Snow Depth Information and Mitigation Before Avalanche

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Agenda

1. **PROJECT OVERVIEW**
    - Motivation & Objectives
    - Project Description
    - CONOPS
    - Functional Requirements
    - Functional Block Diagram
2. **BASELINE DESIGN**
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    - UAV
    - Software
3. **FEASIBILITY**
    - Sensor Package
    - Aircraft Sizing
    - Power Budget/ Battery Performance
    - Software
    - GNSS
4. **END ITEMS**
    - Budget
    - Gantt Chart
    - Status Summary & Remaining Strategy
    - Acknowledgments

Project Overview

Project Overview | Baseline Design | Feasibility Analysis | Summary

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Mission Statement

The SIMBA team will design a UAV to provide the ability to remotely access and monitor snow depth to within ± 10 cm in avalanche prone areas of the Copper Mountain ski resort.

Photo Courtesy of commons.wikimedia.org

Motivation:

- Time consuming (3-4 hours per pit)
- Multiple pits for accurate representation
- Safety Risks
- Locations of snow pit is variable
- Help decide safer snow pit dig sites
- Provide information for explosives planning, boot packing, and ski cutting

Definitions

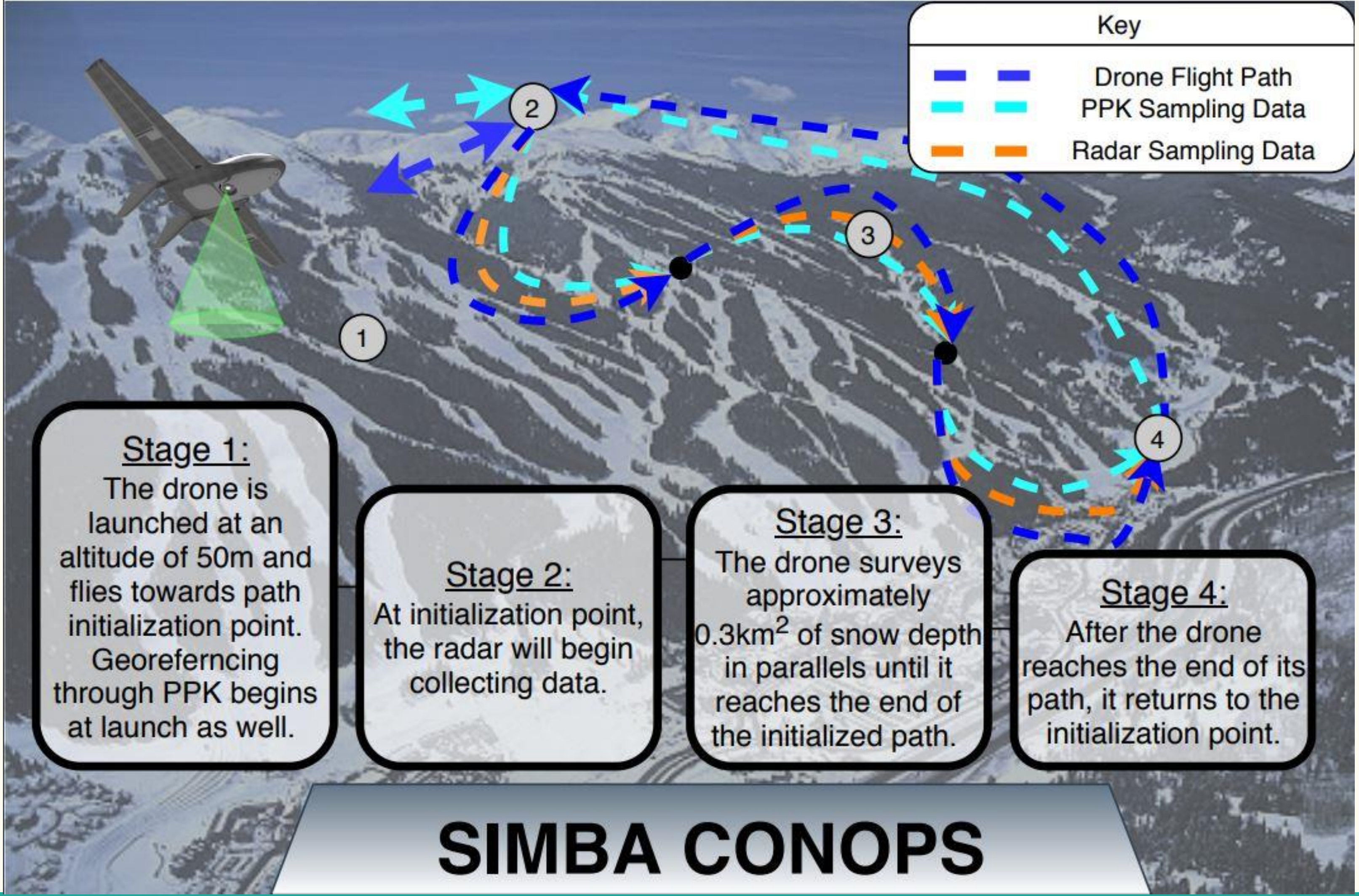
GNSS: Global Navigation Satellite System

GPS: Global Positioning System

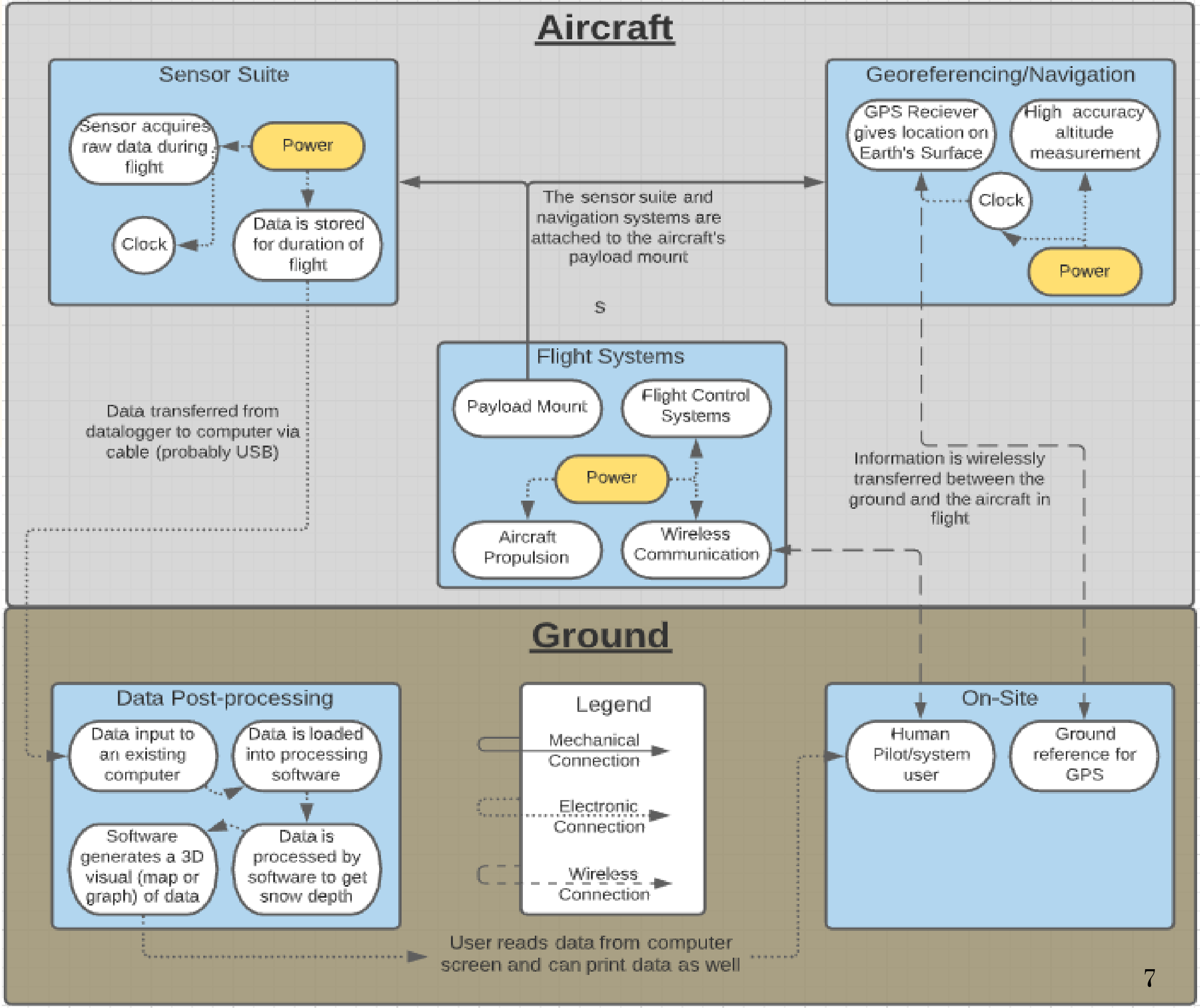
IMU: Inertial Measuring Unit

PPK: Post-Processed Kinematic

UAV: Unmanned Aerial Vehicle


Key
Drone Flight Path
PPK Sampling Data
Radar Sampling Data
1
2
3
4
Stage 1:
The drone is launched at an altitude of 50m and flies towards path initialization point. Georeferncing through PPK begins at launch as well.
Stage 2:
At initialization point, the radar will begin collecting data.
Stage 3:
The drone surveys approximately 0.3km2 of snow depth in parallels until it reaches the end of the initialized path.
Stage 4:
After the drone reaches the end of its path, it returns to the initialization point.
SIMBA CONOPS

Functional Block Diagram



Functional Requirements

FR 1	The system shall implement a snow depth detection system to assist Copper Mountain ski patrol in avalanche mitigation.
FR 2	The system shall be able to operate with acceptable endurance such that data collection occurs in a reasonable amount of time.
FR 3	The system shall be able to operate in typical weather conditions found on the top of Copper Mountain.
FR 4	Data must be stored onboard for the flight duration and transferred to an existing computer system after the flight.
FR 5	The system shall process the data collected and present snow depth data to Copper Mountain ski patrol in the software found at their facilities.
FR 6	The system shall collect location data accurately in order to navigate and assist with snow depth mapping.
FR 7	The system shall be compliant with the stipulations of Federal Aviation Regulation (FAR) 107, which includes avoiding flying over populated regions of the ski resort.

Baseline Design

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Critical Project Elements

All Critical Project Elements

Sensor Package
FR1 FR3 FR4

Aircraft Design
FR2 FR3 FR7

Georeferencing
FR5

Software
FR3 FR6

Focus for PDR

Sensor Package:
To be Purchased

Software:
Available / To be Purchased

Aircraft Design:
To be Designed/Manufactured

Sensor Package

- Radar altimeter for snow depth sensing
- PPK receiver for position data

Software

- ArcGIS for mapping snow depth data
- PPK correction of position data

UAV

- Fixed-wing
- Electric twin tractor propellor configuration

Sensor Package: Snow Depth Sensor

Options Considered: Radar, LiDAR, Photogrammetry, Ultrasonic
Key Criteria: Operating Temperature, Range, Accuracy, Power Budget, Weight, Cost
Design Choice: US-D1 Radar Altimeter

Frequency	24-4.25 GHz
Maximum Detection Range	50 meters
Detection Accuracy	5 centimeters
Size	108 mm x 79 mm x 20 mm
Weight	110 grams
Temperature Range	-20°C to 65°C
Power Required	2 Watts

Sensor Package: Georeferencing

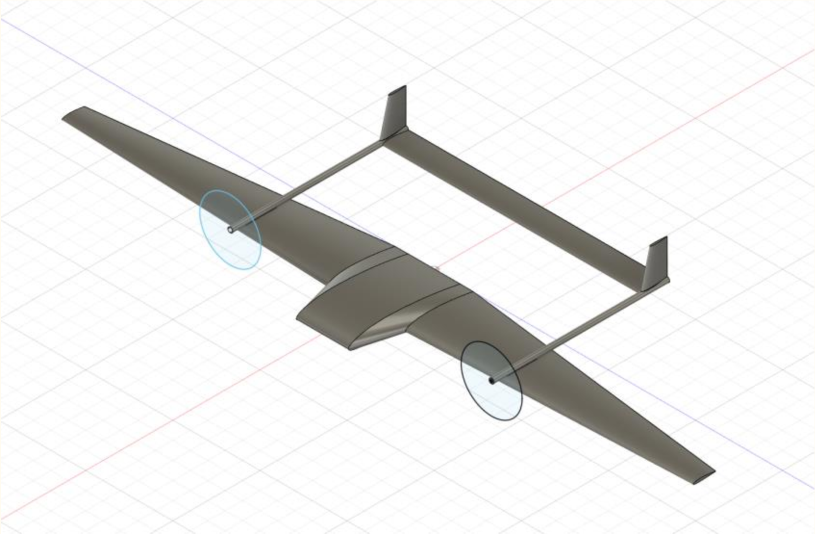
Options Considered: PPK GNSS, GPS, Pressure Altimeter
Key Criteria: Accuracy, cost, operating temp.
Design Choice: PPK GNSS

- SparkFun ZED-F9P receiver board
- Accurate to within 1 cm horizontally and vertically
- Sizing
  - 43 x 43 mm
  - 6.8 grams
- Power consumption < 1W
- Operating temperature range = -40°C to 85°C

UAV: Baseline Design

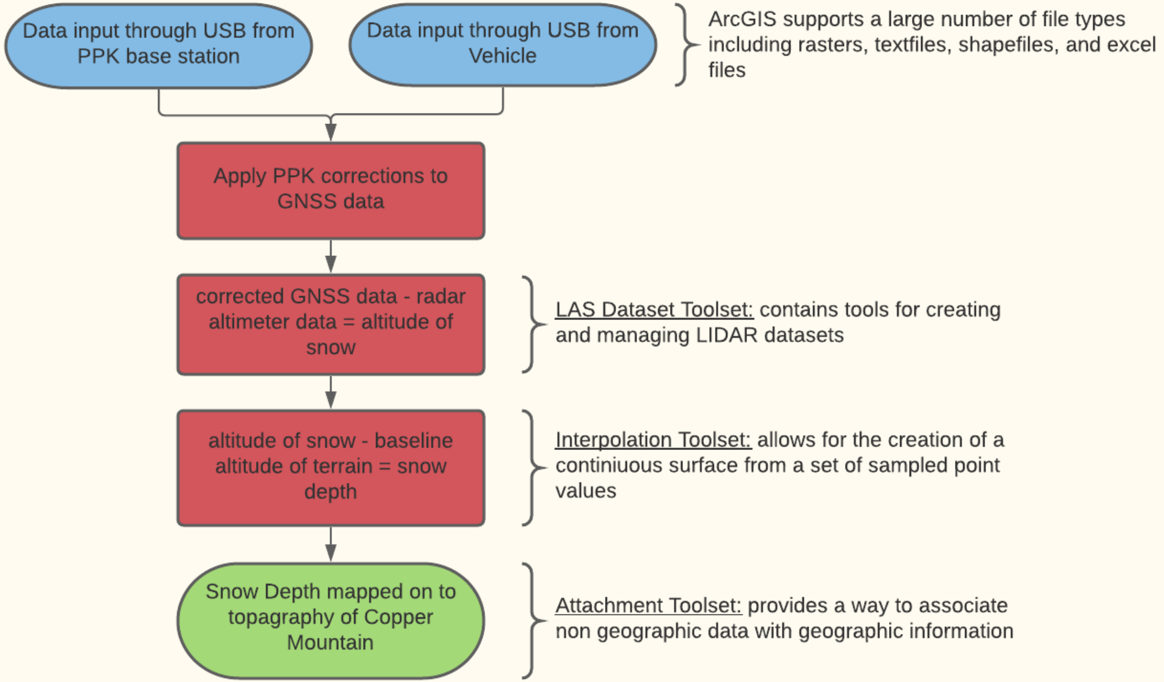
Options Considered: Fixed-wing, multirotor, ground-effect vehicle, airship, stationary ground-based platform
Key Criteria: Payload weight fraction, battery weight fraction, endurance
Design Choice: Fixed Wing

- 12 m/s cruise speed
- Optimized for endurance
- 1 hour flight time
- 2 kg payload
- Blended wing-body
- Twin tractor propeller
- More detail follows in feasibility section



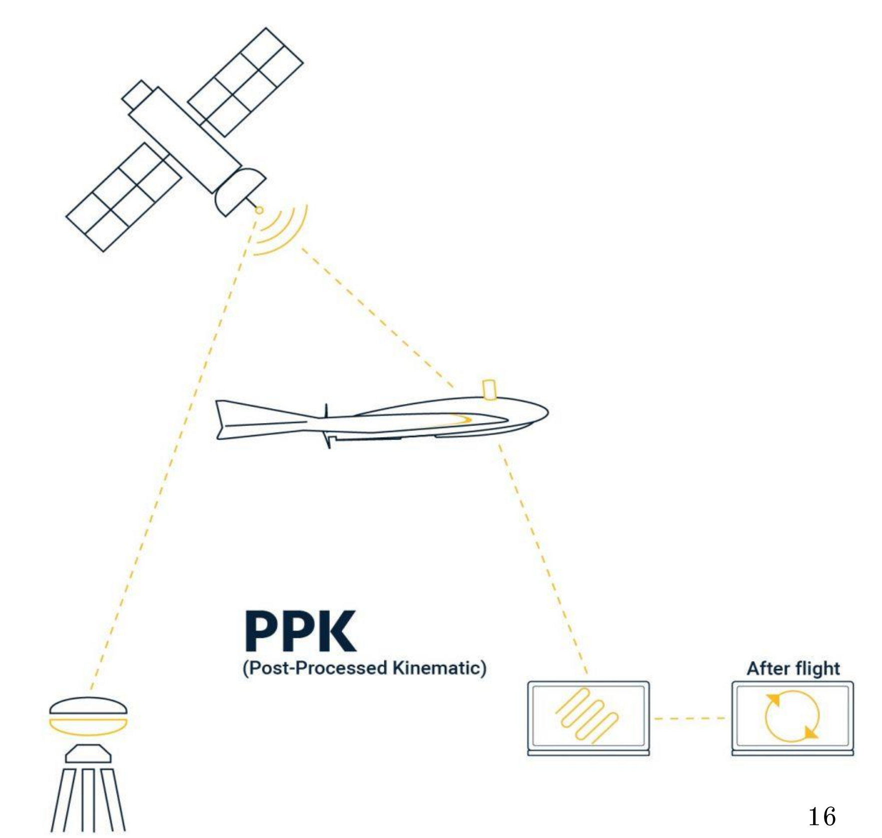
Software: ArcGIS

Options Considered: ArcGIS, Google Earth Engine, Matlab, Python 3
Key Criteria: Cost, 3D Visualization Capability, Ease of Use
Design Choice: ArcGIS



Software: PPK

- A software correction method for GNSS data
- Typical GNSS data is only accurate to about 1 meter
- With PPK, accuracy becomes about 1 cm
- PPK works by combining the receiver's data with data from a nearby base station.



From: https://waypoint.sensefly.com/gcps-rtk-ppk-when-what-why/

Feasibility Analysis

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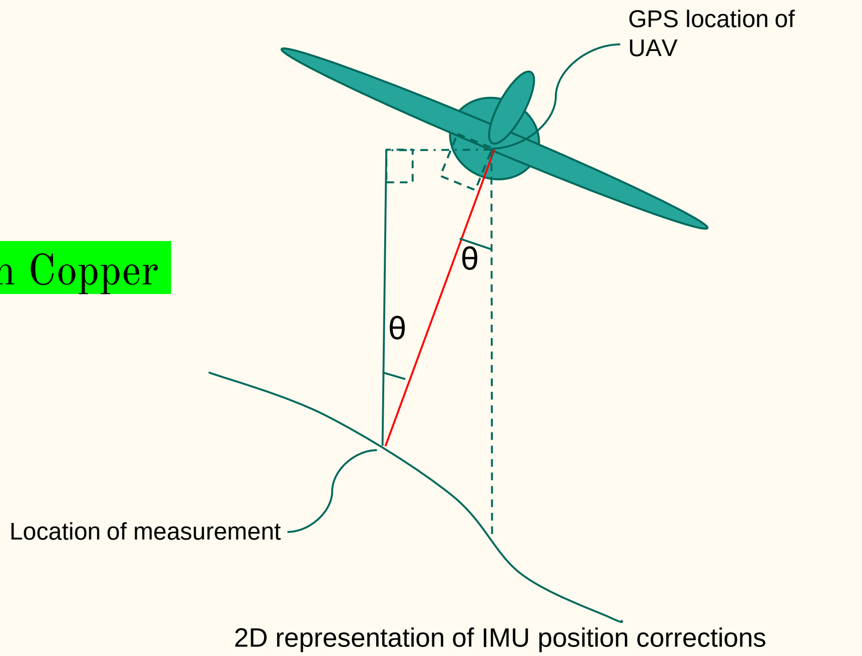
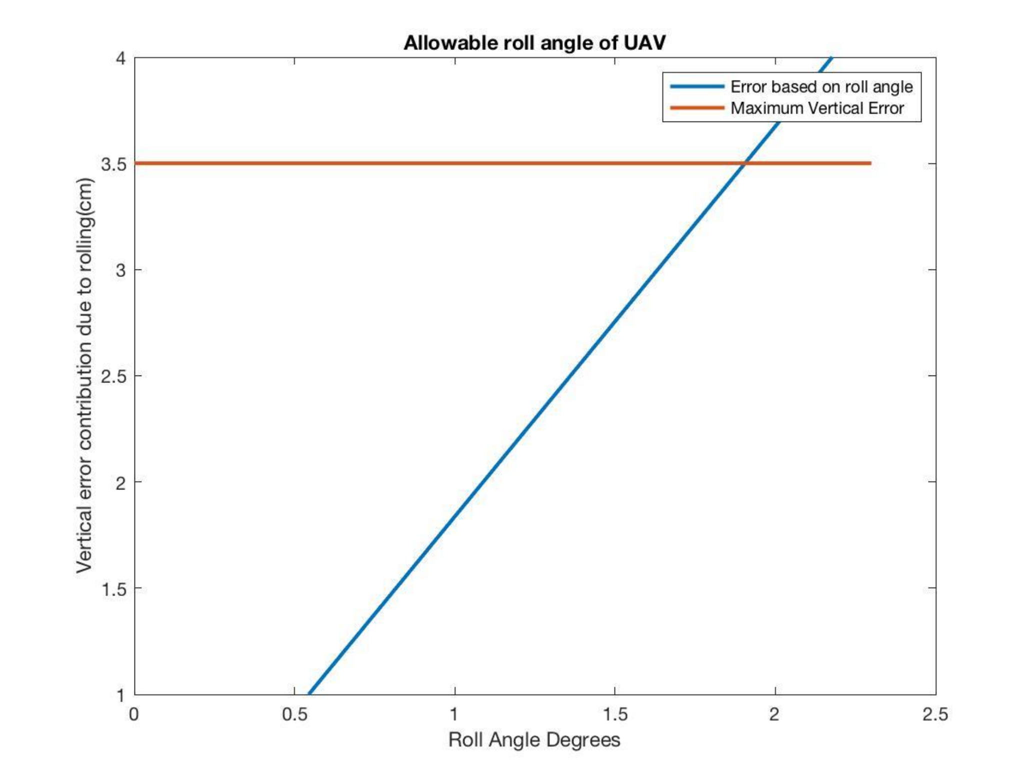
Baseline Feasibility: Sensor

- Provides measurements every 12 cm
  - In direction of travel
- -20°C to 65°C Operational Range
  - Feasible: Meets FR3 and can collect data in Copper conditions
- 50 meter detection range
- Sensor error is 5cm and GPS error is 1 cm horizontally and vertically
  - Error: 6.5cm



Baseline Feasibility: Sensor



- IMU data will provide UAV attitude
- UAV can roll 1.8 deg and maintain total error $<$ 10cm
- Assumes error of 1 deg in IMU and 40 deg maximum slope angle
- Feasible: Meets FR1 and collects snow depth data $\pm$10cm requirement

Baseline Feasibility: Georeferencing

FR 6: Accurate location data to assist in snow depth measurements

- Need to measure snow depth to within 10 cm with a horizontal resolution of 6m x 6m.
- ZED-F9P has claimed accuracy of 1 cm after PPK corrections
- Studies on similar receivers reported an accuracy of 2-5 cm
- May have less accurate results at Copper due to mountainous terrain

Needs on-site testing before feasibility can be determined

Baseline Feasibility: Georeferencing

- Design requirement is to operate at -23°C, listed operating temperature for receiver is -40°C, so plenty of room for error **Feasible: Meets FR 3 requirement for operating temp.**

- Receiver only weighs 7 grams, so not much added weight to aircraft
  Feasible: Allows for FR 2 requirement for flight endurance

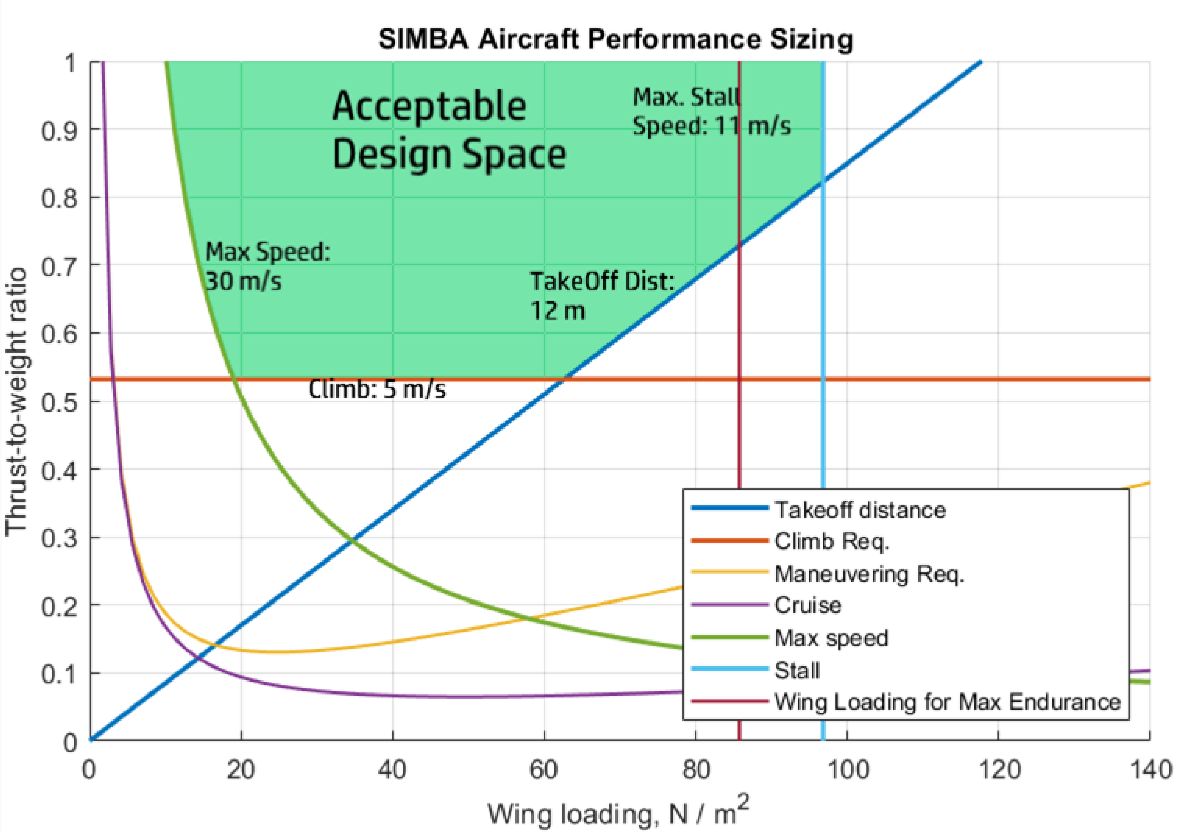
- Receiver only draws about 1 W of power, which is less than 1% of the total power budget **Feasible: Well within power budget**

Baseline Feasibility: Aircraft Sizing

- Takeoff weight: 7.4 kg
- Empty weight: 3.3 kg
- Battery weight: 2.1 kg
- Payload weight: 2 kg
- $S = 0.85\ m^2$
- For $AR = 12$, $b = 3.1$ m
- Empty weight-takeoff weight relation based on similar aircraft operated by IRISS
- Takeoff weight well below legal maximum of 25 kg:

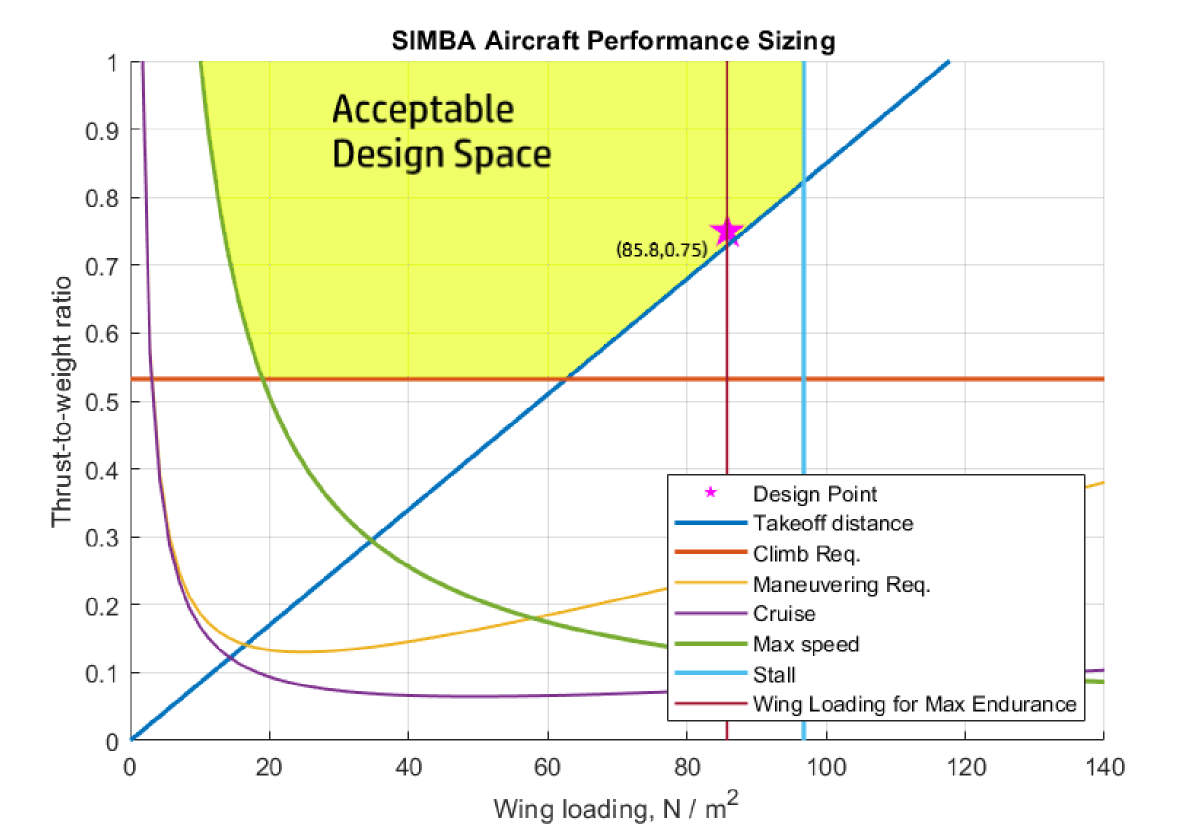
  Feasible: meets FR7 for legal operation in NAS

Baseline Feasibility: Aircraft Sizing



Baseline Feasibility: Aircraft Sizing

- Key parameters chosen: $T/W = 0.75$, $W/S = 85.8\ N/m^2$
- Parameters are within constraints of performance sizing plot: **Feasible: meets FR2 and FR3 for operations in Copper Mountain weather**



Design Feasibility: UAV Power Budget

Component	Quantity	Current (per device at cruise)	Supply Voltage	Supply Power	Efficiency
DC motors	2	1.75A	22.2V	38.9W per	0.85
ESCs	2	2.1A	22.2V	46.9W per	0.83
Servo Motors	8	100mA	5V	0.5W	0.8
Receiver	1	100mA	5V	0.5W	0.8

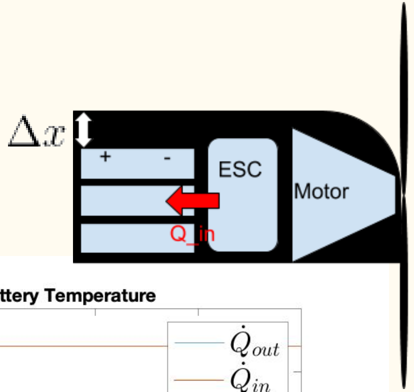
Total minimum Amps: 5.1 Amps

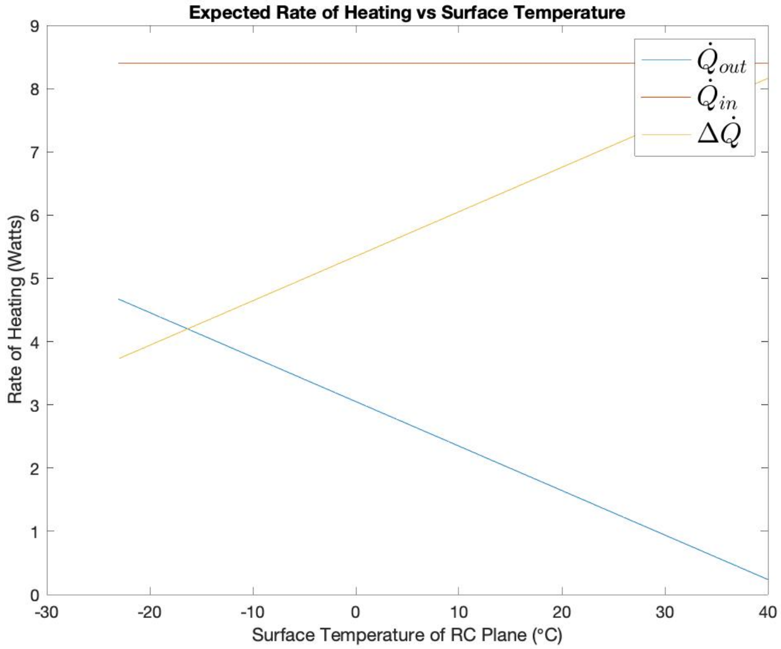
Total minimum Voltage: 22.2V

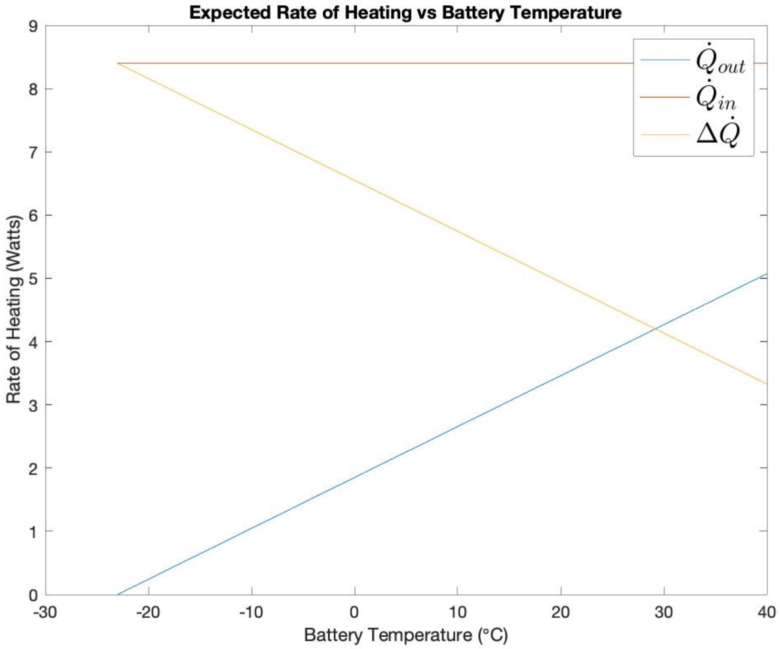
Total Power: 98 Watts, Propulsion power: 94 watts. Approximately equal.

Baseline Feasibility: Batteries in Cold Environments

$$\dot{Q}_{convection} = KA_s\frac{(T_{Batt} - T_s)}{\Delta x} \qquad \dot{Q}_{conduction} = hA_s(T_s - T_\infty)$$



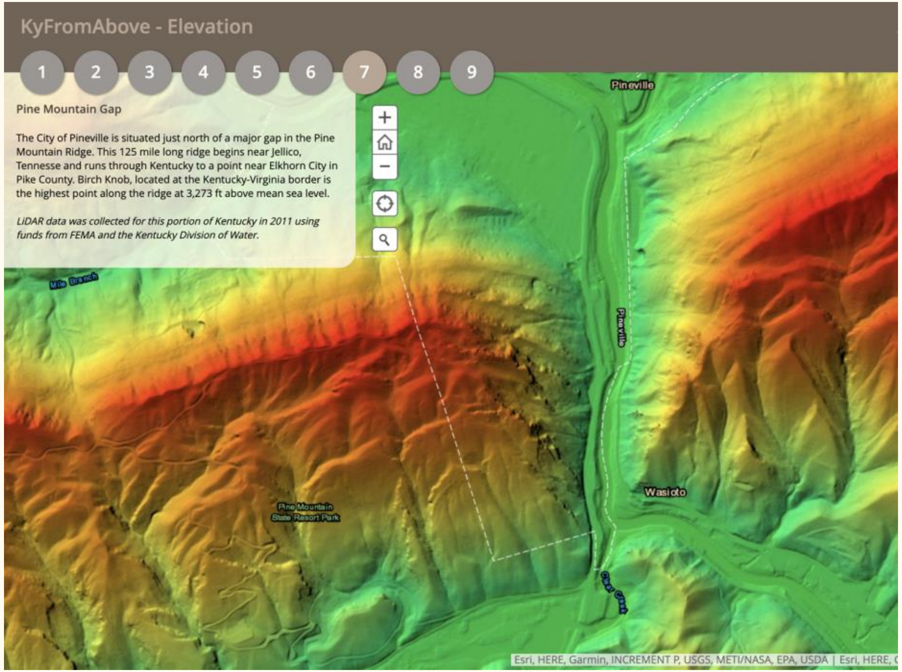




Baseline Feasibility: Software

- Case Study: KyFromAbove, Kentucky's elevation data & Aerial photography program
    - A common basemap for the state of Kentucky created using photography and elevation data in ArcGIS
    - Includes altitude based topography maps created from LIDAR data, similar to the maps that we plan to construct for snow depth

Feasible: ArcGIS is capable of mapping depth data, meets FR5



Summary

Project Overview | Baseline Design | Feasibility Analysis | Summary

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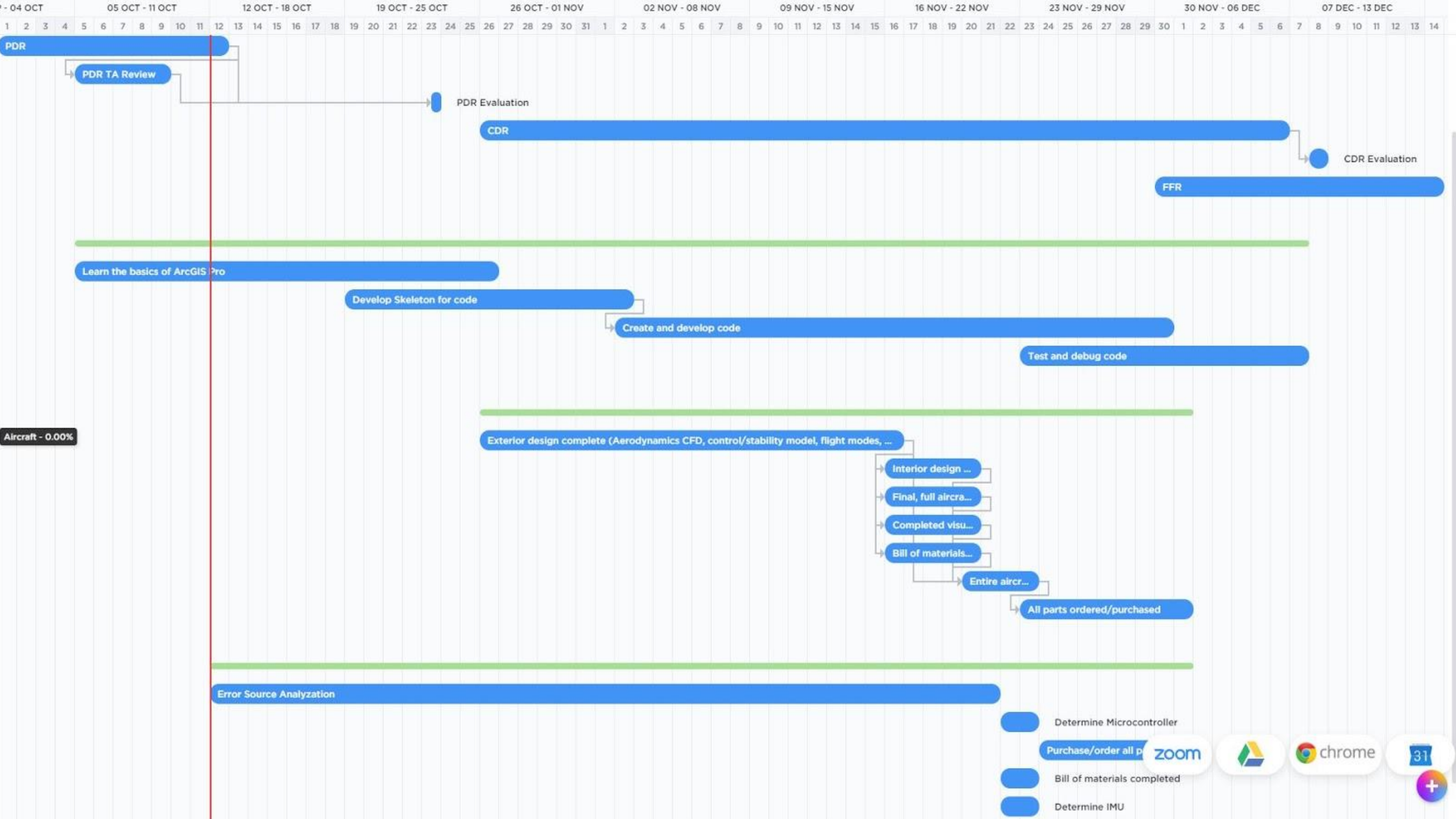
Budget

Sub-team Expenses	Overall Cost
Sensor Package	$1500
Aircraft	$2000
Data Visualization	$0
Georeferencing	$220
ClickUp	$60
Senior Project Funds	$5000
Estimated Budget	$3780
Remaining Budget	$1220



- 04 OCT
05 OCT - 11 OCT
12 OCT - 18 OCT
19 OCT - 25 OCT
26 OCT - 01 NOV
02 NOV - 08 NOV
09 NOV - 15 NOV
16 NOV - 22 NOV
23 NOV - 29 NOV
30 NOV - 06 DEC
07 DEC - 13 DEC
PDR
PDR TA Review
PDR Evaluation
CDR
CDR Evaluation
FFR
Learn the basics of ArcGIS Pro
Develop Skeleton for code
Create and develop code
Test and debug code
Aircraft - 0.00%
Exterior design complete (Aerodynamics CFD, control/stability model, flight modes, ...
Interior design ...
Final, full aircra...
Completed visu...
Bill of materials...
Entire aircr...
All parts ordered/purchased
Error Source Analyzation
Determine Microcontroller
Purchase/order all p
Bill of materials completed
Determine IMU

Status Summary

Baseline Design	Aspects Shown to be Feasible	Continued Studies
Sensor Package	1. Snow depth can be measured to within $\pm$10cm. 2. The sensor is operable in temperatures from -20°C to 65°C.	1. Calibration between Sensor Package, georeferencing, and IMU 2. Research into sources of error
Georeferencing	1. Can operate at -40°C 2. Will fit on aircraft 3. Easily within power budget	1. Vertical accuracy needs to be tested on-site if possible or done via simulation
Aircraft Design	1. Required aircraft weight 2. Aircraft wing loading and thrust-to-weight ratio 3. Battery efficiency in cold climates	1. Detailed design including airfoil selection, dynamics analysis, structural analysis
Software	1. Capable snow depth mapping software	1. Software familiarization amongst the group is needed for proficient use

Strategies for Conducting Remaining Studies

A sensor package focused around a radar altimeter on a fixed-wing UAV is a feasible design for snow-depth sensing on Copper Mountain. Our position data will be calculated using PPK GPS and presented using ArcGIS software already used by the customer.

- Further inquiry into the sensor in this application
  - Communication with manufacturers currently
  - Reaching out to experts and professors
- Site Investigation: Copper Mountain
- Continue research on possible problems and solutions of similar applications

Acknowledgements

- Thanks to Chris Choate of IRISS for providing empty weight and takeoff weight data for IRISS aircraft which was used in sizing the SIMBA aircraft.
- Thank you to Professor Sunberg for his guidance through this project so far.
- Thank you to Lara Buri and other TAs for great feedback on how to improve our presentation.

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Backup Slides

Levels of Success

Level	Snow Data	Position Data and Navigation	Data Processing	Aircraft Design
1	Snow depth is measured to within ±30cm	The aircraft must be able to measure its position and altitude precisely enough to avoid terrain collision. Must collect positional data with an accuracy within ±15cm	Produce a 2D heat map of snow depths	Aircraft maintains steady, level flight at density and altitude conditions found on the peak of Copper Mountain with wind gusts up to 10 knots
2	Snow depth is measured to within ±15cm.	Positional data is collected with an accuracy within ±10cm	A heat map is overlaid onto a map of Copper Mountain	Aircraft maintains steady, level flight at the peak of Copper Mountain with wind gusts up to 20 knots
3	Snow depth is measured to within ±10cm	Positional data is collected with an accuracy within ±5cm		Aircraft maintains steady, level flight at the peak of Copper Mountain with wind gusts up to 25 knots

Electric vs Fuel Engine

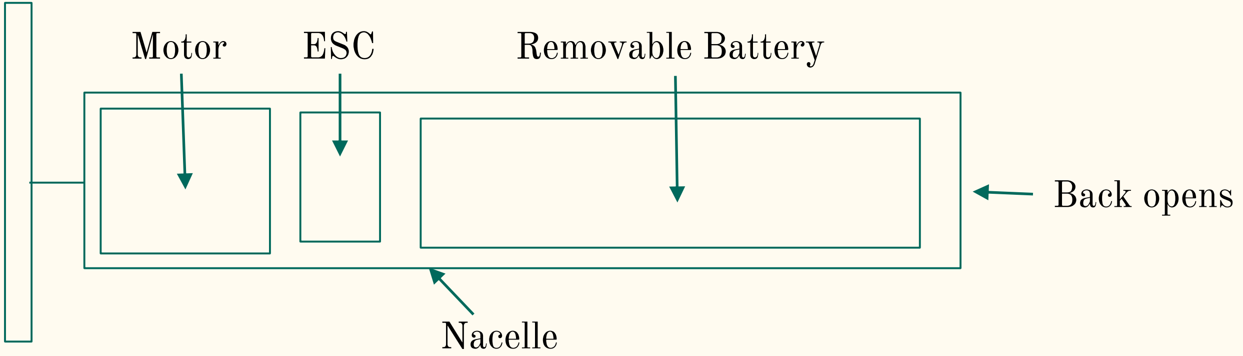
- LiPo energy density is 525.6 kJ/kg vs Glow Fuel energy density is 42.6 MJ/kg
- Thrust-to-weight ratio of 1
  - Total thrust required is 73.6 N, or 36.8 N per motor
- Weight comparison
  - Electric motor: 110 g (x2) for 40 N motor
  - Gas motor: 680 g for 153 N engine (turbocharger not included)
- Operational ceiling
  - Electric motor: defined by the propeller
  - Gas motor: power drop proportional to air density. At 4267.2m, power drop to 65%. Turbo charger is therefore needed.
- Maintenance/Reliability
  - Electric motor: Minimal maintenance
  - Gas motor: Carburetor may require constant maintenance in winter conditions. Engine may not start in cold weather.

Electric vs Fuel Engine Models

- UAV configuration requires 559 kJ for the entire flight with 40% margin
- Electric Motor
  - Total power plant efficiency is 0.493
  - Power source weight: 2.153 kg batteries
  - Powerplant weight: 220g ignoring wires
  - Cost: ~$140 with recharge negligible
  - Ease of use: Install system, minimal maintenance
- Gas Motor (gasoline)
  - Total power plant efficiency is 0.25
  - Power source weight: 400g
  - Powerplant weight: 771g including supercharger, not including plumbing
  - Cost: ~$320, fuel costs $0.68 per refuel. Snowmobile/snowcats run off gasoline
  - Ease of use: Supercharger and engine need to be mated. Continuous maintenance required

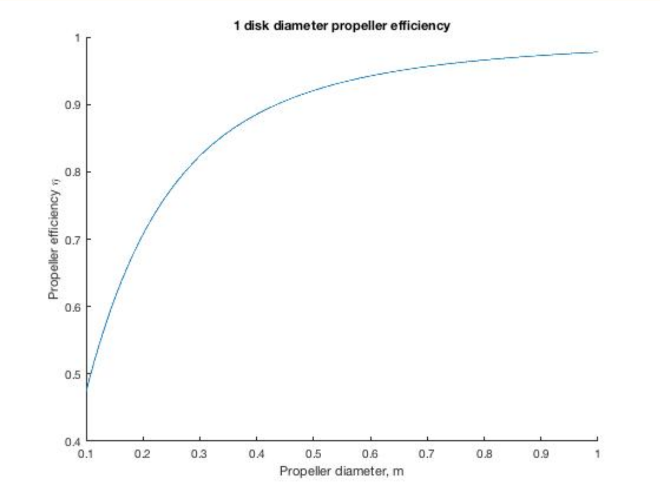
Aircraft Powerplant

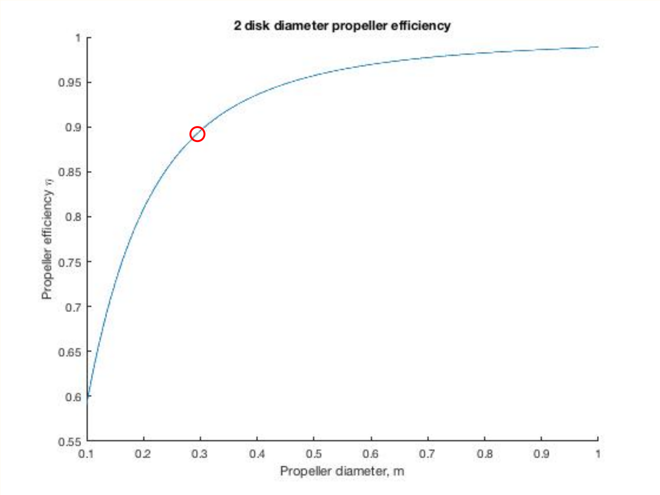
- Thrust-to-weight ratio design point ~1
- Required aircraft thrust is 73.6 N
- Two Engine configuration
  - Increase total actuator disk area
  - Redundancy. Aircraft can still fly in One Engine Operative (OEI)
  - Opens up room in fuselage for sensor package and electronics
- Initial design:



Propeller Efficiency Sensitivity

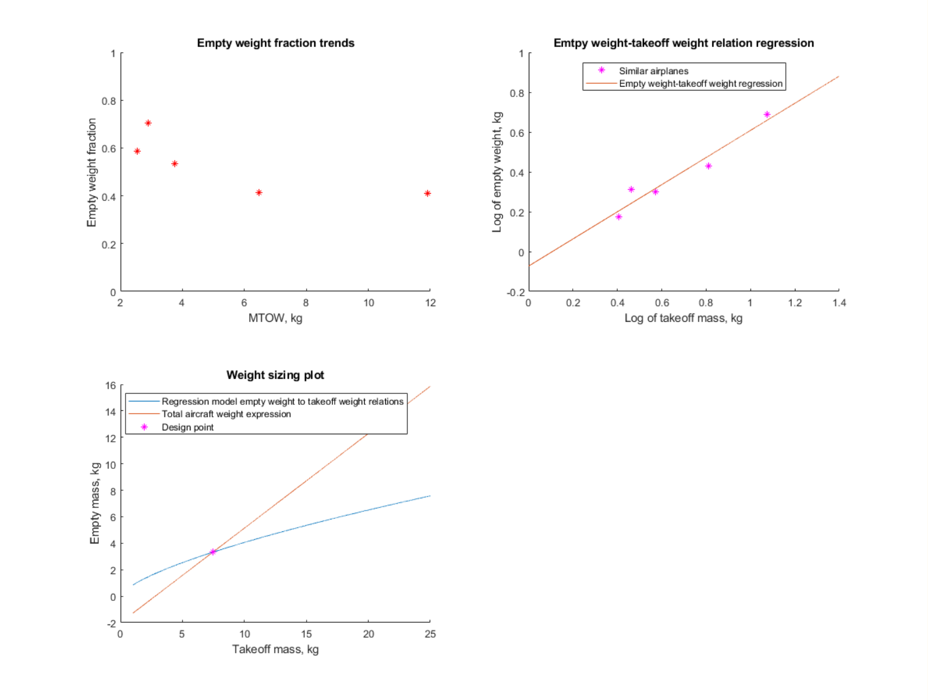
- Propeller efficiency is dependent on the difference between free stream velocity and propeller wake velocity
- Derived Equation: $$\eta_p = \frac{V_\infty}{\frac{V_\infty}{2} + \sqrt{\left(\frac{V}{2}\right)^2 + \frac{T}{2\rho(n\pi r^2)}}}$$





Airplane Sizing Methodology

- Regression model yields relation between takeoff and empty weight
- Estimate battery mass in terms of takeoff mass (next slide)
- Express empty mass in terms of takeoff mass, battery mass, payload mass
- Find intersection



Estimation of Battery Mass Required

Level flight: express thrust in terms of weight, L/D ratio:

$$T = \frac{m_{TO} g}{(L/D)}$$

Multiply by velocity, time to get power and energy respectively:

$$E = \frac{m_{TO} g v t}{(L/D)}$$

Divide by propulsion system efficiency and battery specific energy to get mass:

$$m_{batt} = \frac{m_{TO} g v t}{(L/D) \eta c}$$

Airplane Sizing Parameters Used

Payload mass: 2kg
Cruise speed: 12 m/s
Endurance: 3600 s

L/D max: 10
Battery specific energy: 420 kJ/kg
Propeller efficiency: 0.7

Maximum speed: 30 m/s
Air density: 0.8 kg/m^3
Takeoff ground roll distance: 12 m

Max lift coefficient, takeoff: 1.8
Max lift coefficient, landing: 2.0
Required climb rate: 5 m/s

Maneuvering load factor: 2
Wing aspect ratio: 12
Oswald efficiency: 0.7

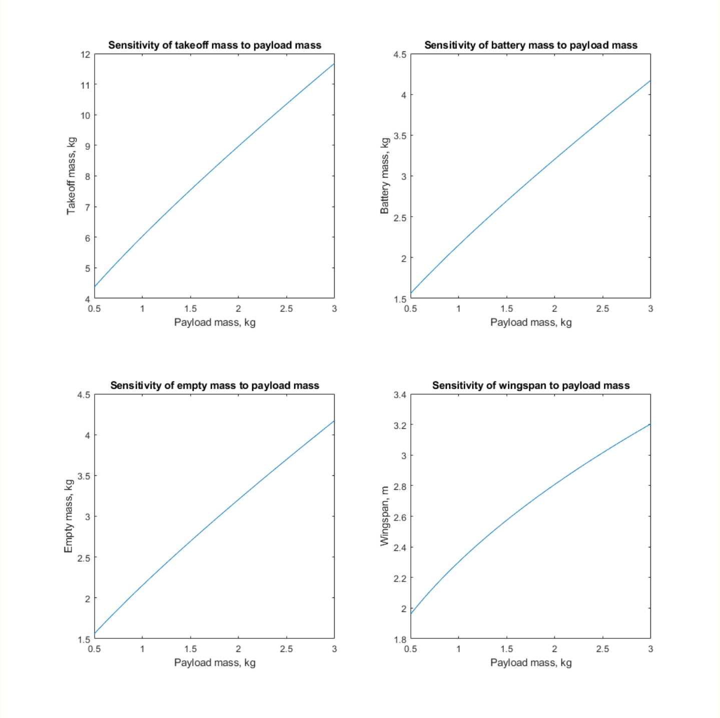
Parasite drag coefficient: 0.028
Battery margin: 1.4
ESC/motor combined efficiency: 0.7

Notes:

- Battery specific energy reduced by 20% to account for cold temperatures.
- Parasite drag coefficient is expected to overestimate vehicle drag.

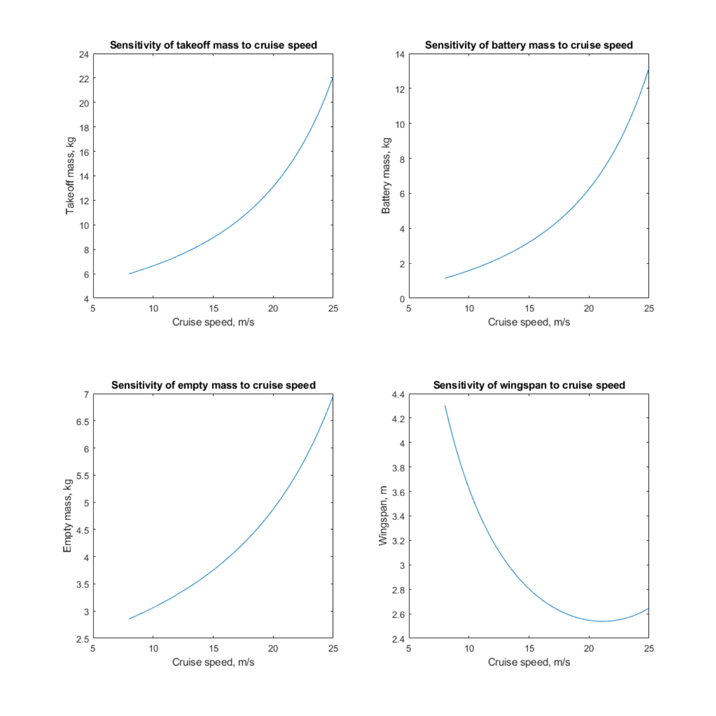
Airplane Sizing Sensitivity to Payload Mass

Nominal values are all as delineated earlier.



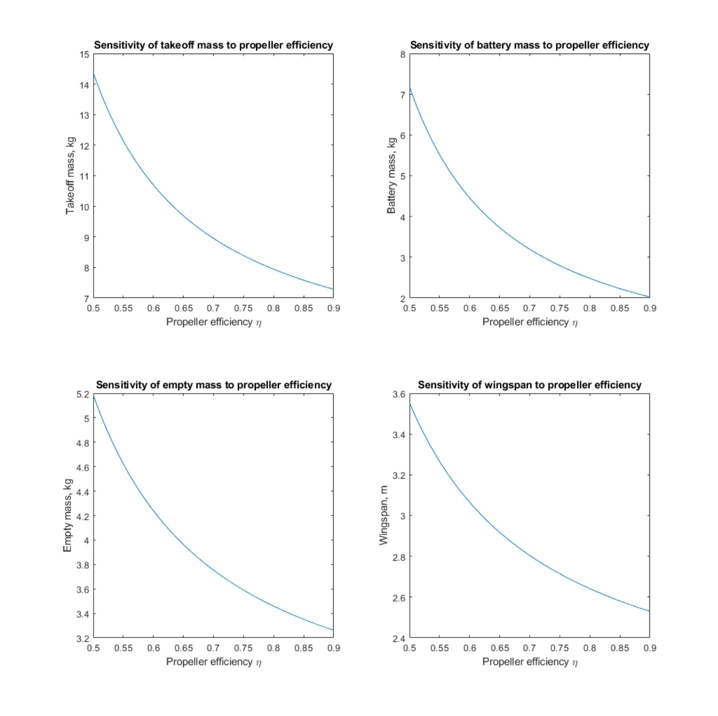
Airplane Sizing Sensitivity to Cruise Speed

Nominal values are all as delineated earlier.



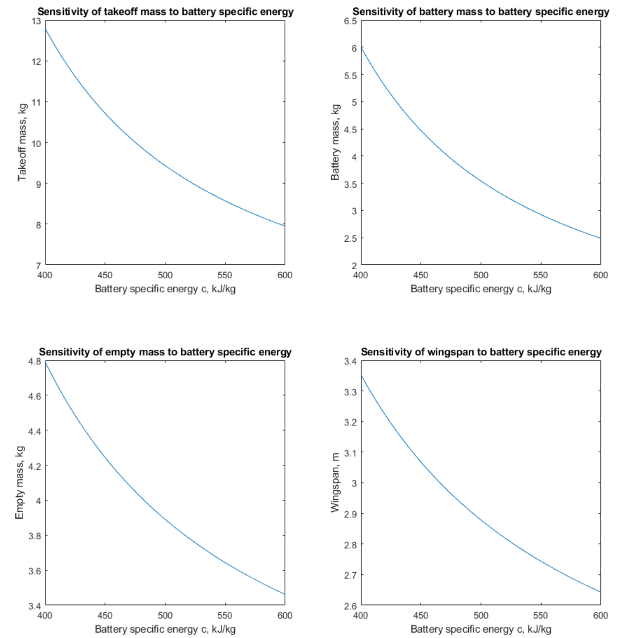
Airplane Sizing Sensitivity to Propeller Efficiency

Nominal values are all as delineated earlier.



Airplane Sizing Sensitivity to Specific Energy

Nominal values are all as delineated earlier.



Wing Loading Calculation

Desire to ensure that specified cruise speed is cruise speed for maximum endurance: specified cruise speed must be point of minimum power required.

$$\left(\frac{W}{S}\right)\Big|_{desired} = \sqrt{0.75 v_{crs}^4 \rho^2 C_{D0} \pi e AR}$$

Subject to constraints of performance sizing plot.

Performance Constraints: Stall Speed

Chosen stall speed of 11 m/s to make manual piloting easier.

Performance constraint equation:

$$\left(\frac{W}{S}\right)_{TO} = \frac{1}{2}\rho v_{S_L}^2 C_{L_{max_L}}$$

Performance Constraints: Takeoff Distance

Takeoff distance are from design requirements. Assuming thrust is significantly greater than drag and friction.

Performance constraint equation:

$$\left(\frac{T}{W}\right)_{TO} = \frac{1.44}{(S_{FL}/1.66)\rho g C_{L_{max_{TO}}}}\left(\frac{W}{S}\right)_{TO}$$

Performance Constraint: Climb

Climb requirements come from design requirements.

Climb gradient is defined as:

$$CGR = \frac{V_{climb}}{V_\infty}$$

Performance constraint equation:

$$\left(\frac{T}{W}\right)_{TO} = CGR + \frac{1}{L/D}$$

Performance Constraint: Maneuvering

Use load factor of 2 for maneuvering constraints.

Performance constraint equation:

$$\left(\frac{T}{W}\right)_{TO} = \frac{qC_{D_0}(T_{TO}/T_{man})}{(W/S)_{TO}} + \frac{n^2}{q\pi ARe}\frac{T_{TO}}{T_{cr}}\left(\frac{W}{S}\right)_{TO}$$

Performance Constraint: Speed

Use speed constraints for nominal cruise speed and dash speed.

Performance constraint equation:

$$\left(\frac{T}{W}\right)_{TO} = \frac{qC_{D_0}(T_{TO}/T_{cr})}{(W/S)_{TO}} + \frac{1}{q\pi ARe}\frac{T_{TO}}{T_{cr}}\left(\frac{W}{S}\right)_{TO}$$

Actual Takeoff, Ground Roll Performance

Chosen thrust-to-weight ratio: 0.75. Chosen wing loading: 85.8 N/m^2. Actual takeoff, climb performance:

Takeoff distance: 11.66 m; 12 m required

Climb performance, all engines operative: 42.4 deg, 8.1 m/s; 5 m/s required

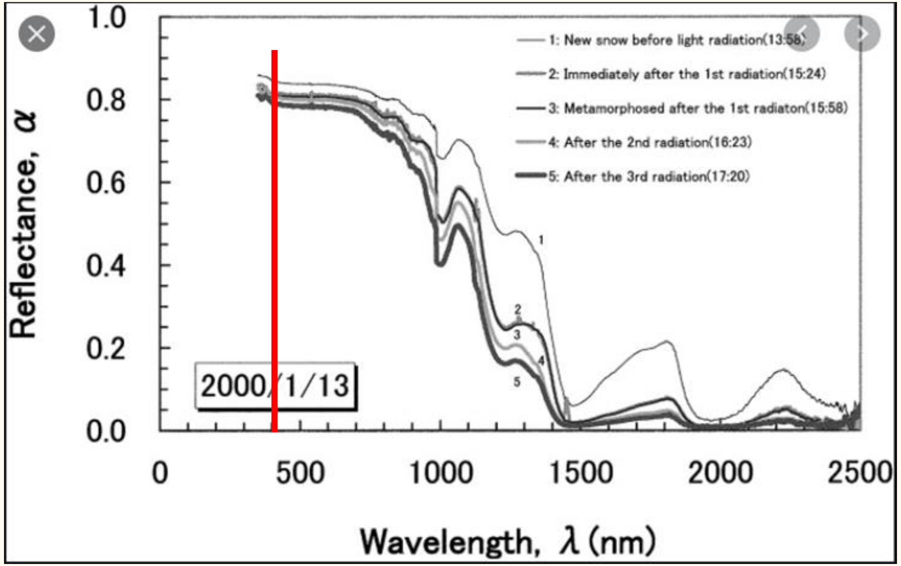
Climb performance, one engine INOP: 17.4 deg, 3.6 m/s

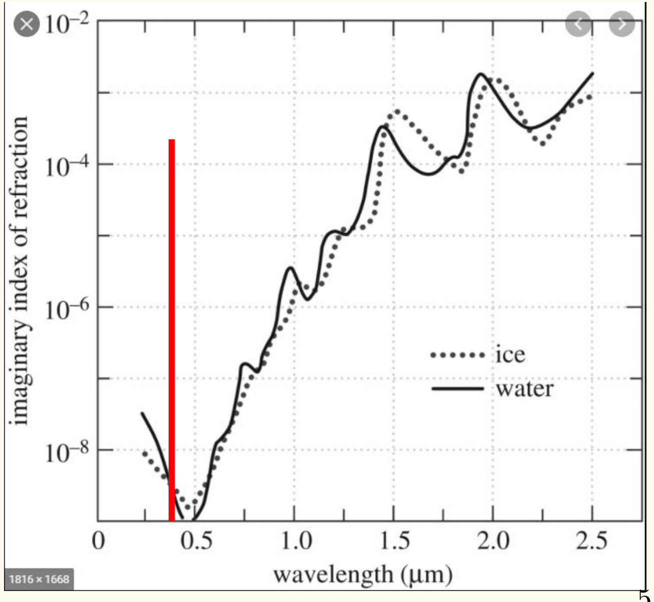
Baseline Feasibility: UAV Training

- Copper Mountain staff already possesses needed FAR107 credentials
- Due to legal concerns with CU teaching a third party, it will likely be the responsibility of Copper Mountain to train their pilot for operating the UAV
- The Academy of Model Aeronautics (AMA) quotes beginner to advanced RC aircraft training programs take 10-16 hours
- The Aircraft Owners and Pilots Association (AOPA) state an average of 16 flight hours for first solo for a private pilot's license

Sensor Package: Radar Altimeter

Operating frequency = 24GHz = 417nm wavelength





Baseline Feasibility: Sensor Package

- Range equation:
  - $R = (F_r t_{swp} c)/(2\Delta F n)$
    - F_r = return signal after low-pass filtering is applied
    - t_{swp} = the period of the signal over the bandwidth
    - ΔF = bandwidth
    - c = the speed of light in a vacuum
    - n is the refractive index of the medium. Assuming dry snow, n can be found by relating the average snowpack density, ρ_s, of an area to the permittivity relation
      - $n = (1 + 0.51\rho_s/1000)^{1/2}$

GNSS Acquisition times

It takes less than a minute for the receiver to acquire a fix on a satellite network

It is possible (even likely) that the receiver may occasionally lose its fix on the satellite network. According to the manufacturer, the average reacquisition time is 1 second. Given this, and the UAV's cruise speed, the aircraft may occasionally lose about 12 meters of GNSS data.

GNSS Manufacturer Data Sheet

Manufacturer: SparkFun

Features

Receiver type	184-channel u-blox F9 engine GPS L1C/A L2C, GLO L1OF L2OF, GAL E1B/C E5b, BDS B1I B2I, QZSS L1C/A L2C	
Nav. update rate	RTK	up to 20 Hz[1]
Position accuracy[2]	RTK	0.01 m + 1 ppm CEP
Convergence time[2]	RTK	< 10 sec
Acquisition	Cold starts Aided starts Reacquisition	24 s 2 s 2 s
Tracking & Nav. Cold starts Hot starts Reacquisition	-167 dBm -148 dBm -157 dBm -160 dBm	
Assistance	AssistNow Online OMA SUPL & 3GPP compliant	
Oscillator	TCXO	
RTC crystal	Built-In	
Anti-jamming	Active CW detection and removal Onboard band pass filter	
Anti-spoofing	Advanced anti-spoofing algorithms	
Memory	Flash	
Supported antennas	Active	

1 The highest navigation rate can limit the number of supported constellations
2 Depends on atmospheric conditions, baseline length, GNSS antenna, multipath conditions, satellite visibility, and geometry

Interfaces

Serial interfaces	2 UART 1 SPI 1 USB 1 DDC (I^2C compliant)
Digital I/O	Configurable timepulse
Timepulse	Configurable: 0.25 Hz to 10 MHz
Protocols	NMEA, UBX binary, RTCM version 3.3

Electrical data

Supply voltage	2.7 V to 3.6 V
Power consumption	68 mA @ 3.0 V (continuous)
Backup supply	1.65 V to 3.6 V

Package

54-pin LGA (Land Grid Array)
17 x 22 x 2.4 mm

Environmental data, quality & reliability

Operating temp.	–40 °C to +85 °C
Storage temp.	–40 °C to +85 °C
RoHS compliant (2015/863/EU)	
Green (halogen-free)	
ETSI-RED compliant	
Qualification according to ISO 16750	
Manufactured and fully tested in ISO/TS 16949 certified production sites	
High vibration and shock resistance	

Support products

u-blox support products provide reference design, and allow efficient integration and evaluation of u-blox positioning technology.

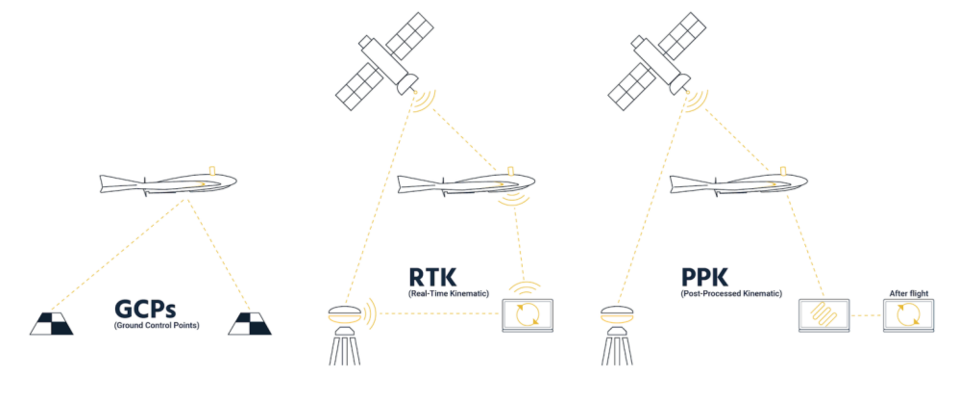
C099-F9P	u-blox ZED-F9P application board, with ODIN-W2 for connectivity. Includes Multi-band antenna (ANN-MB). One board per package.

Product variants

ZED-F9P	u-blox F9 high precision GNSS module with rover and base functionality

More info on GNSS RTK/PPK

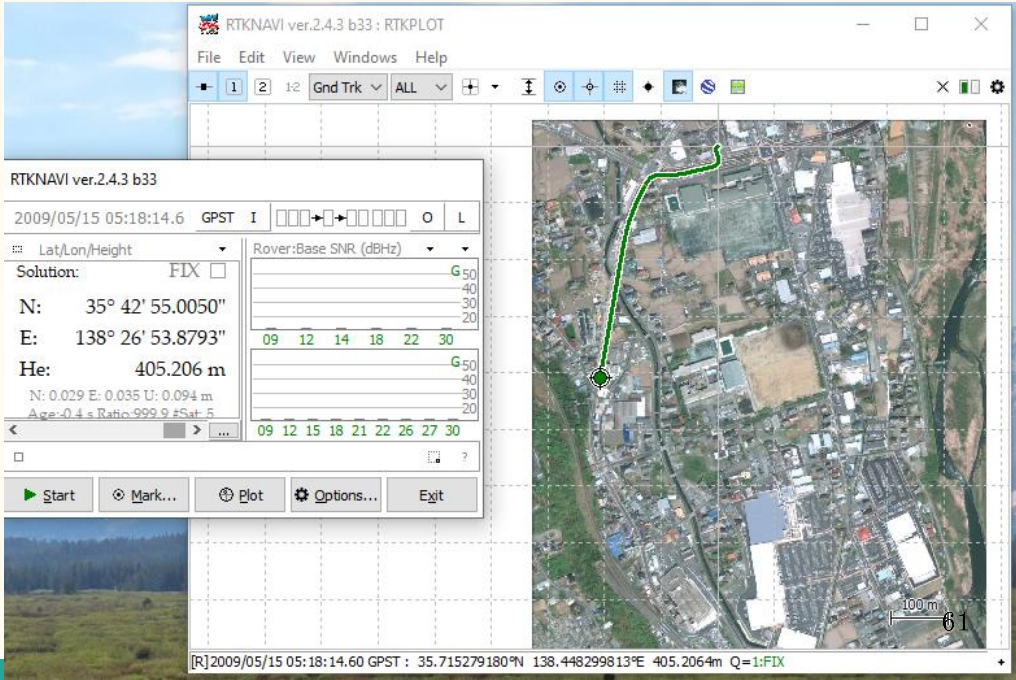
- RTK GNSS is a correction method for getting more accurate data points
- It uses a live link with a base station as a reference point
- This live link can be lost, especially in rough terrain
- However, PPK does not need a live link to the base station, as the correction is done after the data is collected (hence the name Post-Processed)
- Data from the receiver and base station are combined via a software program to create highly accurate and precise data



From: https://waypoint.sensefly.com/gcps-rtk-ppk-when-what-why/

GNSS PPK Software

Some options still need to be explored here. The receiver manufacturer sells PPK software that can be investigated. There is also free software called RTKLIB that might work.

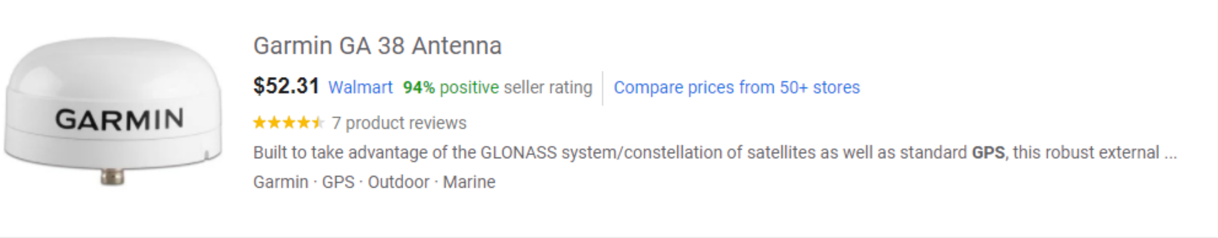


Screenshot from RTKLIB

GNSS Antenna

Will also need to buy an antenna for the receiver for probably around $100, although needs to be looked into further.

Something like one of these:



GNSS CORS Base Station

CORS base station required for PPK referencing located in Breckinridge, CO within 10 miles of Copper