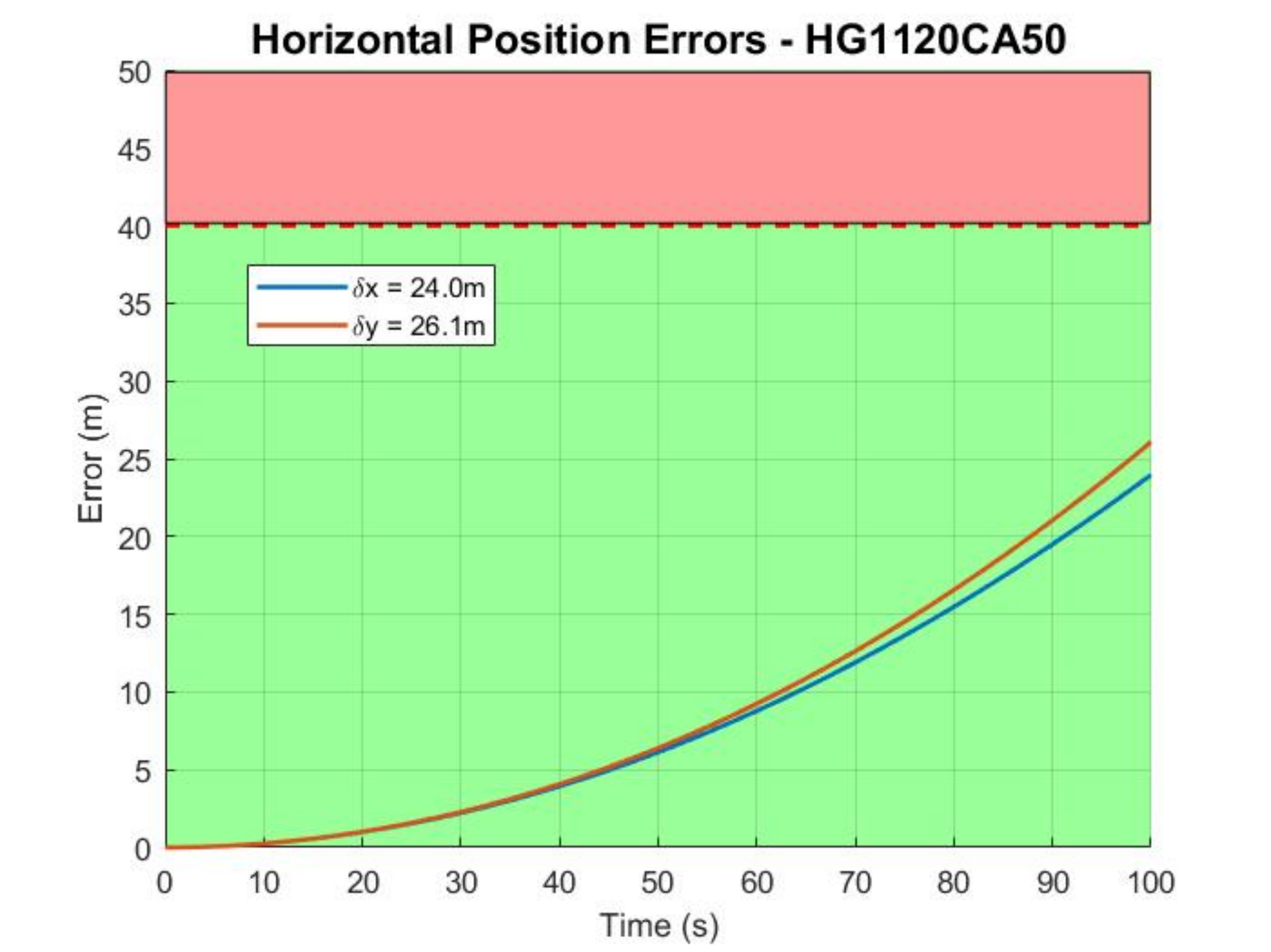


INS ERROR MODEL

- Motivation:
  - Show that an unaided INS can achieve the required accuracy of 40m
- Assumptions:
  - Two dimensional
  - Earth effects negligible
    - Coriolis effect
    - Rotation
  - Sensor bias and random walk parameters are most significant uncertainties



INS ERROR MODEL



Honeywell IMU ($1594.67)

$\delta p = 35.4m$

Error < 40m

feasible ✓

Project Description

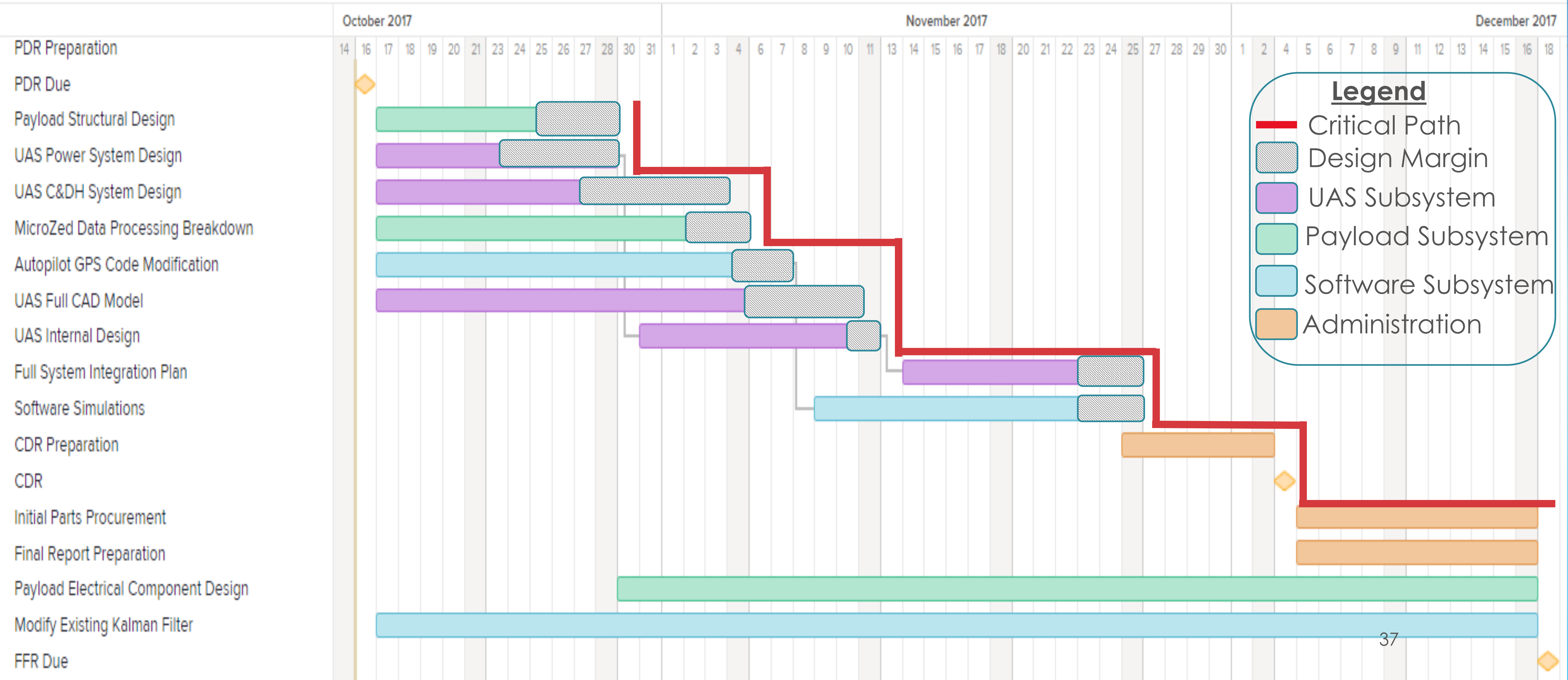
Baseline Design

Evidence of Feasibility

Status Summary

Future Studies

SCHEDULING



October 2017
November 2017
December 2017
14 16 17 18 19 20 21 23 24 25 26 27 28 30 31 1 2 3 4 6 7 8 9 10 11 13 14 15 16 17 18 20 21 22 23 24 25 27 28 29 30 1 2 4 5 6 7 8 9 11 12 13 14 15 16 18
PDR Preparation
PDR Due
Payload Structural Design
UAS Power System Design
UAS C&DH System Design
MicroZed Data Processing Breakdown
Autopilot GPS Code Modification
UAS Full CAD Model
UAS Internal Design
Full System Integration Plan
Software Simulations
CDR Preparation
CDR
Initial Parts Procurement
Final Report Preparation
Payload Electrical Component Design
Modify Existing Kalman Filter
FFR Due
Legend
Critical Path
Design Margin
UAS Subsystem
Payload Subsystem
Software Subsystem
Administration

Project Description

Baseline Design

Evidence of Feasibility

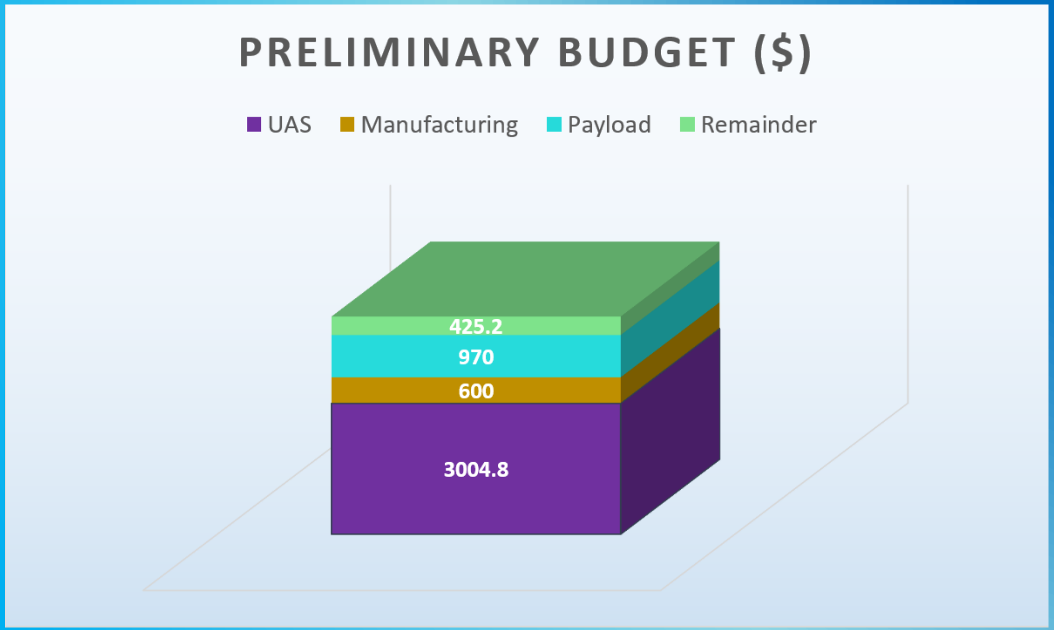
Status Summary

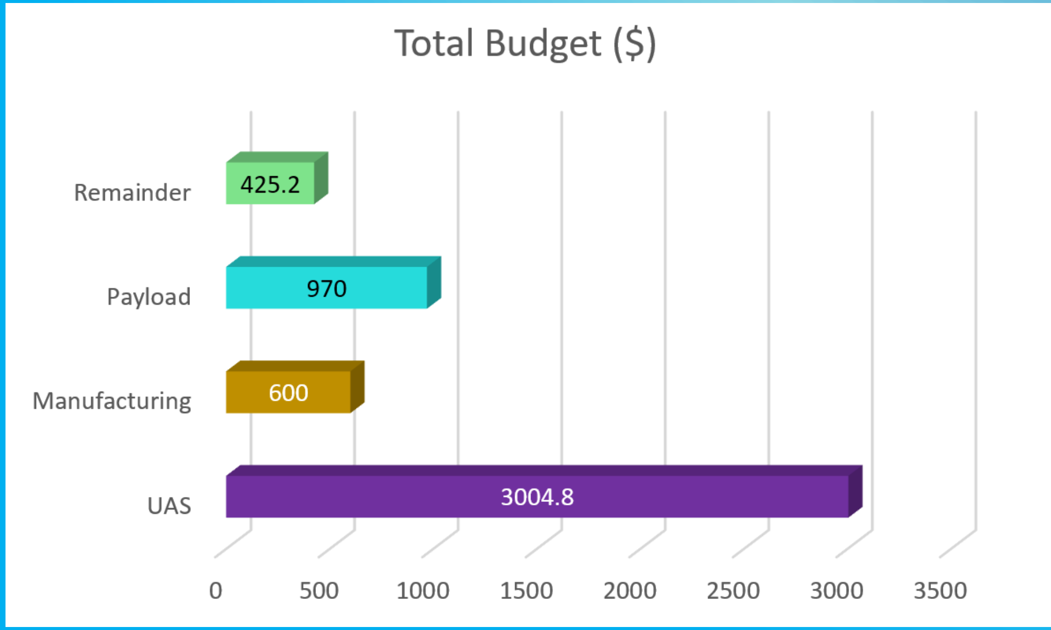
Future Studies

PRELIMINARY BUDGET

System	Expenditures ($)
Total Budget	5000
UAS	3004.8
Payload	970
Manufacturing	600
Total Expense	4574.8

Most Notable Expenses ($)	
INS	1500
Microzed	220
NT1065	500





Note: An Additional 20% was added to UAS expenses to accommodate for potential losses due to component failure.

FEASIBILITY SUMMARY AND FUTURE WORK

	Functional Requirement	Feasibility Shown	Future Work
FR 1.0	The UAS shall have a flight time of 60 minutes	Power Estimate ✓	Refine power estimate as components change
FR 2.0	The UAS shall fly in maximum winds of 30km/hr	RECUV Headwind Model ✓	Flight demonstration and PixHawk simulations
FR 3.0	The UAS shall fly in a GPS denied environment for a distance of up to 2 km and a time of 200 seconds	INS Error Model ✓	3D Error model with additional sensors
FR 4.0	The UAS shall support all flight hardware and instrumentation	Weight Estimation ✓	CG / weight balance analysis and full payload bay CAD model
FR 5.0	The UAS and its testing shall adhere to FAA and CU Boulder regulations		Obtain certification through FAA and CU
FR 6.0	The UAS shall be capable of flying the operational payload	Weight Estimation ✓	CG / weight balance analysis

FEASIBILITY SUMMARY AND FUTURE WORK

	Functional Requirements	Feasibility Shown	Future Work
FR 7.0	The system shall fly autonomously given a pre-programmed flight plan		Additional PixHawk simulations
FR 8.0	The system shall have the ability to switch between the GPS and GPS-denied flight modes within 1 second of RFI detection		Signal switch testing for Wi-Fi signals and simulations using previous data
FR 9.0	The system shall transmit data for all 6 degrees of freedom		Data transmission test and link margin
FR 10.0	The system shall create a profile of RF signal power	Free Space Loss Theory ✓	Create RF power Profile using past data
FR 11.0	The payload components shall be in a stable self-contained structure	Preliminary CAD Model and Talon Payload Analysis ✓	Full CAD model, structural and thermal analysis
FR 12.0	The payload shall have the ability to measure and localize an RFI source in GPS denied environments	PDOA Model ✓	PDOA simulations with past data

REFERENCES

[1].Chen, H., Lin, T., Kung, H. T., Lin, C., & Gwon, Y. (n.d.). Determining RF Angle of Arrival Using COTS Antenna Arrays: A Field Evaluation [Scholarly project]. In School of Engineering and Applied Sciences Harvard University. Retrieved September 29, 2017.

[2].EngineersGarage, "Microcontrollers," EngineersGarage Available: https://www.engineersgarage.com/microcontroller.

[3]. Grade, K., "Introduction to Inertial Navigation and Kalman Filtering," Navigation Laboratory, Jun. 2008.

[4].Zheng, L., & Xue, R. (2011). Signals of Opportunity Navigation Methods for Complex Lower Airspace Flight. *2011 IEEE 5th International Conference on Cybernetics and Intelligent Systems (CIS).*

[5]. *Jackson, B. R., Wang, S., and Inkol, R., "Emitter geolocation estimation using power difference of arrival ," An algorithm comparison for non-cooperative emitters , May 2011.*

REFERENCES

[6]. Arshal, George. "Error equations of inertial navigation", Journal of Guidance, Control, and Dynamics, Vol. 10, No. 4 (1987)

[7]. Goshen-Meskin, Drora and Itzhack Y. Bar-Itzhack. "Unified approach to inertial navigation system error modeling", Journal of Guidance, Control, and Dynamics, Vol. 15, No. 3 (1992)

[8]. Kallapur, Abhijit and Salman, Shaaban & Anavatti, S.G.. (2007). “Application of Extended Kalman Filter Towards UAV Identification”. Studies in Computational Intelligence. 76.

[9]. Taylor, John. (1997) “An Introduction To Error Analysis”.

[10]. Titterton, David H. and Weston, John L. (2004). “Strapdown Inertial Navigation Technology (2nd Edition)”. The Institution of Engineering and Technology.

[11]. https://itsallrc.wordpress.com/2014/02/19/how-to-calculate-drag/

[12]. http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node97.html

REFERENCES

[13]. Brain, M., “How Microprocessors Work,” How Microprocessors Work | HowStuffWorks Available: http://computer.howstuffworks.com/microprocessor.html

[14]. “Microcontroller Invention History - Who Invented first Microcontroller,” Electronic Circuits and Diagram-Electronics Projects and Design Available: http://www.circuitstoday.com/microcontroller-invention-history.

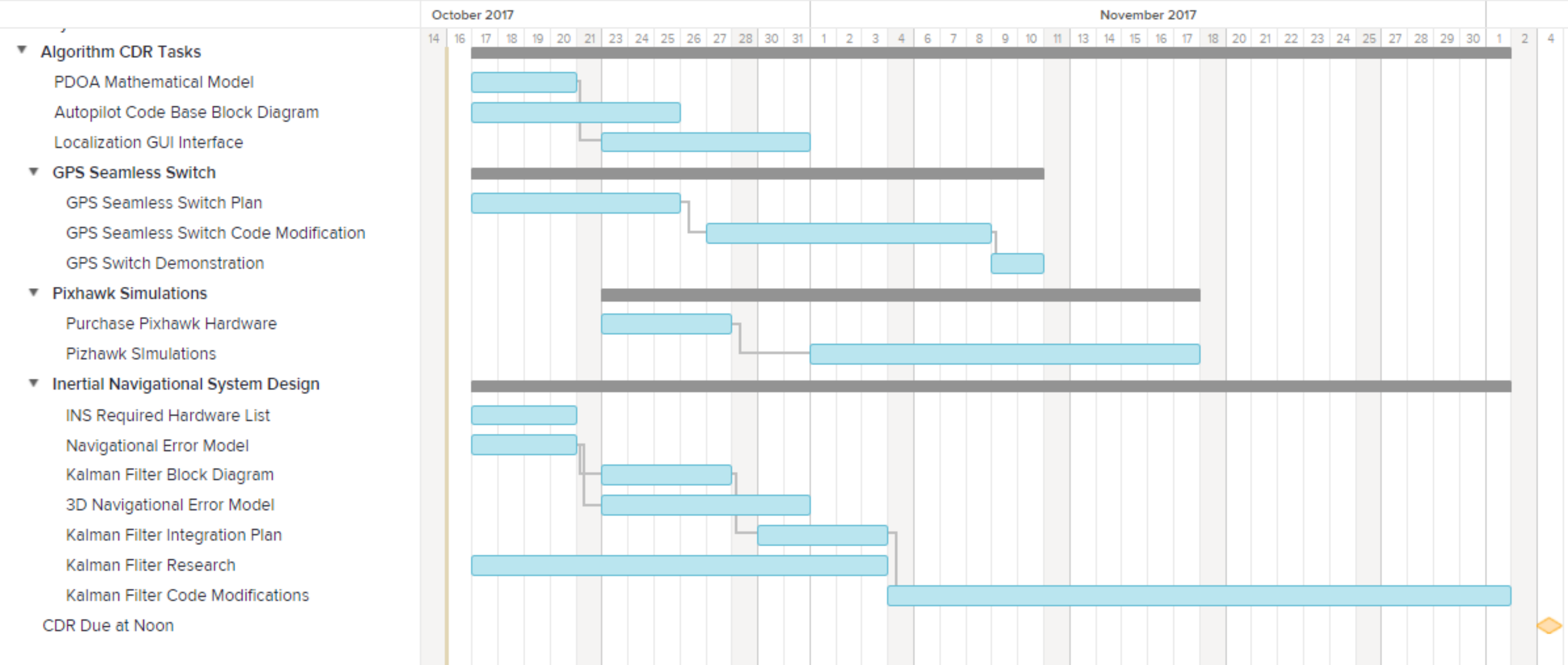
[15]. “What is a Microprocessor? How does it work?,” electroSome Available: https://electrosome.com/microprocessor/.

[16]. Wolf, M., Computers as components: principles of embedded computing system design, Amsterdam: Elsevier/Morgan Kaufmann, 2017.

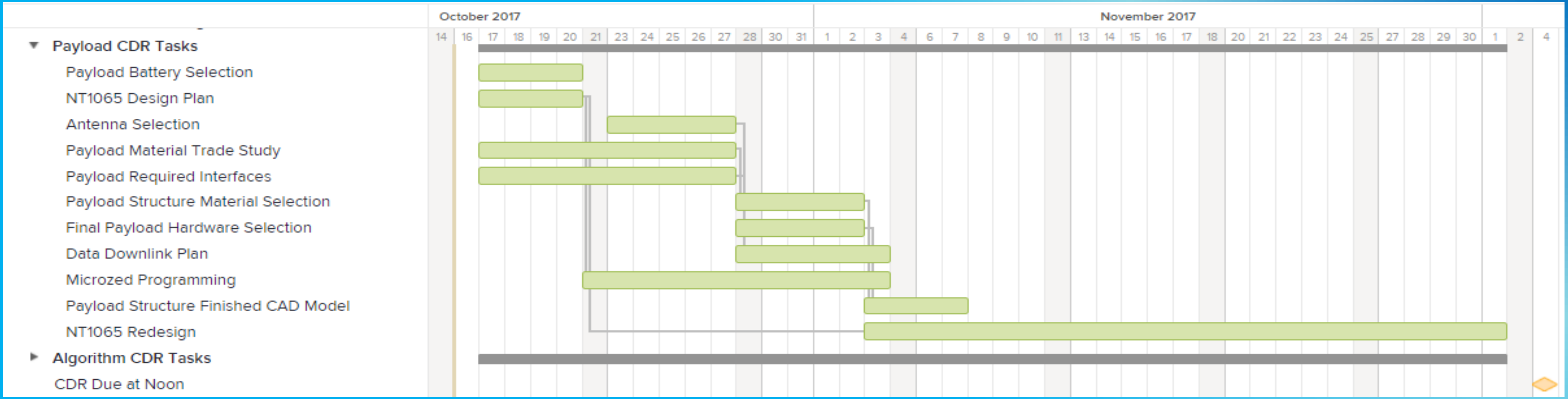
[17] Dixon, C., Integrated Remote and In Situ Sensing (IRISS)

BACK UP SLIDES

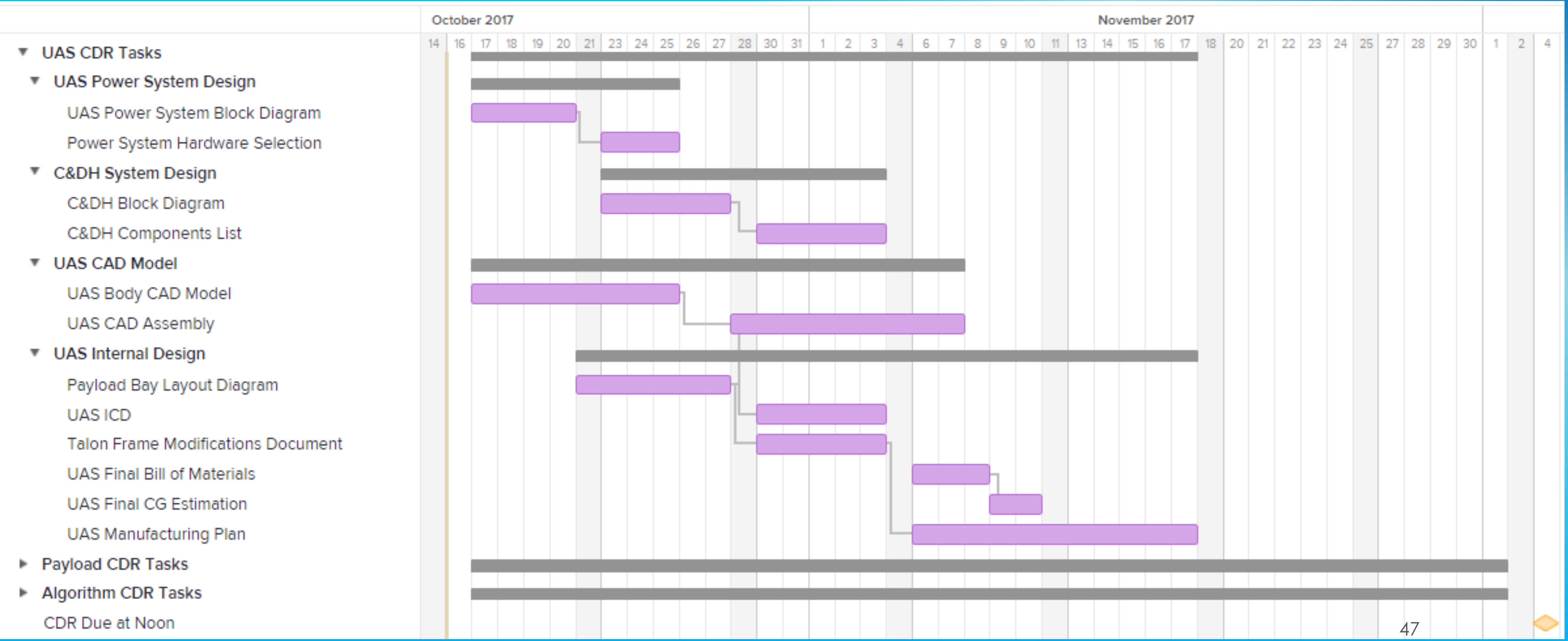
DETAILED FALL SCHEDULES



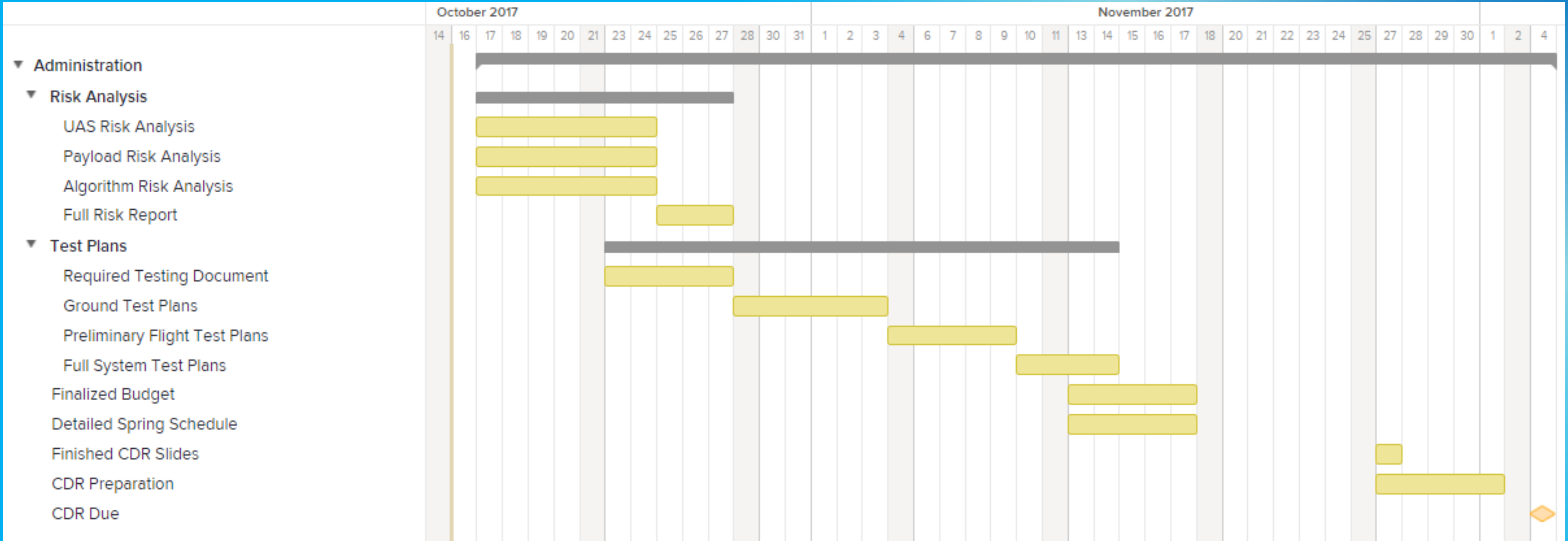
DETAILED FALL SCHEDULES



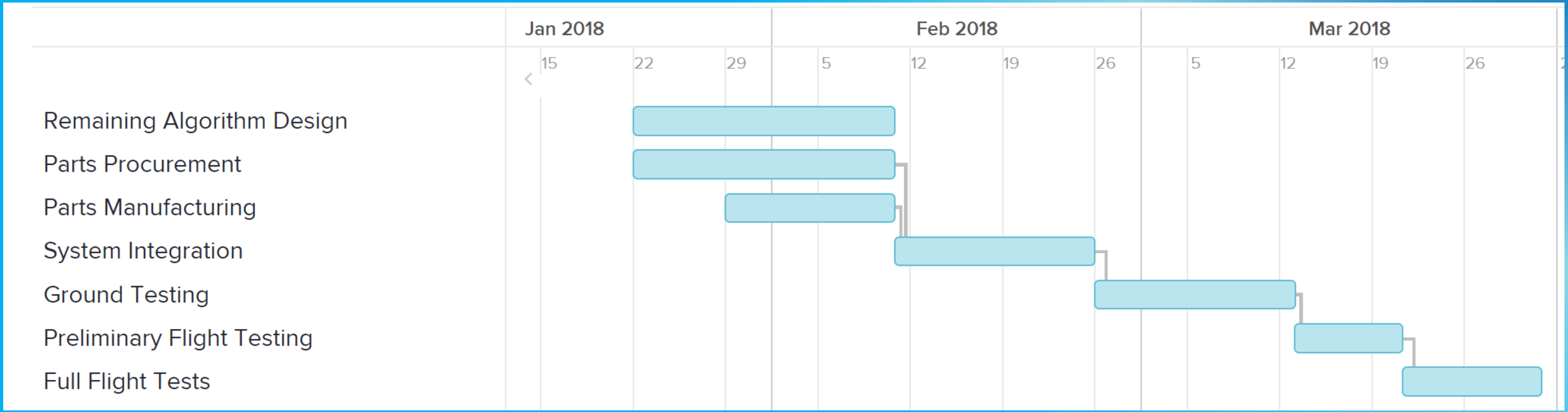
DETAILED FALL SCHEDULES



DETAILED FALL SCHEDULES



PRELIMINARY SPRING SCHEDULE



BUDGET BACKUP SLIDE

Item	System	Quantity	Total Price
Talon Airframe	UAS	1	$130
Pixhawk Px4	UAS	1	$150
7000mah LiPo	UAS	2	$200
INS	UAS	1	$1500
Motor	UAS	1	$70
Propeller	UAS	1	$5
ESC	UAS	1	$90
Camera	UAS	1	$60
Charger	UAS	1	$100

BUDGET BACKUP SLIDE

Item	System	Quantity	Total Price
Charger Case	UAS	1	$13
HS-5055 Servo	UAS	2	$36
HS-5065	UAS	2	$70
Reciever	UAS	1	$40
Wing Extension	UAS	1	$40
Microzed	Payload	1	$220
NT1065	Payload	1	$500
Aluminum Block	Payload	1	$50
LTE Modem	Payload	1	$200

BASELINE DESIGN

UAS PLATFORM

Multi-Rotor

Faults:

- Flight Times Under 1 Hour
- Payload Capacity too Small

Outdoor Blimp

Faults

- Poor Performance in adverse weather and High winds
- Expensive (Over $5000)
- High Maintenance and Launch Preparation

BASELINE DESIGN
UAS PLATFORM

Fixed-Wing

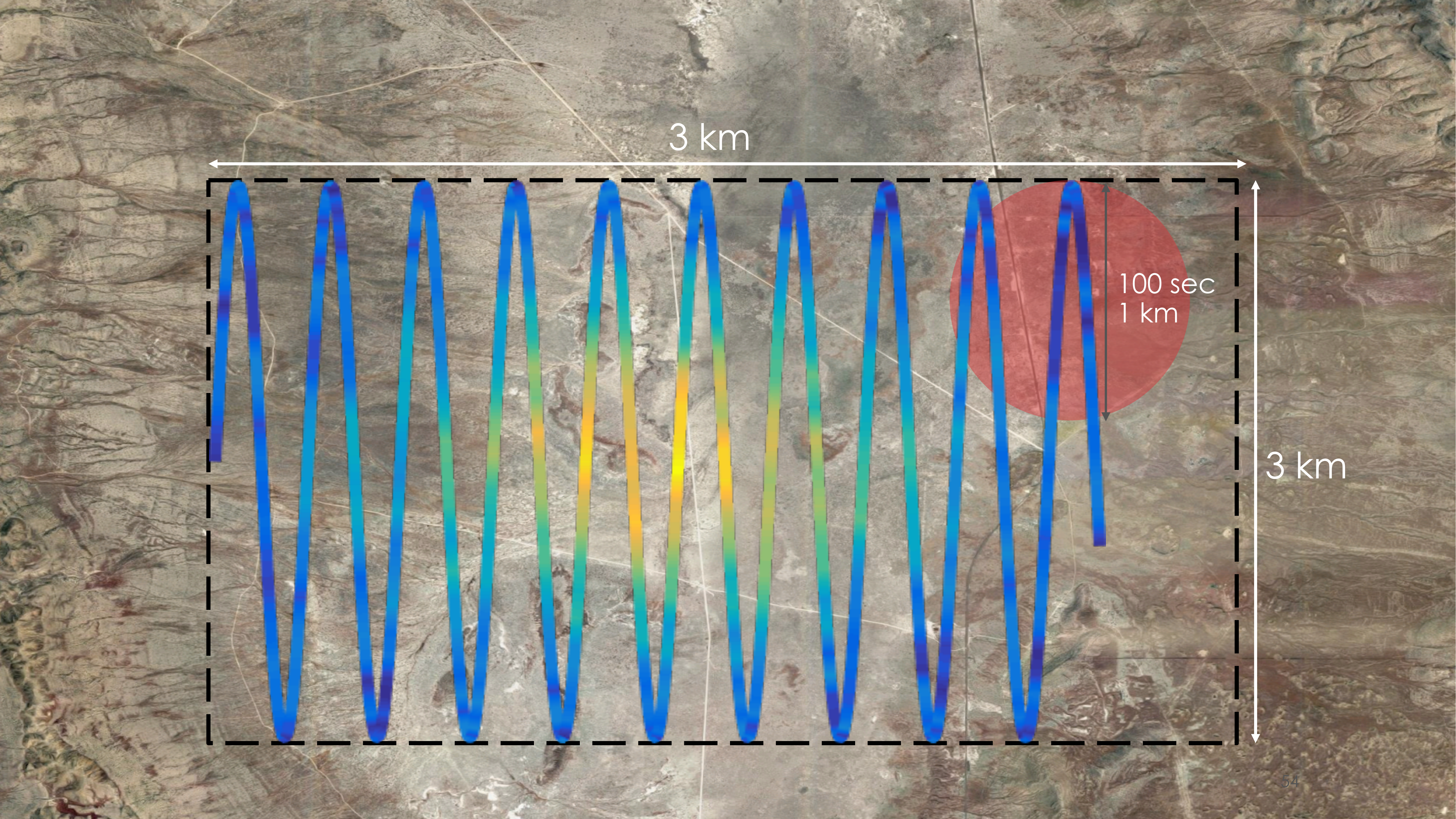
Capabilities:

- Over 1 hour of flight time
- High Payload Capacity
- Good Adverse Weather and High Wind Performance
- Cost effective and Low Maintenance
- Customer Approved



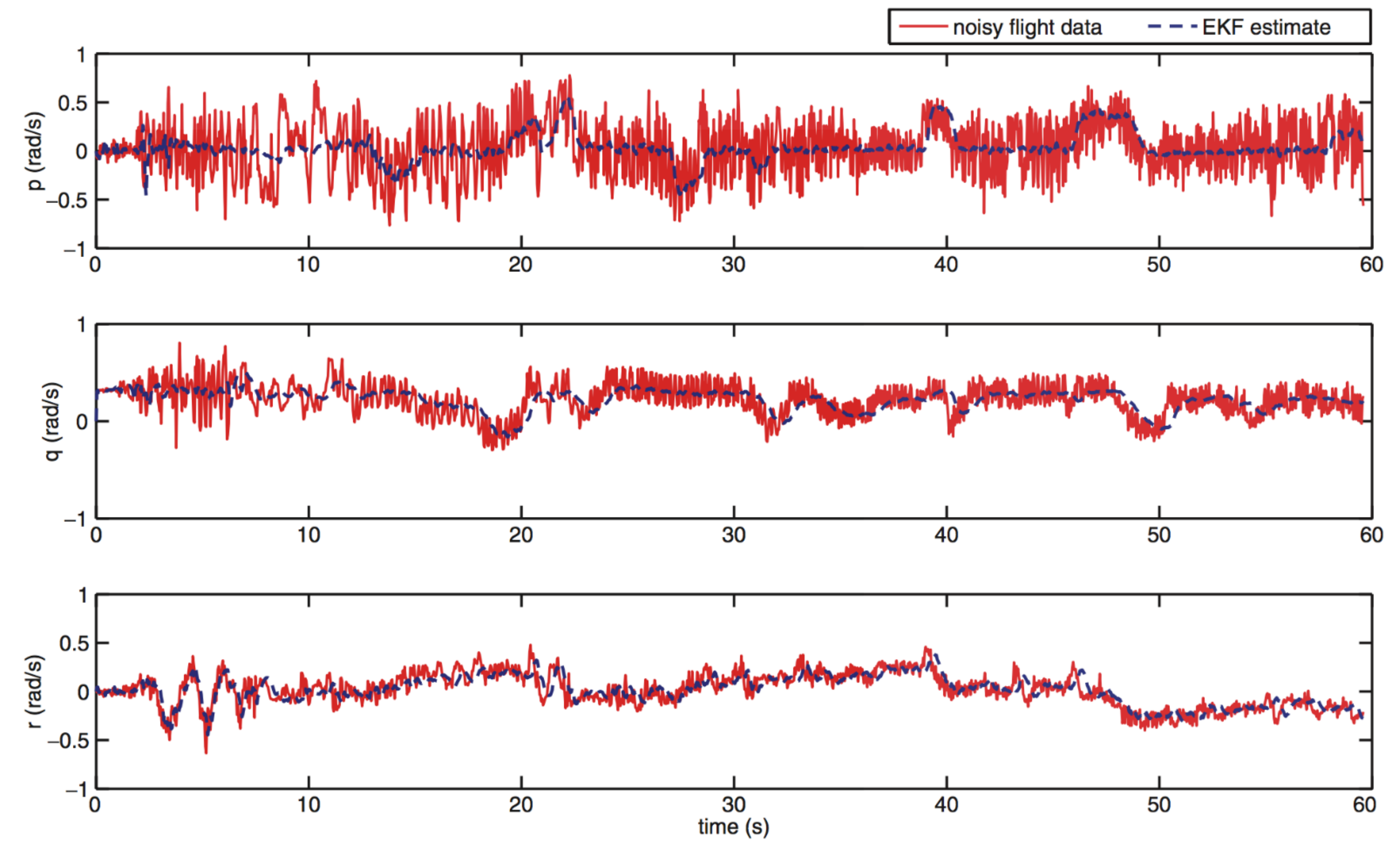

Type of fixed wings:

- Conventional
- V-tail
- Delta
- Dual Boom


3 km
100 sec
1 km
3 km

INERTIAL NAVIGATION
EXTENDED KALMAN FILTER

- EKF vs standard Kalman Filter
- Proven for a Pixhawk powered fixed-wing platform
- Increased state estimation accuracy
- Ability to integrate sensors in addition to the IMU (e.g. magnetometer, flow field, lidar, etc.)

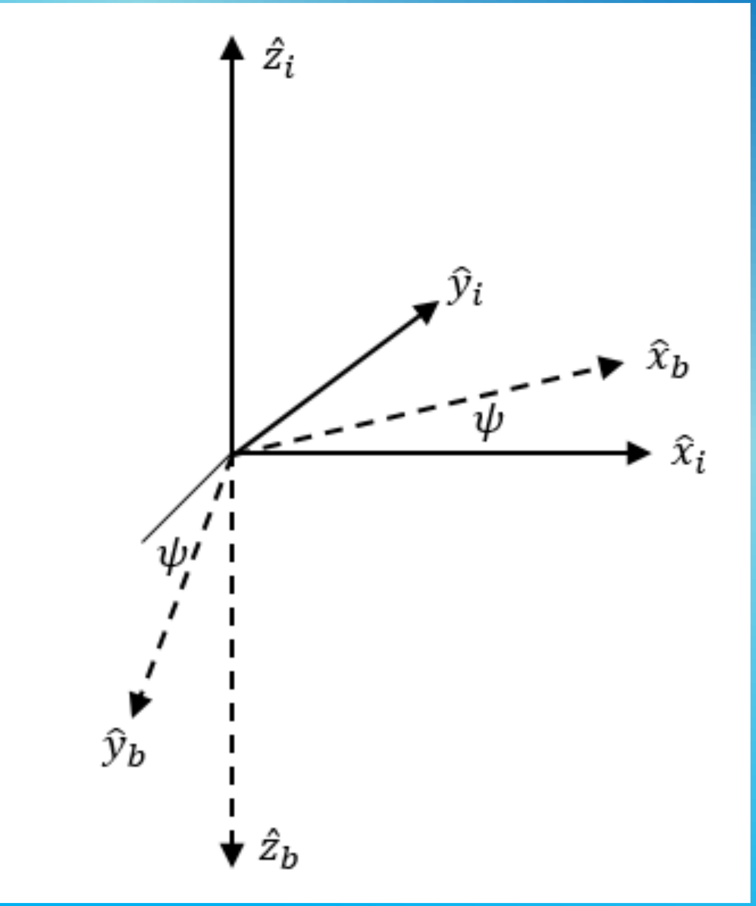


"Application of Extended Kalman Filter Towards UAV Identification."
Studies in Computational Intelligence

INS ERROR MODEL

- 2D Equations of Motion using IMU measurements*

$$\dot{\psi} = -\omega_{zb}$$
$$f_{xi} = f_{xb} \cos\psi + f_{yb} \sin\psi$$
$$f_{yi} = f_{xb} \sin\psi - f_{yb} \cos\psi$$
$$\dot{v}_{xi} = f_{xi}$$
$$\dot{v}_{yi} = f_{yi}$$
$$\dot{x}_i = v_{xi}$$
$$\dot{y}_i = v_{yi}$$



INS ERROR MODEL

- General uncertainty propagation of independent random errors in a function $q = f(x, \ldots, z)$

$$\delta q = \sqrt{\left|\frac{\partial q}{\partial x}\delta x\right|^2 + \cdots + \left|\frac{\partial q}{\partial z}\delta z\right|^2}$$

- Then let

$$\delta \boldsymbol{q} = \begin{bmatrix} \delta\psi \\ \delta v_{xi} \\ \delta v_{yi} \\ \delta x_i \\ \delta y_i \end{bmatrix}$$

INS ERROR MODEL

- Adapted EOM as uncertainties:

$$\delta\dot{\boldsymbol{q}} = \begin{bmatrix} \delta\dot{\psi} \\ \delta\dot{v}_{xi} \\ \delta\dot{v}_{yi} \\ \delta x_i \\ \delta y_i \end{bmatrix} = \begin{bmatrix} -\delta\omega_{zb} \\ \delta f_{xb}\cos\delta\psi + \delta f_{yb}\sin\delta\psi \\ \delta f_{xb}\sin\delta\psi - \delta f_{yb}\cos\delta\psi \\ \delta v_{xi} \\ \delta v_{yi} \end{bmatrix}$$

where,

$$\delta\omega_{zb} = G_{br} + G_{ir} + \frac{ARW}{2\sqrt{t}} \rightarrow \begin{matrix} G_{br} = Gyro\ bias\ repeatability\ [dps] \\ G_{ir} = Gyro\ in\ run\ bias\ [dps] \\ ARW = Angle\ random\ walk\ [\circ/\sqrt{s}] \end{matrix}$$

$$\delta f_{xb} = \delta f_{yb} = A_{br} + A_{ir} + \frac{VRW}{2\sqrt{t}} \rightarrow \begin{matrix} A_{br} = Acc.bias\ repeatability\ [\mathrm{g}] \\ A_{ir} = Acc.in\ run\ bias\ [g] \\ VRW = Velocity\ random\ walk\ [m/s/\sqrt{s}] \end{matrix}$$

INS ERROR MODEL

Derivation of the $\frac{ARW}{\sqrt{t}}$ and $\frac{VRW}{2\sqrt{t}}$ terms:

$$\delta\psi = \delta\psi + ARW \times \sqrt{t}$$
$$\frac{d\delta\psi}{dt} = \delta\dot{\psi} + \frac{1}{2} \times ARW \times t^{-\frac{1}{2}}$$
$$\Rightarrow \omega_z = G_{br} + G_{ir} + \frac{ARW}{2\sqrt{t}}$$

Similarly,

$$\delta v = \delta v + VRW \times \sqrt{t}$$
$$\Rightarrow \delta f = A_{br} + A_{ir} + \frac{VRW}{2\sqrt{t}}$$

INS ERROR MODEL

- Apply the general error propagation formula to the $\delta\dot{\boldsymbol{q}}$ equations, get:

$$\omega_{zb} = \sqrt{G_{br}^2 + G_{ir}^2 + \left(\frac{ARW}{2\sqrt{t}}\right)^2}$$

$$\delta\dot{v}_{xi} = \sqrt{[(\cos\delta\psi + \sin\delta\psi\,)A_{br}]^2 + [(\cos\delta\psi + \sin\delta\psi\,)A_{ir}]^2 + \left[(\cos\delta\psi + \sin\delta\psi\,)\frac{VRW}{2\sqrt{t}}\right]^2 + \left[\left(A_{br} + A_{ir} + \frac{VRW}{2\sqrt{t}}\right)(-\sin\delta\psi + \cos\delta\psi)\delta\psi\right]^2}$$

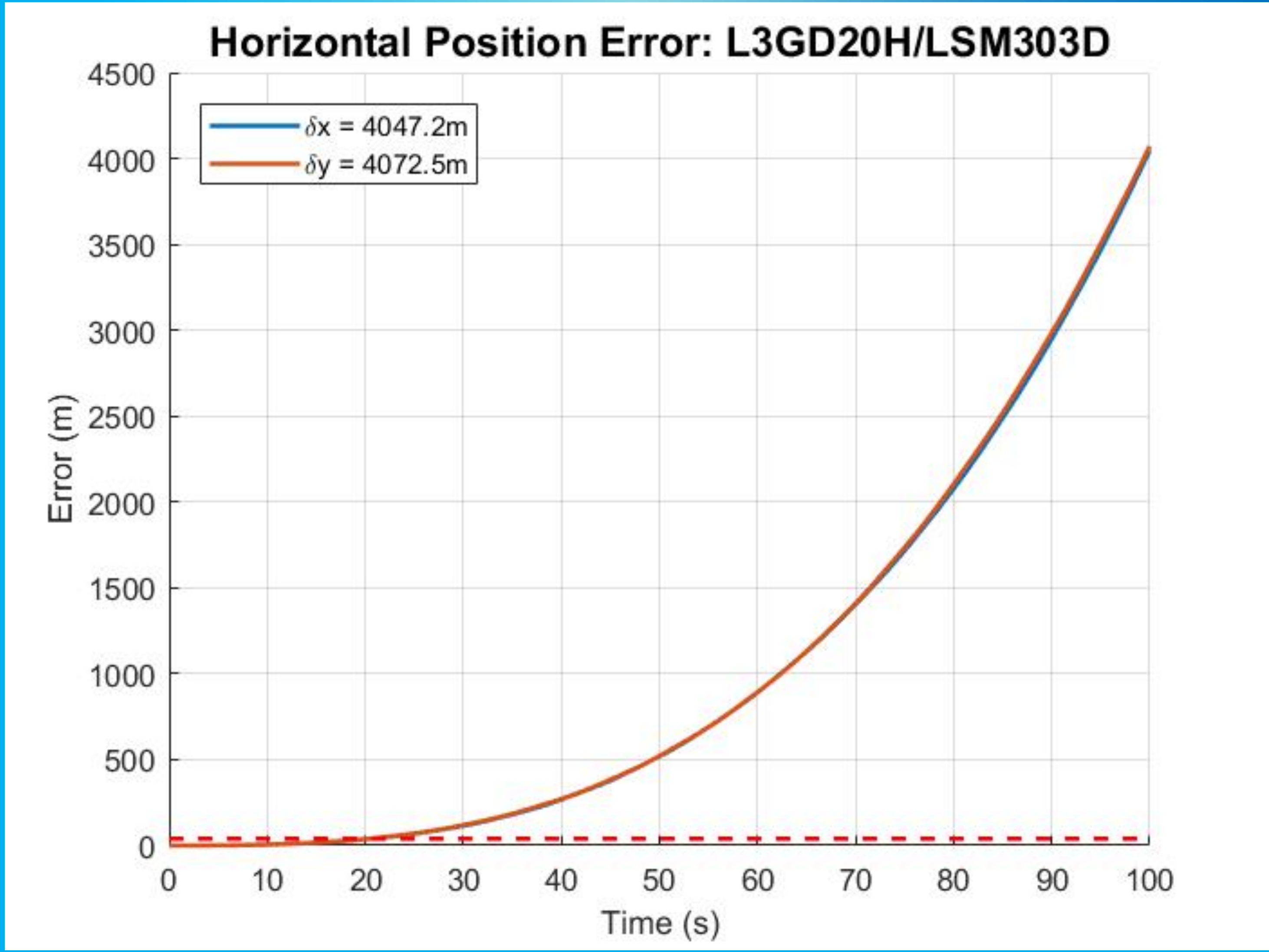
$$\delta\dot{v}_{xi} = \sqrt{[(\sin\delta\psi - \cos\delta\psi)A_{br}]^2 + [(\sin\delta\psi - \cos\delta\psi)A_{ir}]^2 + \left[(\sin\delta\psi - \cos\delta\psi)\frac{VRW}{2\sqrt{t}}\right]^2 + \left[\left(A_{br} + A_{ir} + \frac{VRW}{2\sqrt{t}}\right)(\cos\delta\psi + \sin\delta\psi)\delta\psi\right]^2}$$

$$\delta\dot{x}_i = \delta v_{xi}$$
$$\delta\dot{y}_i = \delta v_{yi}$$

These equations were then numerically integrated using ode45 in MATLAB to obtain characterization plots and total error values

INS ERROR MODEL

Pixhawk IMU
($2.01 – Gyro, $1.43 – Acc.)
$\delta x = 4015m, \delta y = 4034m$
$\delta p = 5742m$



INS TRADE STUDY

Metric	Weight	Driving Requirement	Rationale
Position Estimation Accuracy	0.25	**FR 8, DR 6.2, DR 3.2**	This metric is weighted highly at 0.25 because the accuracy of position estimates made by the GPS-denied flight algorithm is a critical element in creating a RFI profile. Since each RFI measurement must be associated with a location, it is desirable to have high accuracy in the estimations.
Component Cost	0.25	N/A	While there are no functional or design requirements dictating the budget for the GPS-denied guidance method, the variations in cost of the possible components associated with each method must be considered with regard to the overall project budget. Cost is weighted highly at 0.25 due to the generally expensive nature of other required components for project RAMROD.
Rate of Position Estimates	0.10	**DR 9.3, FR 8**	By producing position estimates at a higher rate, the UAS will be more likely to be capable of flying at higher speeds. Higher rates of position estimates will also result in a closer correlation to the RFI measurements in the case that position and RFI data are not synchronized. However, each method has a relatively high rate compared to standard GPS rates, therefore this metric is weighted lower at 0.10.

INS TRADE STUDY

Method Robustness	0.25	**DR 7.3, FR 3, DR 6.2.1, DR 6.2.2**	It is important that the GPS-denied guidance method is robust enough to function with minimal reliance or interfacing with external systems, components, or data. Dependence on external systems or components may subject the UAS to unwanted, additional sources of risk or error, which the team may be unable to properly mitigate. Furthermore, applications of this project may require operation in desolate or hostile territory, where it would be undesirable, or even impossible, to use external dependencies. Therefore, this metric is weighted at 0.25.
Processing Complexity	0.15	**DR 4.1**	The size of the processing unit, and thus its processing power, is restricted mostly by UAS payload size constraints and mass budget. The UAS must be capable of supporting all hardware and instrumentation, so a method requiring a large processing unit is undesirable. The team must also be able to use or write software which processes the data and computes the position estimations. While this metric is important, it isn't as critical as some of the others, hence a slightly lower weight of 0.15.

INS TRADE STUDY

Metric	1	2	3	4	5
Position Estimation Accuracy (m)	>200	150-200	100-149	50-99	0-49
Component Cost (USD)	>3000	2000-2999	1000-1999	100-999	<100
Rate of Position Estimates (Hz)	1-99	100-199	200-299	300-399	>400
Method Robustness	Dependent on additional systems	Much reliance on additional systems	Some reliance on additional systems	Minimal reliance on additional systems	Zero reliance on additional systems
Processing Complexity	Beyond scope	Complex	Moderate	Basic	Trivial

Metric	Weight	INS	LiDAR Based	LTE
Position Estimation Accuracy	0.25	3	5	2
Component Cost	0.25	3	1	4
Rate of Position Estimates (Hz)	0.10	5	3	1
Method Robustness	0.25	4	2	2
Processing Complexity	0.15	3	2	4
TOTAL	**1.0**	3.45	2.6	2.7

UAS SELECTION

TRADE STUDY

Metric	RV Jet	Skywalker	Tech Pod	Sky Hunter	Talon
Cost ($):	170	170	140	140	120
Max Payload (kg):	2	2.3	1	1.2	1
Payload Volume (mm^3):	175 x 170 x 70	300 x 150 x 70	200 x 80 x 70	N/A	500 x 100 x 80
Flight Duration (hr):	1	2	1.5	1.5	1.5
Cruise Speed (km/hr):	60	40	60	N/A	50
Max Speed (km/hr):	100	85	100	N/A	90

UAS SELECTION

TRADE STUDY - JUSTIFICATION

Metric:	1	2	3	4	5
Cost:	320	270	220	170	120
Max Payload:	1	1.33	1.65	1.98	2.3
Payload Volume:	1	1.75	2.5	3.25	4
Autopilot Compatibility:	Not Compatible	Delta Wing	Dual Boom	V-tail	Conventional
Spare Part Availability:	No Spare Parts	Limited Under $100	Limited Under $50	All Parts under $100	All Parts under $50
Flight Duration:	1 Hours	1.25 Hours	1.5 Hours	1.75 Hours	2 Hours
Complexity of Frame:	4+ Hour Assembly	Less Than 4 Hour Assembly	Less Than 3 Hour Assembly	Less Than 2 Hour Assembly	Less Than 1 Hour Assembly
Adverse Weather Performance:	Less than 50 kph max speed	50 kph max speed and below 3 kg	50 kph max speed and above 3 kg	90 kph max speed and below 3 kg	90 kph max speed and above 3 kg
IRISS Support:	Not Supported	N/A	N/A	N/A	Supported

UAS TRADE STUDY

Metric:	Weights	Skywalker x8	Talon	Sky Hunter	RV Jet	Tech Pod
Cost:	0.2	4.00	5.00	4.60	4.00	4.60
Max Payload:	0.1	5.00	2.54	1.62	4.08	1.00
Payload Volume:	0.1	3.76	2.96	1.00	5.00	1.00
Autopilot Compatibility:	0.15	2.00	4.00	3.00	2.00	5.00
Spare Part Availability:	0.1	4.00	3.00	2.00	5.00	1.00
Flight Duration:	0.05	5.00	1.67	1.00	1.00	2.33
Complexity of Frame:	0.05	5.00	4.00	1.00	4.00	3.00
Adverse Weather Performance:	0.1	4.00	3.00	3.00	3.00	2.50
IRISS Support:	0.15	1.00	5.00	1.00	1.00	1.00
Totals:	1	3.43	3.78	2.38	3.21	2.64

MULTI-ROTOR SPECIFICATIONS

Proprietary

Flight Time	55 Minutes
Battery	Lithium Silicon
Frame	Carbon Composite
Payload Capacity	None

Home Built

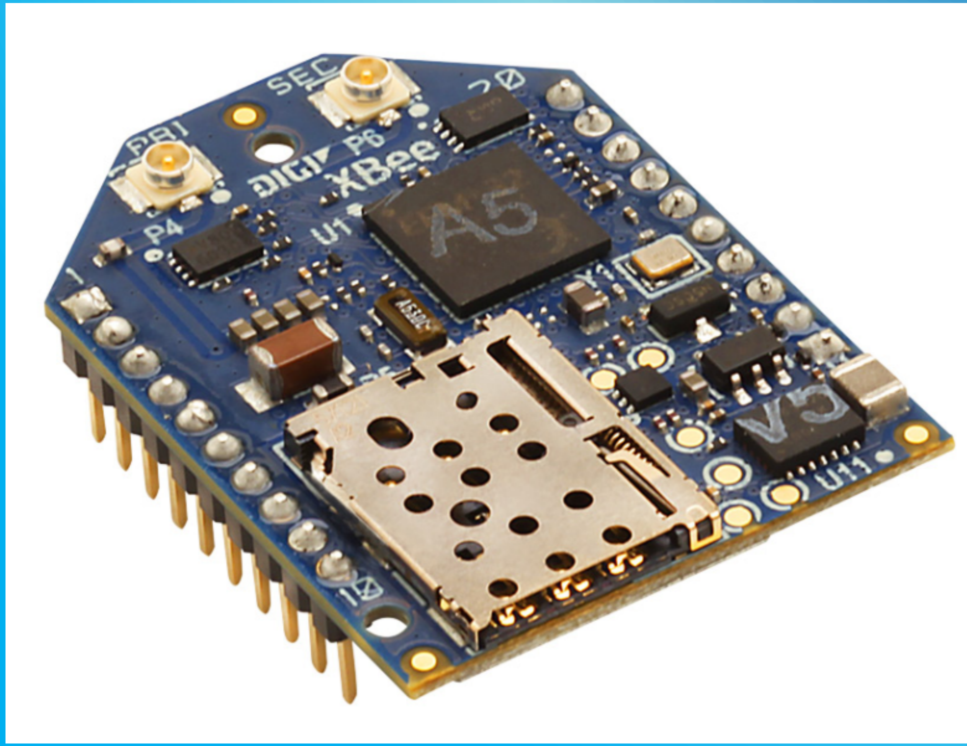
Flight Time	2 hours
Battery	Lithium Ion
Frame	Aluminum
Payload Capacity	None

BLIMP SPECIFICATIONS

Flight Time	**1 Hour**
Battery	Lithium Polymer
Frame	Polyurethane envelope and Helium Filled
Payload Capacity	2 kg
Cost	$5510
Weather Performance	Under 15 kph winds

LTE MODEM

- Used for transmitting IF data to the ground from the payload.
- Still in the process of doing research to pick one out.
- Digi XBee Cellular LTE Cat 1 is a possible modem suggested by the customer.

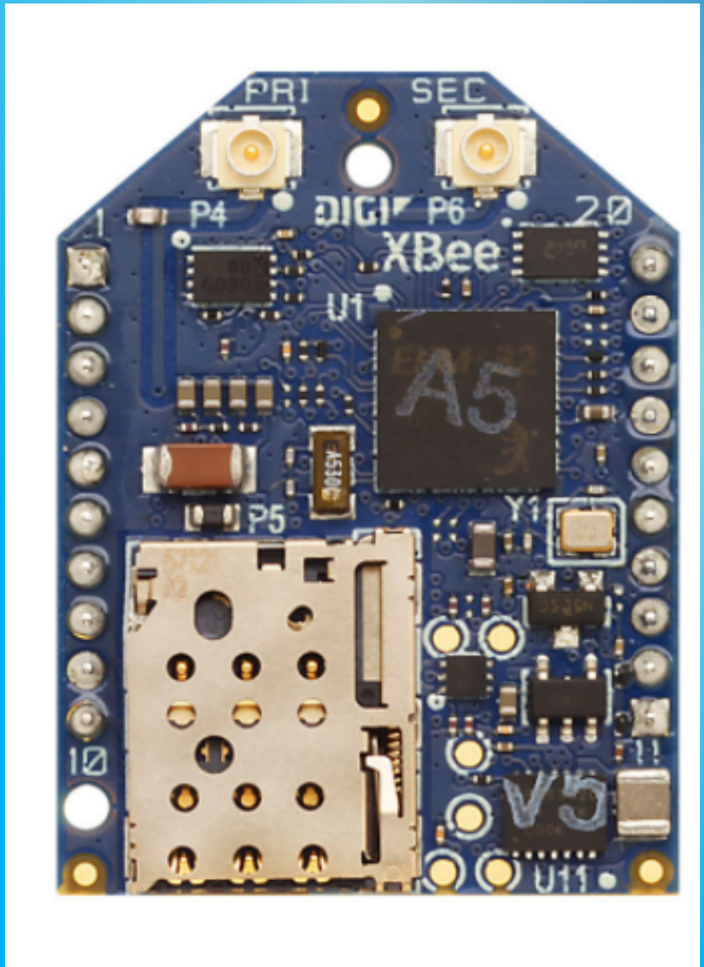


SPECS ON THE DIGI XBEE CELLULAR LTE MODEM

- UART, 921 kbps
- 4 ADC Lines
- 15 GPIO Lines
- Programmable with 24KB RAM. 8KB Flash
- Can add external antenna
- Transmit Power at 23 dBm
- Receive Sensitivity at -102 dBm

SPECS ON THE DIGI XBEE CELLULAR LTE MODEM

- Deep Sleep Mode draws 10 UA
- Supply Voltage 3.3-5.5V
- Transmit Current around 530 mA at 3.3V



MICROPROCESSOR PROS AND CONS

Pros

- High Clock Speed
- Easily Programmable
- Low Power Consumption
- Small in size

Cons

- More expensive than a microcontroller
- External Components
- Cannot be used in compact systems

MICROCONTROLLER PROS AND CONS

Pros

- Small in size
- Reduced cost
- Low power consumption
- Can be used in compact systems
- Power save mode
- Open source

Cons

- Lower clock speed
- Limited I/O
- Limited code space

MICROCONTROLLER VS MICROPROCESSOR TRADE STUDY

Metric	Weight	Driving Requirement	Rational
Clock Speed	0.2	**FR 9.0, DR 9.3, DR 9.5, DR 9.5.1, DR 9.5.2, FR 7**	The board chosen must have a speed high enough to complete all necessary calculations and give correct outputs before the next set of measurements is made (less than 1 second)
Ease of Use	0.2	N/A	It is important to have a board that can be easily modified for changing algorithms and the language used must be easy to understand by the members of the sub-system
Programmability	0.2	**FR 9.0, DR 9.3, DR 9.5, DR 9.5.1, DR 9.5.2**	The board's code must be easily changeable based on changes made to both the localization and flight algorithm
Memory, RAM, ROM, I/O	0.1	**FR 9.0, DR 9.3, DR 9.5, DR 9.5.1, DR 9.5.2**	The board chosen must have enough memory and RAM to store all required data for an entire test, which will last at least an hour

MICROCONTROLLER VS MICROPROCESSOR TRADE STUDY CONTINUED

Metric	Weight	Driving Requirement	Rational
Memory, RAM, ROM, I/O	0.1	**FR 9.0, DR 9.3, DR 9.5, DR 9.5.1, DR 9.5.2**	The board chosen must have enough memory and RAM to store all required data for an entire test, which will last at least an hour
Power Required	0.1	**DR 11.2.1**	The operational payload must have a lifespan of 24 hours, so every component must have the smallest power consumption possible
Overheat Temperature	0.1	**DR 10.5**	Since there is so many electrical components inside the payload structure it is likely that high temperatures could be an issue. A higher operating temperature range of the board components allows for more design flexibility of the structure and reduces the odds of overheating during testing

MICROCONTROLLER VS MICROPROCESSOR TRADE STUDY RESULTS

- Microcontroller will be chosen based on the results of the trade study.
- MCU is cheaper than an MPU.
- MPUs are faster on their own, but with external components, they are slower than an MCU.

Metric	Weight	MCU	MPU
Clock Speed	0.2	3	5
Ease of Use	0.3	5	3
Programmability	0.2	5	1
Memory, RAM, ROM, I/O	0.1	3	5
Power Required	0.1	4	5
Heat generated	0.1	3	5
TOTAL	1.0	4.2	3.2

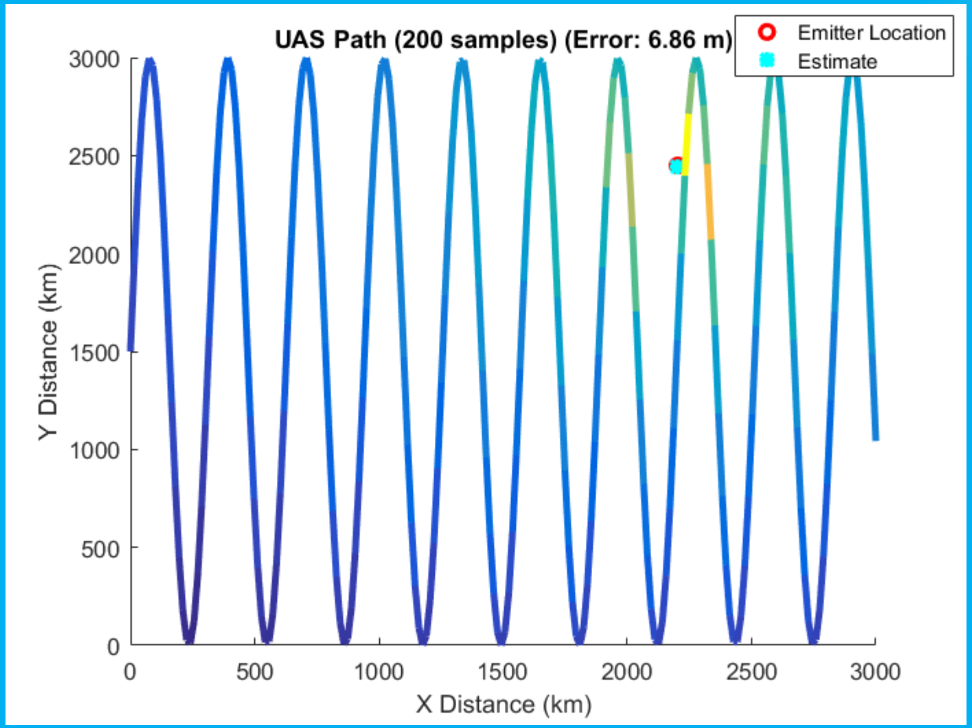
MICROCONTROLLER VS MICROPROCESSOR TRADE STUDY RESULTS

- MCUs are easier to use than an MPU.
- All MCUs are programmable.
- Not all MPUs are programmable.
- Stand alone, MPUs use less power than an MCU, but when the additional components are added it tends to use more power than an MCU.

Metric	Weight	MCU	MPU
Clock Speed	0.2	3	5
Ease of Use	0.3	5	3
Programmability	0.2	5	1
Memory, RAM, ROM, I/O	0.1	3	5
Power Required	0.1	4	5
Heat generated	0.1	3	5
TOTAL	1.0	4.2	3.2

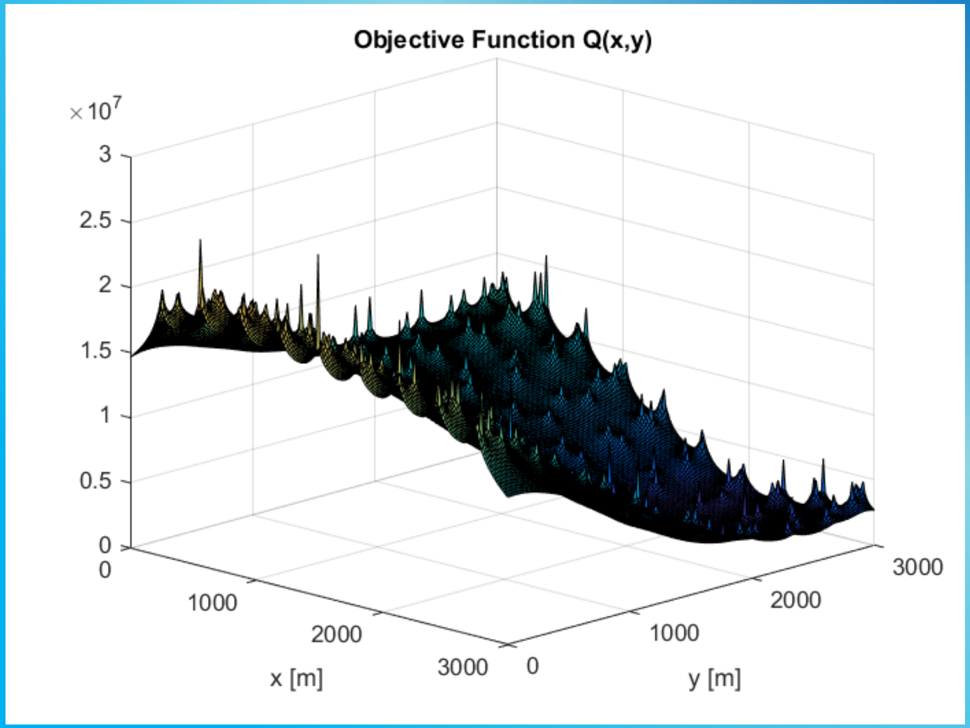
EVIDENCE OF FEASIBILITY: METHOD

ALGORITHM– LOCALIZATION USING PDOA



Simulated trajectory of UAS with +/- 10 meter random error in location measurements

In this example, 200 samples are taken along the UAS path, giving an estimation error of only 6.86 meters.



Objective function provides a likelihood for each (x,y) coordinate on the grid

The coordinate that minimizes this function is where the algorithm estimates as the RFI source location

NONLINEAR LEAST-SQUARES

CURVE-FITTING

- The distance to the receiver can be estimated using nonlinear least-squares curve fitting. If we assume an unknown transmitter location at position (x,y) on a finite search grid, we can use the free space loss principle from the previous slide. The space loss coefficient $\boldsymbol{\alpha}$ is determined by obstructions and ground reflections in the environment.

$$P_{12} = P_1 - P_2 = 10\alpha \log_{10}\left(\frac{d_2}{d_1}\right) \Rightarrow P_{12} = 5\alpha \log_{10}\left[\frac{(x-x_2)^2 + (y-y_2)^2}{(x-x_1)^2 + (y-y_1)^2}\right]$$

- The objective function Q measures the difference between the actual measured power between two grid points and the predicted power difference between two grid points.

$$Q(x,y) = \sum_{k<l}\left[\bar{P}_{kl} - 5\alpha \log_{10}\left[\frac{(x-x_l)^2 + (y-y_l)^2}{(x-x_k)^2 + (y-y_k)^2}\right]\right]^2,$$

- The (x,y) grid point where the objective function Q is minimized is the estimated transmitter location

LINEAR LEAST-SQUARES

CURVE-FITTING

- In order to reduce computation time for localization, the objective function Q can be linearized by comparing every measurement to the very first measurement.
- The following equation can be solved analytically for point (x,y,z) assuming that the power measurement and corresponding grid coordinates are known.

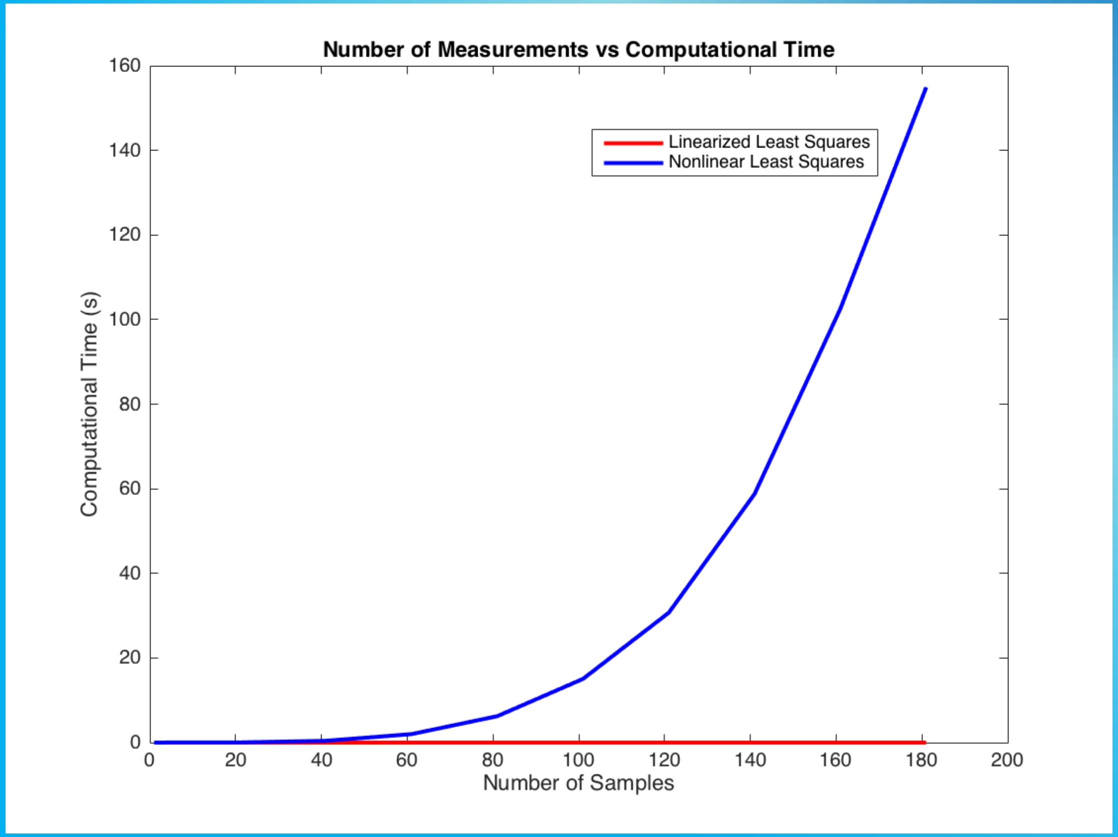
$$2(x_l - x_1)x + 2(y_l - y_1)y + \left(P_l^{-\frac{2}{\alpha}} - P_1^{-\frac{2}{\alpha}}\right)z = r_l^2 - r_1^2, \qquad 1 < l \leq N,$$

- Where index *l* defines every grid location that the UAS travels through and every power measurement taken

COMPUTATIONAL TIME COMPARISON

LINEAR VS NONLINEAR LEAST SQUARES

- The final algorithm will most likely need to evaluate hundreds of times more samples
- 300 samples brought computational time up to over an hour for the nonlinear model, and MATLAB became unresponsive when the simulation was run with 100,000 samples.



SIGNAL ATTENUATION IN FREE SPACE

- The path-loss for a given environment can be approximated by:

$$D^{-\alpha}$$

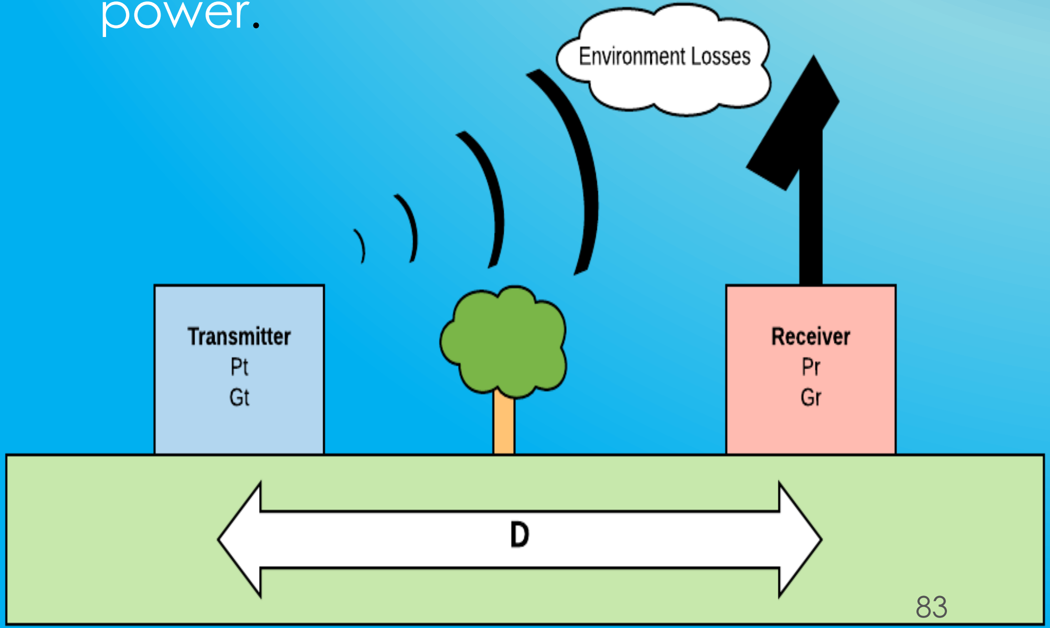
Where **α** is the path-loss exponent.

- Ideally, signal intensity decreases proportional to the inverse square of distance between transmitter and receiver in three-dimensional space. (**α** = -2)

- Factors such as noise interference, ground reflection, obstacles, and imperfect antenna gains can increase signal attenuation.

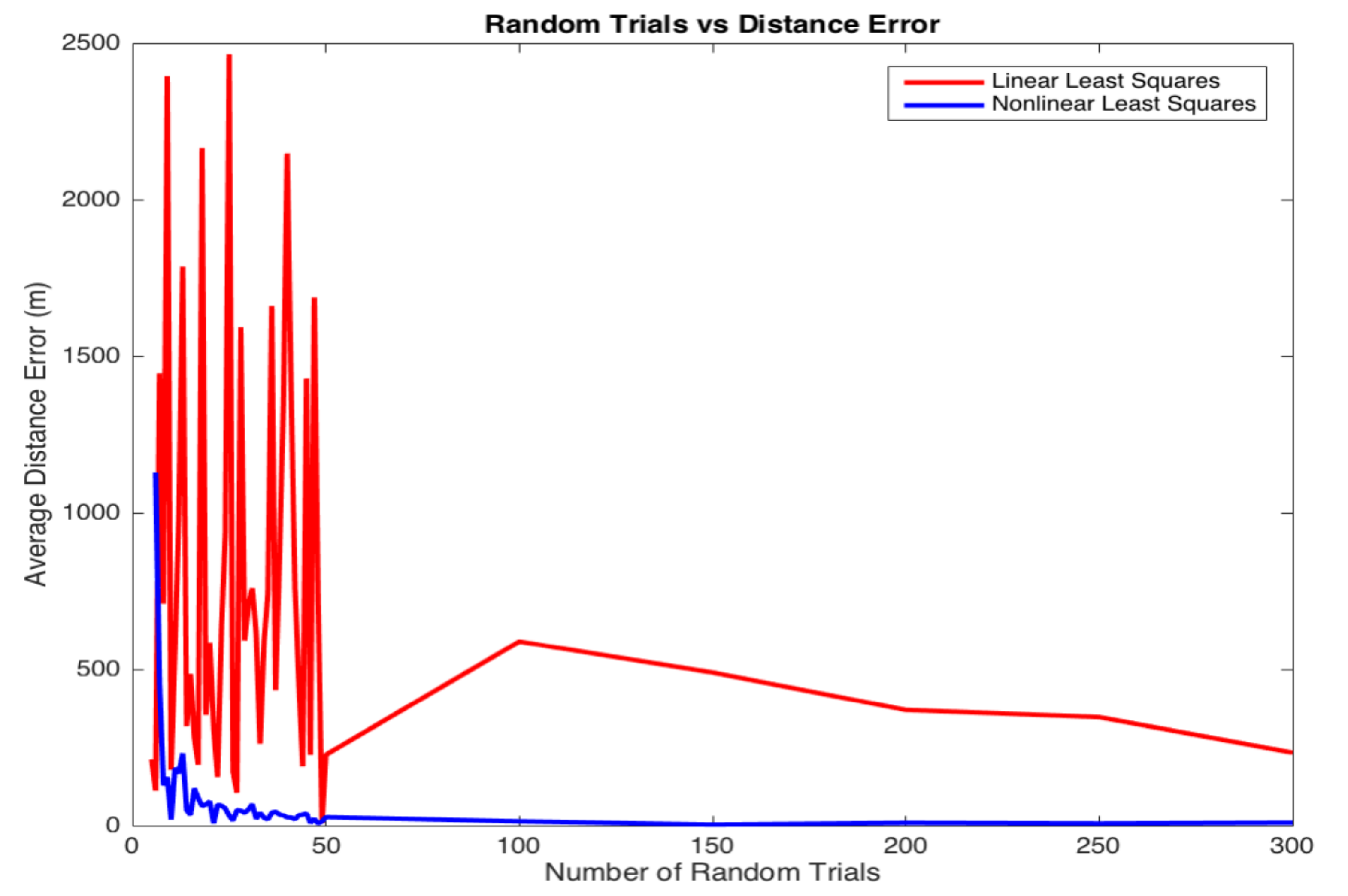
$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi)^2 D^{-\alpha} L}$$

α can be determined by measuring actual signal attenuation in the test environment with known transmitter/ receiver locations and known transmitter signal power.



LOCALIZATION ACCURACY

- Localization Accuracy is shown here for both the linear and nonlinear model
- The linear model is highly inaccurate at low number of trials
- The nonlinear model is very accurate even at low sample numbers



AUTOPILOT TRADE STUDY

METRICS

Table 1: Metrics for Autopilot Trade Study

Metric	Weight	Driving Requirements	Description and Rationale
Open-source	0.3	**DR 6.2**, **DR 7.1**	Extensive modifications will be required to support flying without GPS, and the autopilot software must be able to integrate with these changes. Using a 'black box' will increase the difficulty of modifying the code.
Safety Features	0.1	**DR 6.2**, **FR 5**	The UAS must have certain failsafes, allowing the UAS to be operated safely, minimizing unnecessary risks, and complying with all FAA regulations.
Software Complexity	0.2	**DR 6.2**, **DR 7.1**, **DR 8.1**	Support from community or manufacturer will be crucial to the success of the project, so choosing an autopilot with available resources will be advantageous. Many of the modifications will be difficult to implement, and it is crucial for the team to be able to understand and modify the code base.
Telemetry/ Sensor Capability	0.2	**DR 7.1**, **DR 7.2**	In order to fly without access to GPS data, the software must be able to interface with multiple IMUs and antennae, allowing for communication with a ground station and sensing where the UAS is when there is no reliable data.
Cost of compatible hardware	0.2	**Budget**	The project must be within budget.

AUTOPILOT TRADE STUDY

METRICS AND RESULTS

Table 2: Explanation of Metrics

Metric	1	2	3	4	5
Open-source	Open source	N/A	Not open-source but readily modifiable	N/A	Open-source and readily modifiable
Safety Features	0 elements of: (Geofencing, Failsafe processor, Loss of signal, Obstacle avoidance)	1 element	2 elements	3 elements	4 elements
Software Complexity	Written in languages not known to any team members	N/A	N/A	N/A	Written in C/ C++/ MATLAB throughout
Telemetry / Sensor Capabilities	Cannot interface with any external hardware	Can interface with camera	Can interface with antenna	Can interface with IMUs and antennae	Can interface with any necessary IMUs, antennae, optical flow sensors, etc.
Cost of compatible hardware	Prohibitively expensive ($500+)	Very expensive ($300 - $500)	Moderately expensive ($100 - $300)	Inexpensive (< $100)	Free

Table 3: Trade Study Results: Autopilot

Metric	Weight	MicroPilot	PX4	ArduPilot	Disco
Open-source	0.30	5	5	5	1
Safety Features	0.10	5	4	4	3
Software Complexity	0.20	3	5	5	1
Telemetry/ Sensor Capabilities	0.20	5	5	5	3
Cost of Hardware	0.20	1	3	4	5
TOTAL	**1.0**	3.7	4.5	4.7	2.4

LOCALIZATION TRADE STUDY METRICS AND RESULTS:

Table 22. Localization Method: Trade Study Metrics

Metric	1	2	3	4	5
Design Simplicity (hours)	Impossible	200-300	100-199	50-99	49 >
Potential Localization Accuracy	Cannot Localize	Extremely Susceptible to Noise	Some Noise Interference	Hardly Susceptible to Noise	Not Susceptible to Noise
Hardware Cost/ Requirement	>$800	$400-$799	$300-$499	$150-$299	$0-$149
Power Measurement Capability	NOT Power Sensor Capable	N/A	N/A	N/A	Power Sensor Capable
Ability to Interface with UAS and Payload	Impossible to Integrate	Difficult to Integrate	Possible to Integrate	Easy to Integrate	Highly Compatible

Table 23. Trade Study Results: Localization Method

Metric	Weight	TDOA	AoA	PDOA	Triangulation
Design Simplicity	0.20	5	2	5	2
Potential Localization Accuracy	0.10	3	4	3	4
Hardware Requirement/Cost	0.25	4	1	5	1
Power Measurement Capability	0.20	5	5	5	1
Ability to Interface with UAS and Payload	0.25	2	2	5	1
TOTAL	**1.0**	3.80	2.55	4.80	1.50

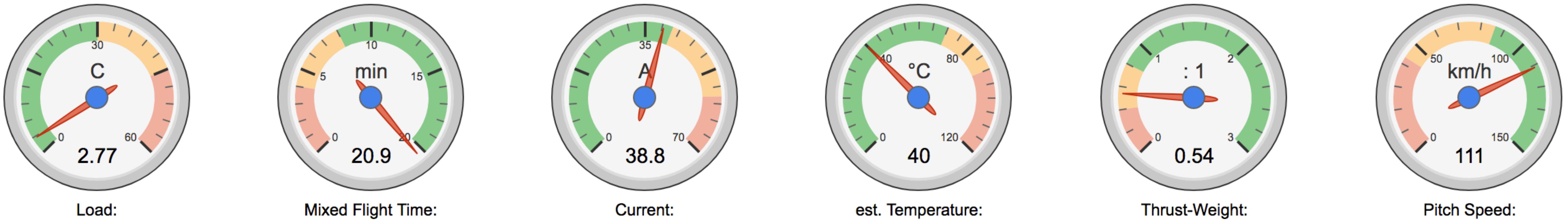
LOCALIZATION TRADE STUDY

Table 21. Considerations and Weighting for Localization Method Trade Study

Consideration	Weight	Driving Requirement	Rationale
Design Simplicity	0.20	**DR 9.4**	Design simplicity has large implications for on-board processor power required and design time for the localization algorithm. The hardware available for use with the algorithm is limited by payload design requirements, and simplicity would allow for integration with the payload hardware and UAS software, which is stated in DR 9.4.
Localization Accuracy	0.10	**DR 9.2.1**	The accuracy of location is important for the success of the project, however, there are many methods that will provide high accuracy with many other drawbacks. DR 9.2.1 states the necessity of signal localization, and the degree of accuracy
Hardware Requirement/-Cost	0.25	N/A	The cost of hardware is a consideration for this method because different methods of localization require different hardware interface. It is stated that the algorithm must utilize hardware from the payload only, so additional hardware will add cost and mass to the payload design.
Power Measurement Capability	0.20	**DR 7.2, 9.3**	Design Requirement 9.3 states that the localization algorithm must create a power profile of the signal source. The localization method must also support power measurements, preferably with no extra hardware requirements.
Ability to Interface with UAS and Payload	0.25	**DR 9.1, DR 9.4, DR 9.5**	The algorithm will be designed for use with the UAS system and payload, and must be able to integrate with hardware and software that is available and compatible with the payload and UAS.

RECUV Talon eCalc Screenshots

General	Model Weight: 3500 g / 123.5 oz – incl. Drive	# of Motors: 1 (on same Battery)	Wing Area: 54.5 dm² / 844.8 in²	Drag: coeffcient 0.027 Cd	Cross Section: 8.1 dm² / 125.6 in²	Field Elevation: 1609 m ASL / 5280 ft ASL	Air Temperature: 21 °C / 70 °F	Pressure (QNH): 900 hPa / 26.58 inHg
Battery Cell	Type (Cont. / max. C) - charge state: LiPo 14000mAh - 30/45C - normal	Configuration: 3 S 1 P	Cell Capacity: 1400(mAh / 1400(mAh total	max. discharge: 85%	Resistance: 0.001 Ohm	Voltage: 3.7 V	C-Rate: 30 C cont. / 45 C max	Weight: 844 g / 29.8 oz
Controller	Type: CC Phoenix Edge HV 80	Current: 80 A cont. / 80 A max	Resistance: 0.001 Ohm	Weight: 125 g / 4.4 oz	Wire extension battery: AWG10=5.27mm²	Length: 0 mm / 0 inch	Wire extension motor: AWG10=5.27mm²	Length: 0 mm / 0 inch
Motor	Manufacturer - Type (Kv) - Cooling: E-flite - Power 25B (1250) / medium / search...	KV (w/o torque): 1250 rpm/V / Prop-Kv-Wizard	no-load Current: 2 A @ 10 V	Limit (up to 15s): 58 A	Resistance: 0.02 Ohm	Case Length: 54 mm / 2.13 inch	# mag. Poles: 14	Weight: 183 g / 6.5 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 10 inch / 254 mm	Pitch: 6 inch / 152.4 mm	# Blades: 2	PConst / TConst: 1.08 / 1.0	Gear Ratio: 1 : 1	Flight Speed: 0 km/h / 0 mph	calculate



RECUV Talon eCalc Screenshots

Remarks:

Battery

Load:	2.77	C
Voltage:	10.96	V
Rated Voltage:	11.10	V
Energy:	155.4	Wh
Total Capacity:	14000	mAh
Used Capacity:	11900	mAh
min. Flight Time:	18.4	min
Mixed Flight Time:	20.9	min
Weight:	2532	g
	89.3	oz

Motor @ Optimum Efficiency

Current:	31.49	A
Voltage:	10.96	V
Revolutions*:	12418	rpm
electric Power:	345.0	W
mech. Power:	301.5	W
Efficiency:	87.4	%

Motor @ Maximum

Current:	38.80	A
Voltage:	10.92	V
Revolutions*:	12176	rpm
electric Power:	423.8	W
mech. Power:	369.4	W
Efficiency:	87.2	%
est. Temperature:	40	°C
	104	°F

Wattmeter readings

Current:	38.8	A
Voltage:	10.96	V
Power:	425.2	W

Propeller

Static Thrust:	1884	g
	66.5	oz
Revolutions*:	12176	rpm
Stall Thrust:	1216	g
	42.9	oz
avail.Thrust @ 0 km/h:	1884	g
avail.Thrust @ 0 mph:	66.5	oz
Pitch Speed:	111	km/h
	69	mph
Tip Speed:	583	km/h
	362	mph
specific Thrust:	4.45	g/W
	0.16	oz/W

Total Drive

Drive Weight:	3124	g
	110.2	oz
Power-Weight:	123	W/kg
	56	W/lb
Thrust-Weight:	0.54	: 1
Current @ max:	38.80	A
P(in) @ max:	430.7	W
P(out) @ max:	369.4	W
Efficiency @ max:	85.8	%
Torque:	0.29	Nm
	0.21	lbf.ft

Airplane

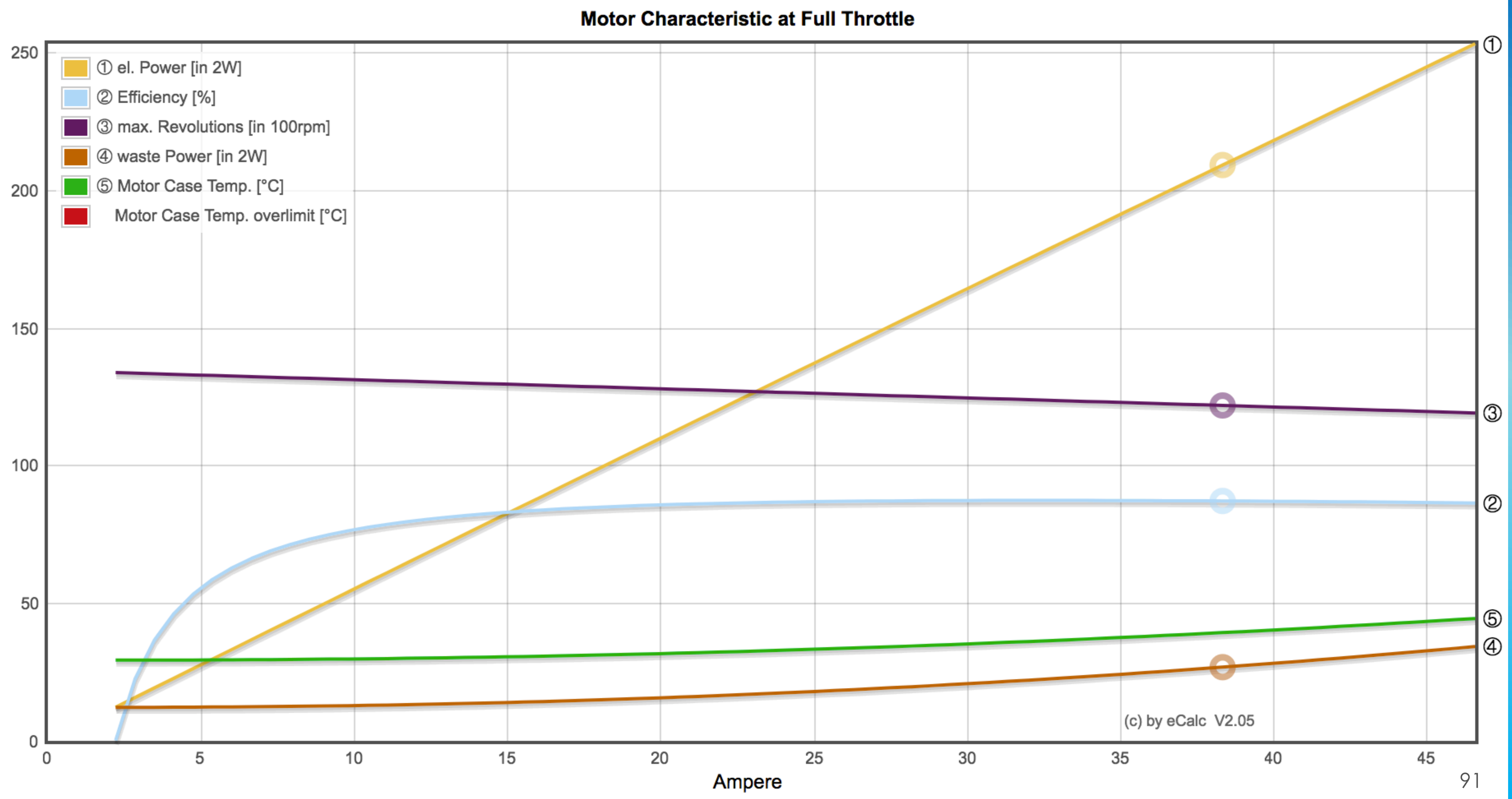
All-up Weight:	3500	g
	123.5	oz
Wing Load:	64	g/dm²
	21	oz/ft²
Cubic Wing Load:	8.7	
est. Stall Speed:	43	km/h
	27	mph
est. Speed (level):	102	km/h
	63	mph
est. Speed (vertical):	-	km/h
	-	mph
est. rate of climb:	5.8	m/s
	1135	ft/min

share add to >> Download .csv (0) << clear

Motor Partial Load

Propeller	Throttle	Current (DC)	Volage (DC)	el. Power	Efficiency	Thrust		Spec. Thrust		Pitch Speed		Speed (level)		Motor Run Time
rpm	%	A	V	W	%	g	oz	g/W	oz/W	km/h	mph	km/h	mph	(85%) min
1800	14	0.3	11.1	3.1	38.4	41	1.5	13.3	0.47	16	10	-	-	2549.5
2700	21	0.6	11.1	7.0	57.5	93	3.3	13.2	0.47	25	15	-	-	1130.9
3600	28	1.2	11.1	13.7	69.4	165	5.8	12.0	0.42	33	20	-	-	575.7
4500	35	2.2	11.1	24.3	76.6	257	9.1	10.6	0.37	41	26	-	-	325.0
5400	42	3.6	11.1	39.8	80.9	371	13.1	9.3	0.33	49	31	-	-	198.7
6300	49	5.5	11.1	61.1	83.6	504	17.8	8.3	0.29	58	36	-	-	129.2
7200	57	8.1	11.1	89.4	85.3	659	23.2	7.4	0.26	66	41	55	34	88.2
8100	64	11.4	11.1	125.8	86.4	834	29.4	6.6	0.23	74	46	68	42	62.6
9000	72	15.6	11.0	171.3	87.0	1029	36.3	6.0	0.21	82	51	75	47	45.9
9900	**80**	**20.7**	**11.0**	**227.0**	**87.4**	**1245**	**43.9**	**5.5**	**0.19**	**91**	**56**	**83**	**52**	**34.6**
10800	**88**	**26.8**	**11.0**	**294.2**	**87.5**	**1482**	**52.3**	**5.0**	**0.18**	**99**	**61**	**91**	**56**	**26.6**
11700	96	34.2	11.0	374.0	87.5	1739	61.4	4.7	0.16	107	66	98	61	20.9
12176	100	38.8	11.0	423.8	87.2	1884	66.4	4.4	0.16	111	69	102	63	18.4

RECUV Talon eCalc Screenshots

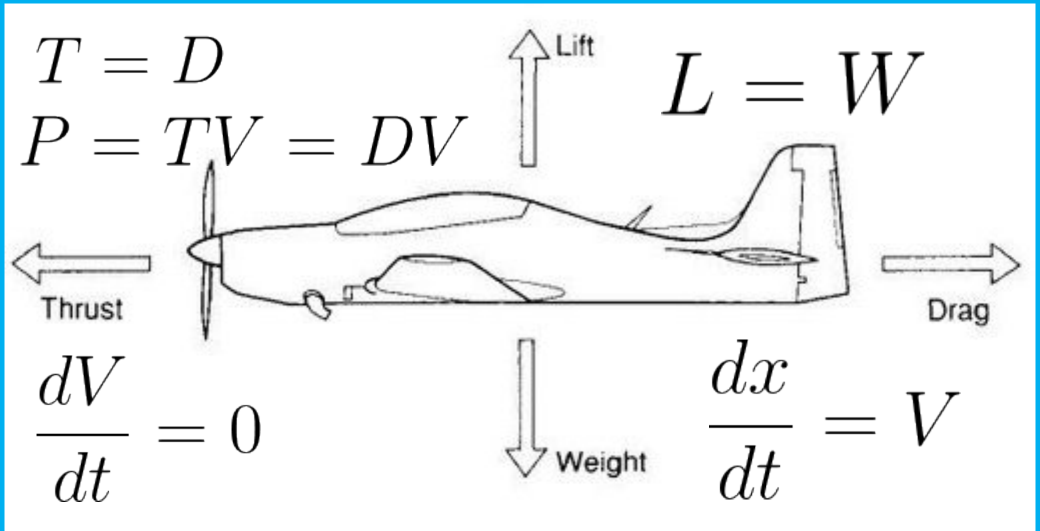


UAS Model

Foundational Questions

1. Can the selected UAS platform achieve a 60-minute flight time? Which airframes can/can't?
2. What is the upper limit of endurance for our UAS platform?
3. How can we optimize for minimum power consumption onboard the UAS?
4. How much will the UAS weigh given airframe and electronics? How heavy does the battery need to be? How much power is required?

UAS Model - Overview



Assumptions
E = 63 min (inc. 5% buffer)
Worst-case headwind is 10 m/s
Steady, level flight throughout
Battery discharge depth is 85%
Overall system efficiency is 85%

UAS Model - Overview

Equations	Quantity [Units]
$m_b = \frac{C_b}{\sigma}$	Battery Mass [kg]
$W = g(m_e + m_{elec} + m_{fp} + m_b)$	Total Weight [N]
$C_{D,0} = \sum_{i=1}^{N} k_i c_{f_i} S_{wet_i} / S_{ref}$	Parasite Drag Coefficient [none]
$P_{flight} = \frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V}\left(\frac{1}{\pi e b^2}\right)$	Power Required For Steady, Level Flight [W]
$P_{true} = \frac{P_{flight}}{\eta_{overall}}$	Propulsion System Power Required for Steady, Level Flight [W]
$E = 3600\eta_{overall}\frac{V_b D_b C_b}{P_{flight}}$	Endurance [s]

UAS Model - Overview

Name	Variable	Value
Density	ρ [kg/m^3]	1.047
Wing Area	S [m^2]	0.545
Wingspan	*b [m]*	1.718
Efficiency Factor	e [%]	80
Propulsive Efficiency	$\eta_{overall}$ [%]	85
Battery Discharge Depth	D_b [%]	85
Endurance	E [min]	63
Capacity Density	σ [mAh/kg]	16600
Battery Voltage	V_b [V]	11.1

Still Need to Determine:

Name	Variable
Velocity	V [m/s]
True Power Req'd	P_{true} [W]
Parasite Drag Coeff.	$C_{D,0}$ *[none]*
Battery Weight	W_b [N]
Total Weight	W [N]
Total Drag	D [N]

UAS Model

$$P_{flight} = TV = DV$$

$$P_{flight} = V(\frac{1}{2}\rho V^2 S)(C_{D,0} + \frac{C_L^2}{\pi e AR})$$

$$C_L = \frac{W}{\frac{1}{2}\rho V^2 S}$$

$$P_{flight} = \frac{1}{2}\rho V^3 S\left(C_{D,0} + \frac{W^2}{(\frac{1}{2}\rho V^2 S)^2}\left(\frac{1}{\pi e AR}\right)\right)$$

$$P_{flight} = \frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi e AR}\right)$$

$$P_{flight} = \frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V}\left(\frac{1}{\pi e b^2}\right)$$

$$P_{true} = \frac{P_{flight}}{\eta_{overall}}$$

Can find $V_{min,PR}$ by setting $\frac{\partial P_{flight}}{\partial V} = 0$

$$\frac{\partial P_{flight}}{\partial V} = 0 = \frac{3}{2}\rho V^2 S C_{D,0} - \frac{W^2}{\frac{1}{2}\rho V^2}\left(\frac{1}{\pi e AR}\right)$$

$$V_{min,PR} = \left[\frac{4}{3}\left(\frac{W}{S}\right)^2\left(\frac{1}{\rho^2 C_{D,0}}\right)\left(\frac{1}{\pi e AR}\right)\right]^{\frac{1}{4}}$$

UAS Model

Parameters

<u>Well-Known Parameters</u>

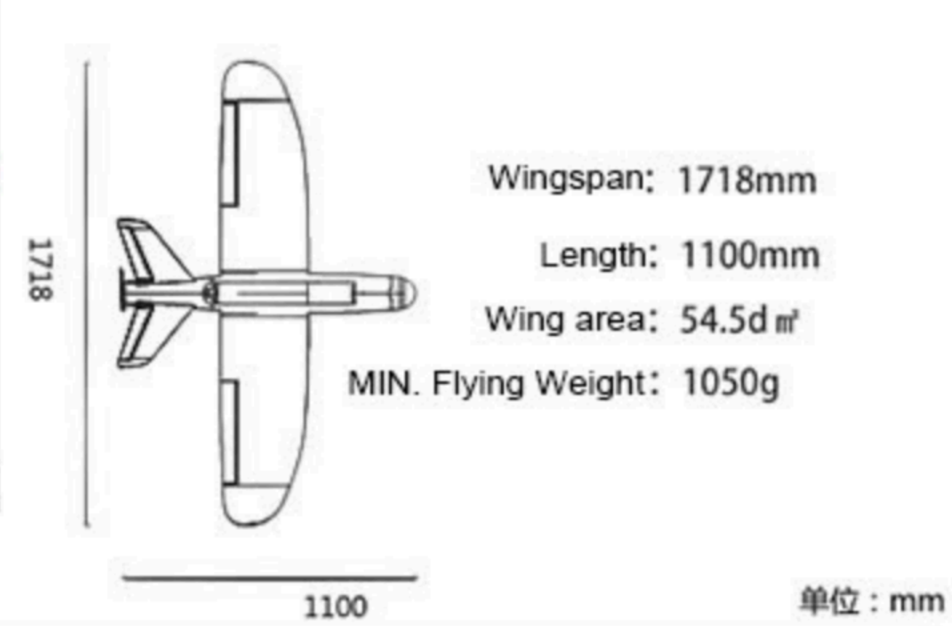
- S - Wing Area (given by manufacturer, easy to measure)
- AR - Wing Aspect Ratio (easy to measure b (wing span) and then calculate)
- W - Total Weight (easy to measure on a scale)
- E - Endurance (easy to measure with a timer)

<u>Unknown Parameters, Fairly Easy to Measure</u>

- ρ - Air Density (Take temp + pres measurements)
- V - Airspeed (use total + static pressure from pitot tube measurement)

<u>Unknown Parameters, Difficult to Measure</u>

- CD,0 - Parasitic Drag Coefficient (difficult to estimate and measure)
- e - wing efficiency factor (difficult to measure/estimate)



UAS Model

Most Impactful Parameters

<u>Which</u> parameters will have the largest impact upon the Power Required (and hence endurance?)

- *V* -> V^3 in first term, 1/V in second term (Which terms will dominate for given airframes? How much effect does a given velocity increase have on required power?)
- *W* -> W^2 in second term (how much of a power increase is required for a given weight increase?)
- *b* -> $1/b^2$ in second term (does increasing wingspan (also increases weight) produce an appreciable decrease in required power?)
- η - Overall efficiency of the propulsion system could be extremely low

Less important parameters

- $C_{D,0}$ - wide range of values, could significantly impact power required

Drag Buildup

Drag Buildup

$$C_{D,0} = \sum_{i=1}^{N} k_i c_{f_i} S_{wet_i} / S_{ref}$$

k is form factor
c_f is skin friction coefficient
S_{wet} is wetted area
$N = 3$ (wing, fuselage, tail)
$S_{ref} = S_{wing}$

$$c_f = \frac{0.455}{(\log_{10}(Re_L))^{2.58}}$$

$$Re_L = \frac{\rho V L}{\mu}$$

$$k = 1 + 2(t/c) + 60(t/c)^4$$ Wing and Tail

$$k = 1 + 1.5(d/l)^{1.5} + 7(d/l)^3$$ Fuselage

$$S_{wet} = 2(1 + 0.2(t/c))S_{ref}$$ Wing and Tail

$$S_{wet} = 2\pi(d/2)^2 + \pi d l$$ Fuselage

$$C_{D,0} = C_{D,0,wing} + C_{D,0,fuselage} + C_{D,0,tail}$$

RECUV Talon Drag Buildup Screenshots from Excel

Design Conditions	
Speed [m/s]	15 m/s
Altitude [m]	1609
Density [kg/m^3]	1.047
Crud Factor	0.28
Viscosity [Pa-s]	0.00001754

Wing Properties	
MAC [m]	0.3175
t/c	0.1192
b [m]	1.718
S [m^2]	0.545
Swet [m^2]	1.071

Fuselage Properties	
d [m]	0.143
l [m]	1.1
Swet [m^2]	0.526

Tail Properties	
c_r [m]	0.197
c_t [m]	0.114
t/c	0.122
b [m]	0.273
N_fins	2
Swet [m^2]	0.174

Plane Properties	
AR	5.41564037
e	0.8
CL	
W [N]	32.8
eta	0.85

RECUV Talon Drag Buildup Screenshots from Excel

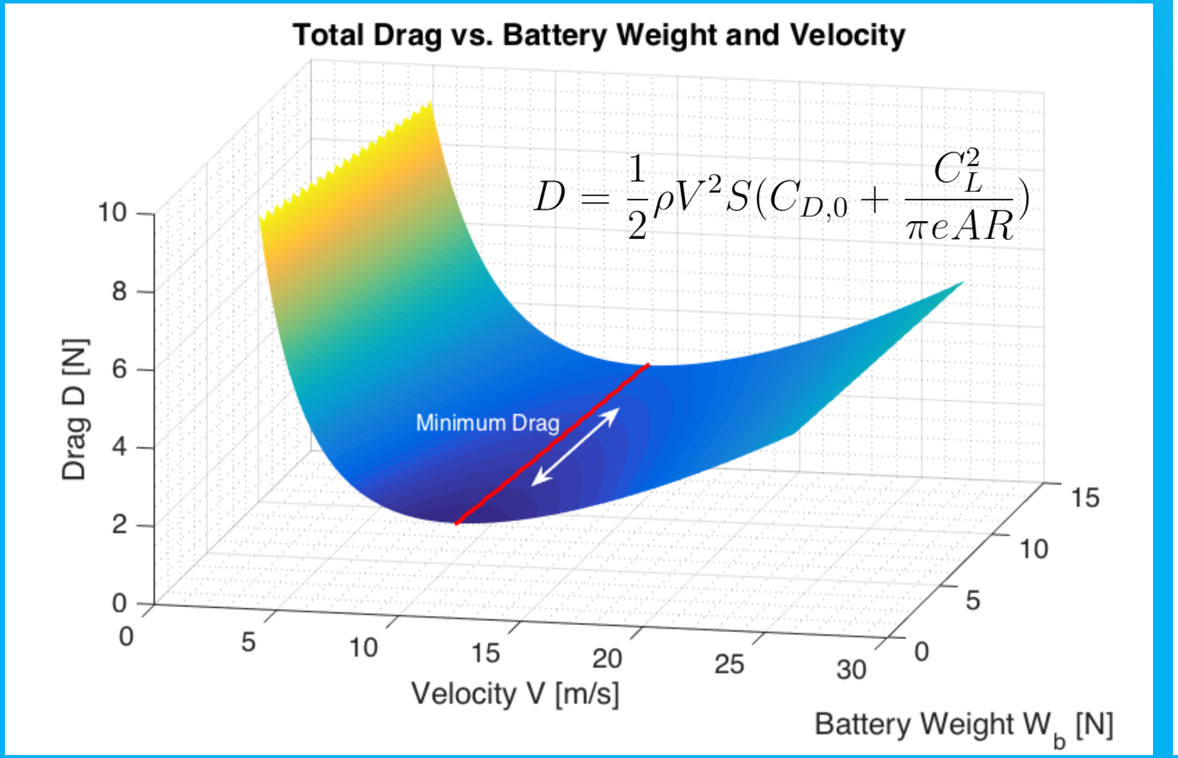
Velocity [m/s]	Velocity [KTAS]	Wing Re	Wing Cf	Wing FF	Wing f	Wing C_D0	Fuselage Re	Fuselage Cf	Fuselage FF	Fuselage f	Fuselage C_D0
0	0.00	0.0	#NUM!	1.25051313	#NUM!	#NUM!	0	#NUM!	1.08568725	#NUM!	#NUM!
1	1.94	18952.3	0.01070284	1.25051313	0.01433431	0.0263015	65661.3455	0.00787727	1.08568725	0.004501	0.008258707
2	3.89	37904.5	0.00898046	1.25051313	0.01202753	0.0220689	131322.691	0.00673687	1.08568725	0.00384938	0.00706309
3	5.83	56856.8	0.00814731	1.25051313	0.01091169	0.0200215	196984.036	0.00617387	1.08568725	0.00352769	0.006472828
4	7.78	75809.0	0.00761995	1.25051313	0.0102054	0.0187255	262645.382	0.00581331	1.08568725	0.00332167	0.006094807
5	9.72	94761.3	0.00724299	1.25051313	0.00970054	0.0177991	328306.727	0.00555346	1.08568725	0.0031732	0.005822378
6	11.66	113713.5	0.00695394	1.25051313	0.00931341	0.0170888	393968.073	0.00535297	1.08568725	0.00305864	0.005612176
7	13.61	132665.8	0.00672189	1.25051313	0.00900262	0.0165186	459629.418	0.00519121	1.08568725	0.00296621	0.005442581
8	15.55	151618.0	0.00652947	1.25051313	0.00874492	0.0160457	525290.764	0.00505652	1.08568725	0.00288924	0.005301366
9	17.49	170570.3	0.00636604	1.25051313	0.00852603	0.0156441	590952.109	0.0049417	1.08568725	0.00282364	0.005180991
10	19.44	189522.5	0.00622461	1.25051313	0.00833662	0.0152966	656613.455	0.00484204	1.08568725	0.00276669	0.005076502
11	21.38	208474.8	0.00610041	1.25051313	0.00817027	0.0149913	722274.8	0.00475427	1.08568725	0.00271654	0.004984483
12	23.33	227427.0	0.00599	1.25051313	0.0080224	0.01472	787936.146	0.00467606	1.08568725	0.00267185	0.004902485
13	25.27	246379.3	0.00589086	1.25051313	0.00788963	0.0144764	853597.491	0.00460568	1.08568725	0.00263164	0.004828697
14	27.21	265331.5	0.0058011	1.25051313	0.00776941	0.0142558	919258.837	0.00454182	1.08568725	0.00259515	0.004761747
15	29.16	284283.8	0.00571923	1.25051313	0.00765976	0.0140546	984920.182	0.00448347	1.08568725	0.00256181	0.004700571
16	31.10	303236.0	0.00564408	1.25051313	0.00755912	0.0138699	1050581.53	0.00442982	1.08568725	0.00253116	0.004644327
17	33.05	322188.3	0.00557474	1.25051313	0.00746625	0.0136995	1116242.87	0.00438024	1.08568725	0.00250283	0.004592341
18	34.99	341140.5	0.00551044	1.25051313	0.00738013	0.0135415	1181904.22	0.00433419	1.08568725	0.00247651	0.004544064
19	36.93	360092.8	0.00545056	1.25051313	0.00729993	0.0133944	1247565.56	0.00429125	1.08568725	0.00245198	0.004499044
20	38.88	379045.0	0.00539459	1.25051313	0.00722497	0.0132568	1313226.91	0.00425106	1.08568725	0.00242901	0.004456903
21	40.82	397997.3	0.00534208	1.25051313	0.00715464	0.0131278	1378888.26	0.00421331	1.08568725	0.00240744	0.004417325
22	42.76	416949.5	0.00529267	1.25051313	0.00708847	0.0130064	1444549.6	0.00417774	1.08568725	0.00238712	0.004380042
23	44.71	435901.8	0.00524605	1.25051313	0.00702604	0.0128918	1510210.95	0.00414415	1.08568725	0.00236793	0.004344823
24	46.65	454854.0	0.00520195	1.25051313	0.00696697	0.0127834	1575872.29	0.00411234	1.08568725	0.00234975	0.00431147
25	48.60	473806.3	0.00516013	1.25051313	0.00691096	0.0126807	1641533.64	0.00408214	1.08568725	0.0023325	0.004279812
26	50.54	492758.6	0.00512039	1.25051313	0.00685774	0.012583	1707194.98	0.00405342	1.08568725	0.00231609	0.004249699
27	52.48	511710.8	0.00508255	1.25051313	0.00680706	0.01249	1772856.33	0.00402605	1.08568725	0.00230044	0.004220999
28	54.43	530663.1	0.00504645	1.25051313	0.00675871	0.0124013	1838517.67	0.00399991	1.08568725	0.00228551	0.004193597
29	56.37	549615.3	0.00501196	1.25051313	0.00671251	0.0123165	1904179.02	0.00397491	1.08568725	0.00227123	0.00416739
30	58.32	568567.6	0.00497894	1.25051313	0.00666829	0.0122354	1969840.36	0.00395097	1.08568725	0.00225755	0.004142286
31	60.26	587519.8	0.00494729	1.25051313	0.00662591	0.0121576	2035501.71	0.003928	1.08568725	0.00224442	0.004118206
32	62.20	606472.1	0.00491692	1.25051313	0.00658522	0.012083	2101163.06	0.00390594	1.08568725	0.00223182	0.004095074
33	64.15	625424.3	0.00488772	1.25051313	0.00654612	0.0120112	2166824.4	0.00388472	1.08568725	0.00221969	0.004072826
34	66.09	644376.6	0.00485963	1.25051313	0.0065085	0.0119422	2232485.75	0.00386428	1.08568725	0.00220801	0.004051402
35	68.03	663328.8	0.00483256	1.25051313	0.00647225	0.0118757	2298147.09	0.00384458	1.08568725	0.00219676	0.004030749
36	69.98	682281.1	0.00480646	1.25051313	0.00643729	0.0118115	2363808.44	0.00382557	1.08568725	0.0021859	0.004010817
37	71.92	701233.3	0.00478126	1.25051313	0.00640353	0.0117496	2429469.78	0.00380721	1.08568725	0.0021754	0.003991563
38	73.87	720185.6	0.0047569	1.25051313	0.00637092	0.0116898	2495131.13	0.00378945	1.08568725	0.00216525	0.003972944
39	75.81	739137.8	0.00473335	1.25051313	0.00633937	0.0116319	2560792.47	0.00377226	1.08568725	0.00215543	0.003954926
40	77.75	758090.1	0.00471054	1.25051313	0.00630883	0.0115758	2626453.82	0.00375561	1.08568725	0.00214592	0.003937472

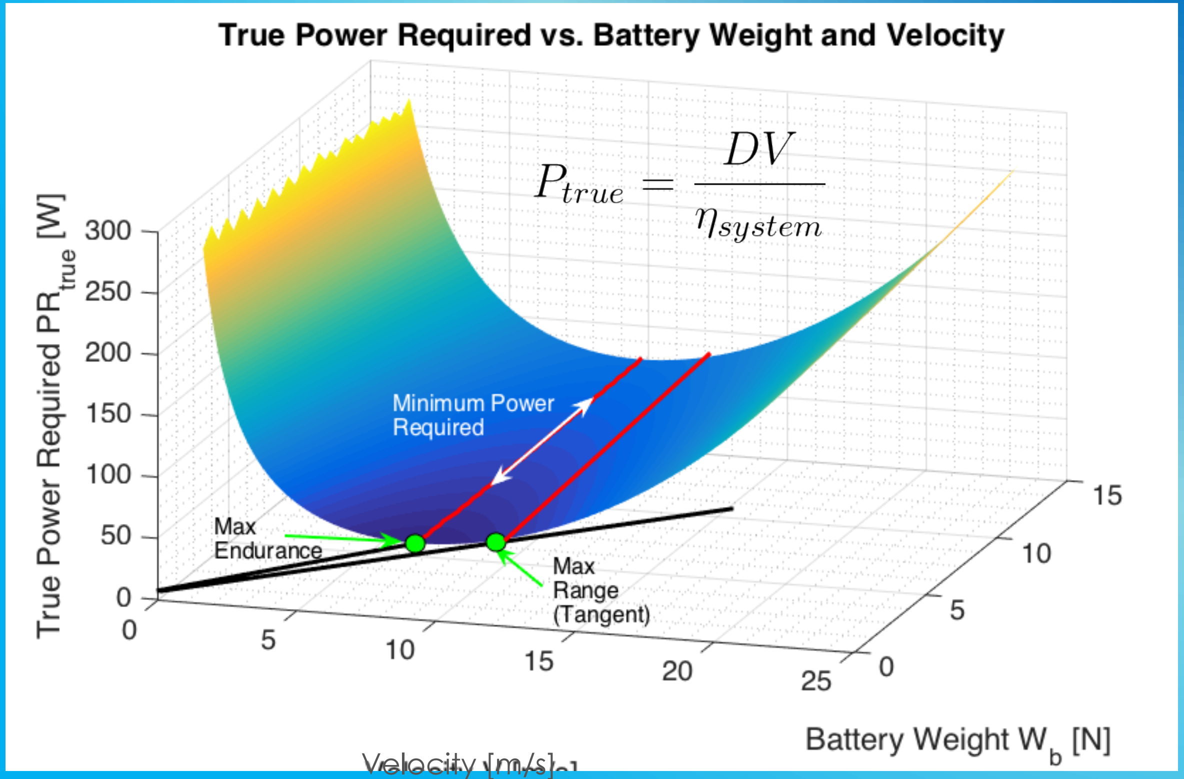
RECUV Talon Drag Buildup Screenshots from Excel

Tail Re	Tail Cf	Tail FF	Tail f	Tail C_D0	Total C_D0	CL	C_Di	C_D	D_0	D_i	D	PR	PR_true
0	#NUM!	1.25729201	#NUM!	#NUM!	#NUM!	#DIV/0!	#DIV/0!	#DIV/0!	#NUM!	#DIV/0!	#NUM!	#NUM!	#NUM!
16295.9521	0.01113808	1.25729201	0.00243595	0.00446964	0.04995818	114.96368	971.027735	971.077693	0.01425344	277.041495	277.055749	277.055749	325.94794
32591.9042	0.00932102	1.25729201	0.00203855	0.00374047	0.0420767	28.7409199	60.6892334	60.7313101	0.04801919	69.2603738	69.308393	138.616786	163.078572
48887.8563	0.00844455	1.25729201	0.00184686	0.00338874	0.03825027	12.7737422	11.9879967	12.026247	0.09821781	30.7823884	30.8806062	92.6418185	108.990375
65183.8084	0.00789066	1.25729201	0.00172573	0.00316647	0.03582308	7.18522997	3.79307709	3.82890017	0.16352951	17.3150935	17.478623	69.9144919	82.2523434
81479.7605	0.00749517	1.25729201	0.00163923	0.00300776	0.03408549	4.59854718	1.55364438	1.58772987	0.24312117	11.0816598	11.324781	56.6239049	66.6163587
97775.7127	0.00719217	1.25729201	0.00157296	0.00288617	0.03275157	3.19343554	0.7492498	0.78200137	0.33639372	7.69559709	8.03199081	48.1919449	56.6964057
114071.665	0.00694909	1.25729201	0.0015198	0.00278863	0.03167972	2.34619754	0.40442638	0.4361061	0.44288461	5.65390807	6.09679268	42.6775488	50.2088809
130367.617	0.00674765	1.25729201	0.00147574	0.00270779	0.03079025	1.79630749	0.23706732	0.26785757	0.56222012	4.32877337	4.89099348	39.1279478	46.0328798
146663.569	0.00657663	1.25729201	0.00143834	0.00263916	0.03003424	1.41930469	0.14799996	0.1780342	0.69408846	3.42026538	4.11435384	37.0291845	43.5637465
162959.521	0.0064287	1.25729201	0.00140599	0.00257979	0.02937965	1.1496368	0.09710277	0.12648242	0.83822343	2.77041495	3.60863839	36.0863839	42.4545693
179255.473	0.00629882	1.25729201	0.00137758	0.00252768	0.02880446	0.95011305	0.0663225	0.09512696	0.99439355	2.28959914	3.28399269	36.1239196	42.4987289
195551.425	0.00618342	1.25729201	0.00135234	0.00248137	0.02829293	0.79835889	0.04682811	0.07512104	1.16239464	1.92389927	3.08629391	37.035527	43.5712082
211847.377	0.00607983	1.25729201	0.00132969	0.0024398	0.02783345	0.68025846	0.03399838	0.06183183	1.34204447	1.63929879	2.98134326	38.7574624	45.5970146
228143.33	0.00598606	1.25729201	0.00130918	0.00240217	0.02741723	0.58654939	0.02527665	0.05269388	1.53317885	1.41347702	2.94665587	41.2531822	48.5331555
244439.282	0.00590055	1.25729201	0.00129048	0.00236785	0.02703747	0.51094969	0.01918079	0.04621827	1.7356486	1.23129554	2.96694414	44.504162	52.3578377
260735.234	0.00582209	1.25729201	0.00127332	0.00233637	0.02668882	0.44907687	0.01481671	0.04150553	1.94931723	1.08219334	3.03151057	48.5041692	57.0637285
277031.186	0.0057497	1.25729201	0.00125749	0.00230732	0.02636698	0.3977982	0.01162615	0.03799313	2.17405913	0.95862109	3.13268022	53.2555637	62.6536044
293327.138	0.00568259	1.25729201	0.00124281	0.00228039	0.02606845	0.35482617	0.00925	0.03531845	2.40975805	0.85506634	3.2648244	58.7668392	69.1374578
309623.09	0.00562011	1.25729201	0.00122915	0.00225531	0.02579038	0.31845895	0.00745105	0.03324142	2.65630596	0.76742797	3.42373392	65.0509445	76.530523
325919.042	0.00556171	1.25729201	0.00121637	0.00223188	0.02553037	0.2874092	0.00606892	0.03159929	2.91360198	0.69260374	3.60620572	72.1241144	84.8518992
342214.994	0.00550693	1.25729201	0.00120439	0.0022099	0.02528641	0.26068862	0.00499292	0.03027933	3.18155163	0.62821201	3.80976364	80.0050364	94.1235722
358510.946	0.0054554	1.25729201	0.00119312	0.00218922	0.02505681	0.23752826	0.00414516	0.02920197	3.46006609	0.57239978	4.03246587	88.7142492	104.369705
374806.899	0.00540679	1.25729201	0.00118249	0.00216971	0.02484012	0.21732265	0.00346993	0.02831005	3.74906162	0.52370793	4.27276955	98.2736996	115.616117
391102.851	0.0053608	1.25729201	0.00117243	0.00215126	0.02463509	0.19958972	0.00292676	0.02756184	4.04845905	0.48097482	4.52943387	108.706413	127.889898
407398.803	0.0053172	1.25729201	0.0011629	0.00213376	0.02444062	0.18394189	0.00248583	0.02692646	4.35818337	0.44326639	4.80144976	120.036244	141.219111
423694.755	0.00527578	1.25729201	0.00115384	0.00211714	0.02425579	0.17006461	0.0021249	0.02638069	4.67816331	0.4098247	5.087988	132.287688	155.632574
439990.707	0.00523633	1.25729201	0.00114521	0.00210131	0.02407977	0.15770052	0.00182716	0.02590693	5.00833104	0.38002949	5.38836052	145.485734	171.159687
456286.659	0.00519871	1.25729201	0.00113698	0.00208621	0.02391182	0.14663735	0.00157979	0.02549161	5.34862187	0.35336925	5.70199113	159.655752	187.830296
472582.611	0.00516277	1.25729201	0.00112912	0.00207179	0.02375131	0.13669879	0.0013729	0.02512421	5.69897401	0.32941914	6.02839315	174.823401	205.67459
488878.563	0.00512837	1.25729201	0.0011216	0.00205798	0.02359765	0.12773742	0.0011988	0.02479645	6.05932832	0.30782388	6.3671522	191.014566	224.723019
505174.515	0.0050954	1.25729201	0.00111439	0.00204475	0.02345035	0.11962922	0.00105144	0.02450179	6.42962811	0.28828459	6.7179127	208.255294	245.006228
521470.468	0.00506375	1.25729201	0.00110747	0.00203205	0.02330893	0.11226922	0.00092604	0.02423498	6.80981898	0.27054834	7.08036732	226.571754	266.555005
537766.42	0.00503334	1.25729201	0.00110082	0.00201985	0.023173	0.10556812	0.0008188	0.0239918	7.19984866	0.2543999	7.45424856	245.990203	289.400238
554062.372	0.00500408	1.25729201	0.00109442	0.00200811	0.02304218	0.09944955	0.00072663	0.02376881	7.59966682	0.23965527	7.83932209	266.536951	313.572884
570358.324	0.00497589	1.25729201	0.00108825	0.00199679	0.02291613	0.0938479	0.00064708	0.02356321	8.00922499	0.22615632	8.23538131	288.238346	339.103936
586654.276	0.00494871	1.25729201	0.00108231	0.00198589	0.02279454	0.08870654	0.00057812	0.02337267	8.42847643	0.21376659	8.64224301	311.120748	366.02441
602950.228	0.00492247	1.25729201	0.00107657	0.00197536	0.02267715	0.08397639	0.00051811	0.02319526	8.85737598	0.20236778	9.05974376	335.210519	394.365317
619246.18	0.00489711	1.25729201	0.00107102	0.00196518	0.02256369	0.07961474	0.00046569	0.02302938	9.29588003	0.19185699	9.48773702	360.534007	424.157655
635542.132	0.00487259	1.25729201	0.00106566	0.00195534	0.02245394	0.07558427	0.00041973	0.02287367	9.74394638	0.18214431	9.92609069	387.117537	455.432396
651838.084	0.00484885	1.25729201	0.00106047	0.00194581	0.02234767	0.0718523	0.00037931	0.02272698	10.2015342	0.17315093	10.3746851	414.987404	488.220475

Evidence of Feasibility

UAS Endurance – Drag Buildup





- $C_{D,0} = f(V, airframe)$
- $C_L = f(W,S,V)$

- Choose endurance optimization to reach 63+ minute flight time

$E \propto 1/P_{true}$

UAS ENDURANCE – RECUV TALON

RECUV Talon Drive System

Component	Type
Motor	E-Flite Power 25BL (1250 Kv)
Battery	Thunder Power RC TP7000-3SH (14000 mAh)
ESC	Phoenix Edge HV 80A
Propeller	APC 9x7 10x7

- RECUV operates XUAV Talon in long-endurance configuration with suite of sensors and antennas
- Serves as excellent point of reference for RAMROD Talon-based UAS

60 min+ Flight time is feasible on this airframe

RECUV Talon Overview

Component	Weight [g]
Battery Weight [g]	**422 (x2)**
Total Weight [g]	**3343**
Motor Power Rating [W]	**700 (1250 Kv)**
Motor Power Rating [W]	**700 (1250 Kv)**
Battery Capacity [mAh]	**7000 3S 11.4 V (x2)**
Optimal Cruise Speed [m/s]	**14-17**
Endurance [min]	**60-90**

UAS ENDURANCE – RECUV TALON

RECUV XUAV Talon
Airframe
Motor
Battery
ESC
Prop

See Backup Slides for List of RECUV Talon components

Propeller	Throttle	Current (DC)	Voltage (DC)	El. Power
rpm	%	A	V	W
7200	57	8.2	11.1	89.4
8100	65	11.5	11.1	125.8

Thrust	Sp. Thrust	Pitch Speed	Speed (Level)	Motor Run Time
g	g/W	km/h	km/h	(85%) min
859	7.4	66	55 (15.3 m/s)	87.5
834	6.6	74	68	62.1

Ecalc Calculations also show feasibility of 60+ min flight time on RECUV Platform

UAS WEIGHT BREAKDOWN

Component	Mass [g]
Talon Airframe	1050
Battery	845
Payload	900
Additional Hardware	537
TOTAL	**3,332**

Component	Mass [g]
MicroZed	100
NT1065T	250
Casing	400
Battery	150
TOTAL	**900**