University of Colorado, Boulder
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

SIMBA

Conceptual Design Document

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I. Project Description

A. Purpose

Current avalanche prediction techniques often require researchers to spend hours digging 1-2 m deep snow pits on the side of avalanche prone areas. This presents an inherent safety risk to those digging as snow pit locations can be difficult to decide as snow depths can have high variability due to changing environmental conditions. Our project aims to provide the ability to remotely access and monitor snow depth in high risk areas of the Copper Mountain ski resort to help maximize safety and minimize time spent digging these pits. Snow depth data that is collected over a given area for several months would help ski patrol decide where to dig more tactically. Accurate and regularly updated snow depth data can also enhance current avalanche prediction models and can provide information for explosives planning, boot packing, and ski cutting. Equipped with more data, ski patrol will be safer and more efficient when maintaining the mountain resort.

B. Project Objectives

The objectives of this project are found in table 1, which contains the three levels of success determined for our remote sensing vehicle. Tier one focuses on researching an accessible and commercially available sensor package capable of measuring snow depth with an acceptable level of accuracy. This sensor would then be mounted on an aircraft capable of flying in high altitudes. The next level of success involves mounting the sensor package on a drone that can stabilize the sensor so it can take accurate snow depth measurements in adverse weather conditions. The second level of success also includes greater sensor accuracy and resolution and better data visualisation after the flight has been conducted. The final level of success is a drone capable of flying an efficient flight path such that the sensor can gather information as quickly and accurately as possible for the given area. This requirement includes greater sensor accuracy, more precise location data, and an aircraft capable of flying in severe weather conditions. The sensor and drone combination will be tested in high altitude conditions similar to those found on Copper Mountain. Level three success is the design goal of the team.

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 must be able to maintain steady, level flight at density and altitude conditions found on the top of Copper Mountain with wind gusts up to 10 knot.
2	Snow depth is measured to within ±15cm.	Positional data is collected with an accuracy within ±10cm	A heat map is overlayed onto a map of Copper Mountain	Aircraft must be able to maintain steady, level flight at density and altitude conditions found on the top of Copper Mountain with wind gusts up to 20 knot.
3	Snow depth is measured to within ±10cm.	Positional data is collected with an accuracy within ±5cm		Aircraft must be stable in 25 knots winds at density and altitude conditions found at the top of Copper Mountain.

C. Concept of Operations

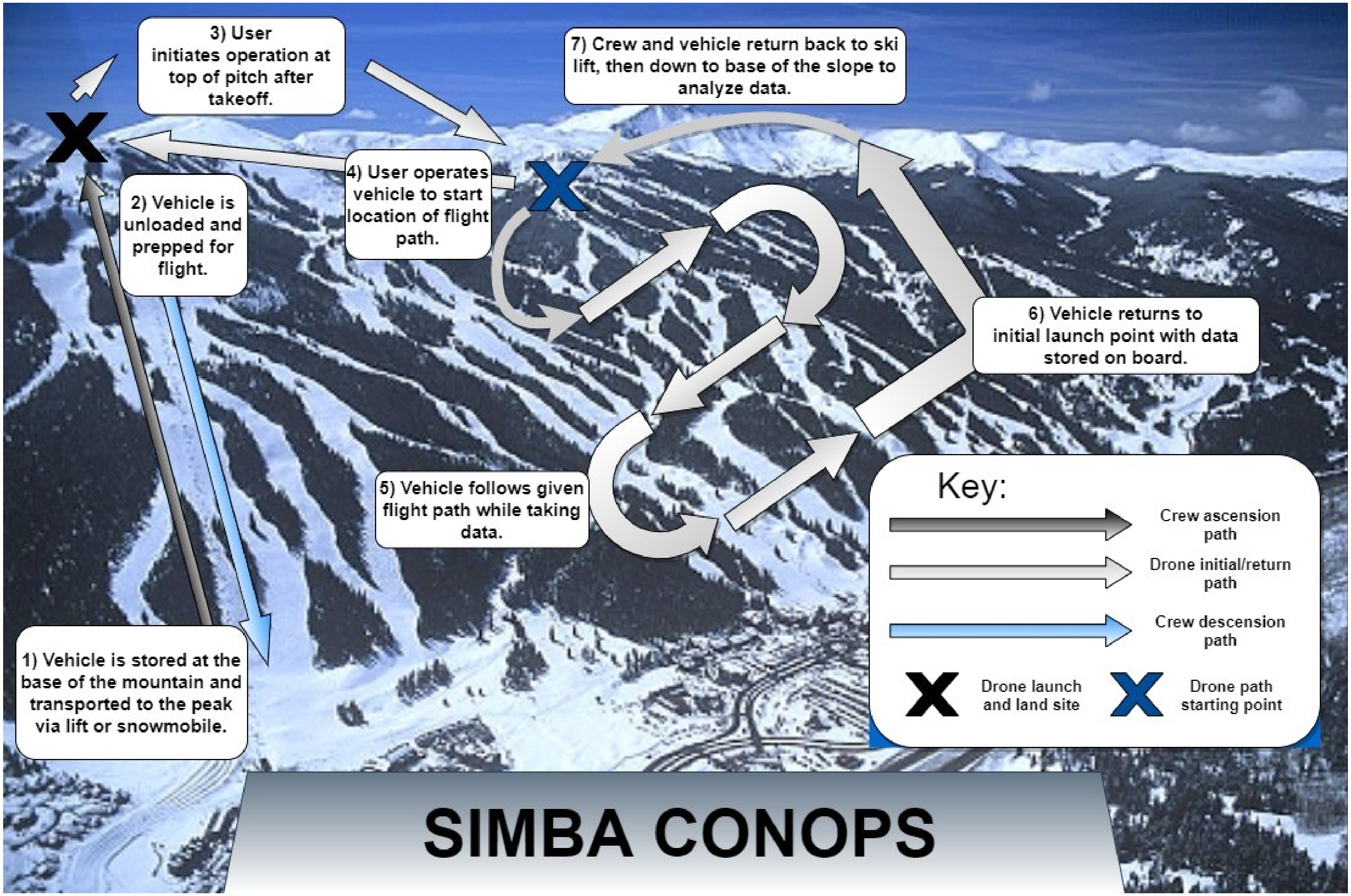

Fig. 1 Concept of Operation for project SIMBA

D. Functional Block Diagram

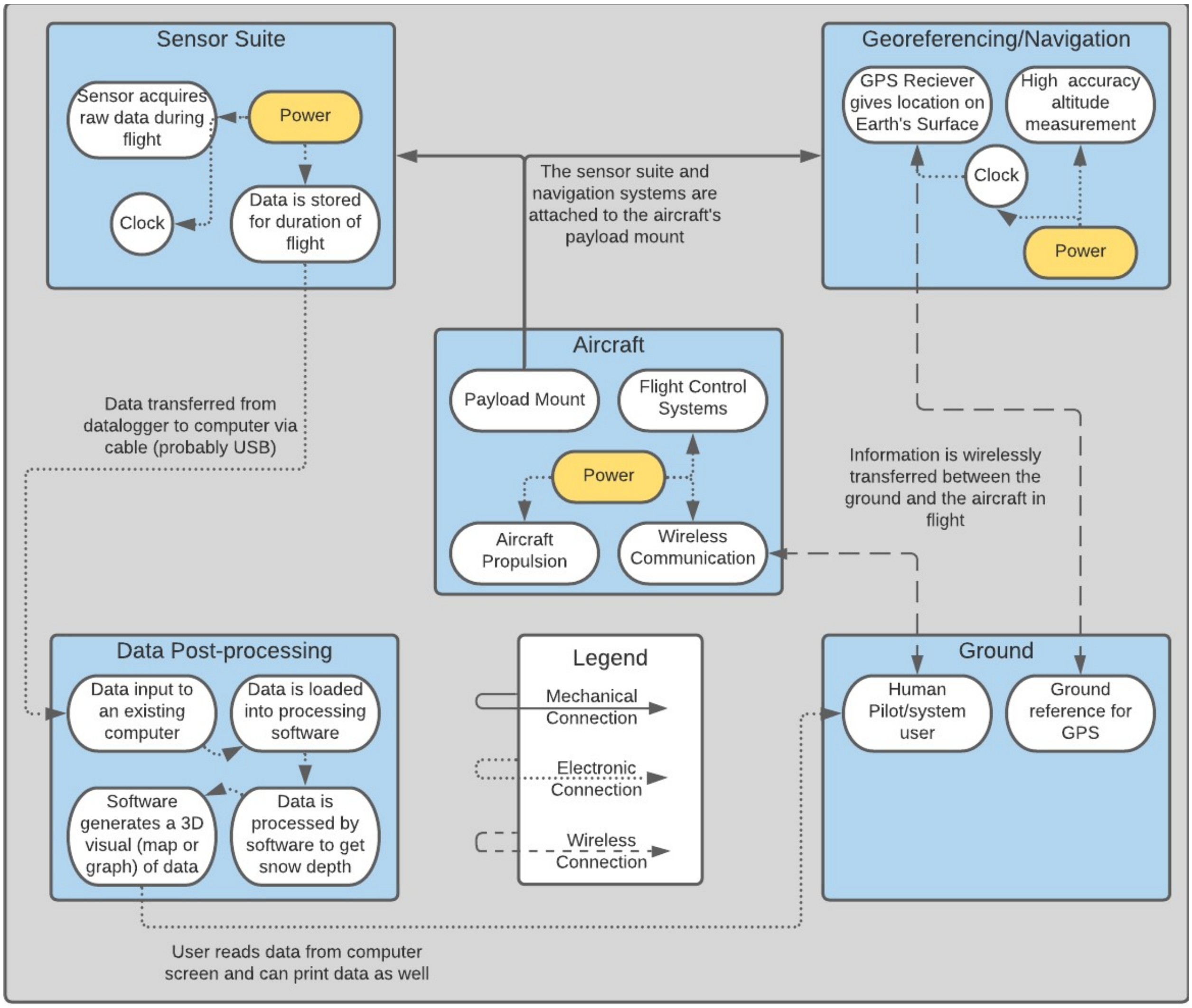

Fig. 2 Functional Block Diagram for SIMBA

E. 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 will occur in a reasonable amount of time.
FR 3	The system shall be able to operate in the 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

II. Design Requirements

FR 1: The system shall implement a snow depth detection system to assist Copper Mountain ski patrol in avalanche mitigation.

Motivation: The mission calls for accurate measurements of snow depth.
Validation: Multiple fully integrated system tests are performed to quantify the distance measurements precision and accuracy between the system and a snowy surface.

DR 1.1: The snow depth measurements shall be accurate to ±10cm.

Motivation: This was the accuracy determined by the customer for the collected information to be useful.
Validation: A test is performed to determine the statistical spread for the distance measurements for the sensor package for a given, known distance.

DR 1.2: The snow depth data shall have a maximum spatial resolution of at least 6m by 6m.

Motivation: This was the accuracy determined by the customer for the collected information to be useful.
Validation: To account for varying terrain within the 6m by 6m area such as a steep cliff, careful flight planning must be conducted or smaller spatial resolution must be achieved. A flight test is performed to test the systems ability to create collect data in a minimum of 6m by 6m spaces.

DR 1.3: The system shall be able to meet requirements in areas clear of foliage.

Motivation: The mission requires coverage of clear areas only as most areas of concern are above tree line.
Validation: A flight test is performed in a clear open area to confirm snow depth accuracy can be reliable achieved.

DR 1.4: The sensor package must meet these requirements at an altitude of no more than 122m (400ft) above ground level.

Motivation: Compliance with FAR 107.51
Validation: A test is performed with the sensor package from 0 to 122m away from a snowy surface. The test is a pass if the instrument is able to determine the required accuracy for some location during the testing.

FR 2: The system shall be able to operate with acceptable endurance such that data collection will occur in a reasonable amount of time.

Motivation: It will not be possible for the system to collect snow depth measurements in a timely manner if the system has to be recharged multiple times during a measuring session.
Validation: A fully integrated flight test is performed to determine if the system is able to collected measurements for the required area without having to return to home for recharging/resetting the system.

DR 2.1: The system shall have the endurance to collect snow data on an area of at least 0.3 km^2. This means the vehicle must have the endurance, stability, and maneuverability so the sensor package can collect the snow depth to the required accuracy. See section 3 for aircraft specifics.

Motivation: A certain amount of the mountain must be surveyed to obtain enough data to make an informed decision.
Validation: A fully integrated flight test is performed to determine if the vehicle has the necessary endurance such that the sensor package can collected the required data resolution.

FR 3: The system shall be able to operate in the typical weather conditions found on the top of Copper Mountain.

Motivation: A typical day is considered one standard deviation worse then the average weather condition calculated from multiple days of weather data for the peak of Copper Mountain.
Validation: A fully integrated flight test will be performed for the given worst case weather condition. The vehicle passes if the sensor package is able to collect the required data accuracy and resolution in one flight.

DR 3.1: The system shall have a service ceiling of no less than 4,267 m (14,000 ft) density altitude.

Motivation: Estimated upper bound for density altitude during winter operations
Validation: A flight test with dummy payload is performed at a density density altitude of 4,267 m (14,000 ft) for the endurance time required by the sensor package to get the required resolution over the given testing area.

DR 3.1.1: The aircraft must be able to climb/descend at at least 5 m/s at Vy at 4,267 m (14,000 ft) density altitude.

Motivation: Escape 305m/min (1,000 ft/min) downdraft.
Validation: A test flight with dummy payload is performed at a density altitude of 4,267 m (14,000 ft) is conducted where the vehicle is attempted to be flown at a 305 m/min (1,000 ft/min) climb rate, or a test flight is conducted at a lower density altitude, the climb rate is measured, and climb rate equations are used to determine the climb rate at 4,267 m (14,000 ft) density altitude.

DR 3.1.2: Landing and takeoff requirements must be met at this density altitude.

Motivation: Will be landing and taking off from the top of Copper Mountain.
Validation: A test flight with dummy payload at a density altitude of 4,267 m (14,000 ft) is conducted where the aircraft is attempted to to go from stationary to flying condition in an area of 12m by 12m.

DR 3.2: The system shall be able to operate and collect data in temperature as low as -23°C. This means that all mechanical subsystems must be operable in these temperatures and the aircraft must meet endurance and performance requirements at these temperatures.

Motivation: Requirement from customer.
Validation: A ground test is performed where all mechanical systems are moved in a -23°C environment looking for freedom of motion alongside the battery system which will also be tested at the -23°C environment.

DR 3.2.1: Fuel/oil system does not freeze/battery pack is able to supply sufficient power through the entire flight profile.

Motivation: Propulsion system must be able to deliver the shaft horsepower necessary for flight across the entire mission profile.
Validation: The battery will be tested in a -19°C environment with a dummy load. The total discharge power is measured is then compared to the estimated power required to fly the vehicle.

DR 3.2.2: Aircraft structural material should not see significant change (>10%)to any of its properties (i.e. tensile strength, elasticity, shear strength, etc) at this operating temperature vs room temperature or 23°C.

Motivation: Aircraft must maintain structural integrity in all flight conditions.
Validation: A serious of ground tests are conducted on each type of material used within the system. Tensile strength, elasticity, shear strength, etc will be measured at room temperature (20°C) and then -19°C. The results are compared.

DR 3.3: The system shall be able to operate in 4 m/s of sustained wind.

Motivation: Minimum realistic wind based on weather data. Level 2: 10 m/s. Level 3: 18m/s.
Validation: Simulate the vehicle in wind and measure how the vehicle translates and rolls.

DR 3.4: The system shall be able to endure a 1m/s gust factor from any 3D direction.

Motivation: Estimated values for windshear/gust factor. Level 2: 4 m/s. Level 3: 6m/s.
Validation: Simulate the vehicle in 1m/s gust and measure how the vehicle translates and rolls.

DR 3.4.1: The aircraft shall not roll more than TBD degrees based on sensor accuracy in any axis during a gust to provide the sensor package with the needed stability for the required accuracy.

Motivation: The aircraft must provide the sensor package with its required stability even in gusting winds. Gusts from any 3D dimension could generate a moment rolling the aircraft.
Validation: Multiple simulations with gust of 1 m/s coming from a variety of direction. The resulting role of the vehicle is measured.

DR 3.4.2: The aircraft shall not translate more than TBD meters based on sensor accuracy in any axis to provide the sensor package with the needed stability for the required accuracy.

Motivation: The aircraft must provide the sensor package with its required stability even in gusting winds. Gusts from any 3D dimension could generate translations forces moving the aircraft
Validation: Multiple simulations with gust of 1 m/s coming from a variety of direction. The resulting translation of the vehicle is measured.

DR 3.5: The system shall be able to take off and land in a 20mx20m area and climb to 4.6 m (15 ft).

Motivation: The aircraft needs to be able to enter and leave self sustained flight so that no system sustains damage.
Validation: In the worst flight condition TBD, a flight test with a dummy payload is conducted to measure vehicle takeoff distance.

DR 3.5.1: The aircraft must be able to takeoff and land in both snow in the required area. This means that when operating in snow conditions, the aircraft shall not apply a pressure to the ground greater than blank at anytime during the mission. It is expected that landing will dynamically double the pressure the aircraft exerts.

Motivation: Operation winter conditions will require the aircraft to operate in snowy conditions. The requirement will keep the aircraft from sinking into the snow on takeoff or landing which could flip/roll the aircraft, or keep it from achieving liftoff.
Validation: The foot print of the vehicle is measured and then divided by the measured vehicles takeoff mass. This value is then compared to a selected snow condition resistance to deflection.

DR 3.5.2: The aircraft must be able to takeoff and land on rough, rocky terrain in the given area.

Motivation: Sometimes the takeoff landing area with be wind swept, or the aircraft will be operated outside of winter conditions were no snow is present.
Validation: A flight test is conducted where the vehicle with a dummy payload lands on rough rocky terrain. System damage is then assessed.

DR 3.5.3: Aircraft ground roll shall not exceed a 12mx12m area

Motivation: Ground roll should not exceed 60% of the total takeoff distance to provide enough time to get to 15.25m (50 ft) within the takeoff/landing area for clearing obstacles
Validation: At a density altitude of 4,267 m (14,000 ft), 0 m/s wind speed, the take off role is measured with a video camera.

DR 3.6: Aircraft must have necessary lifting capabilities for the mission while staying under the FAA weight restriction.

Motivation: The vehicle can not fly if FAA weight restrictions are exceeded. However, the mission is a failure if the vehicle can not lift the required mass to complete the mission.
Validation: The fully integrated system weight is measured. Next, a flight test is conducted to see if the vehicle can lift the takeoff mass off the ground in the required takeoff distance and have the required climb rate.

DR 3.6.1: Aircraft must be able to lift its weight up to the limit of 25kg (55lbs).

Motivation: FAR107.3. requirements
Validation: The fully integrated system weight is measured and compared to the FAR107.3 restriction.

DR 3.6.2: The aircraft must be able to carry the payload weight and meet required endurance.

Motivation: The vehicle can only complete the mission if it is able to lift the payload airborne for the required endurance time.
Validation: A flight test with dummy payload is conducted to see if the vehicle can lift the takeoff mass off the ground in the required takeoff distance.

DR 3.7: Turn radius not greater than 10m

Motivation: Adequate maneuverability to avoid terrain and other obstacles; provide for 20mx20m grid.
Validation: A flight test with dummy payload is conducted at flight speed and the turning radius is measured.

DR 3.8: Propulsion vibrations must be low enough to not effect snow depth measurement accuracy.

Motivation: Vibration could lead to blurred images for photogrammetry or errors in other range finders.
Validation: The maximum frequency and amplitude of vibrations are determined by the selected sensor. A flight test with dummy payload is conducted with a sensor that measures vibrations. The recorded vibrations are then compared against the vibration restriction set by the sensor package.

DR 3.9: Aircraft and its stability augmentation system must be able to provided the sensor with the required 6 degrees of freedom for accurate snow depth measurements

Motivation: The aircraft and controlling software must provide a stable enough platform for the sensor package. This represents all 6 DOFs.
Validation: The required stability in each DOF is determined by the payload package. In typical weather conditions (FR 3) are simulated for the aircraft. With no pilot input, the system stability is measured and compared to the required stability set by the sensor package.

DR 3.9.1: There should be no fast ($|\tau| < 0.5$ s) unstable dynamic modes.

Motivation: $|\tau| < 0.5$ s ensures both that the vehicle is controllable and the sensor package can collect the needed measurement accuracy.
Validation: The system is simulated with a multiple disturbances. The system response is then measured and τ is calculated.

DR 3.9.2: There should not be any stable but very underdamped modes ($|\zeta < 0.3$) (slow oscillation)

Motivation: $\zeta < 0.3$ ensures both that the vehicle is controllable and the sensor package can collect the needed measurement accuracy.

Validation: The system is simulated with a multiple disturbances. The system response is then measured and ζ is calculated.

DR 3.9.3: The augmentation system must not be put the aircraft into any unstable mode by any form of vibration the aircraft could see (aeroelastic flutter, propulsion vibration, etc)

Motivation: The aircraft will see short period oscillations (especially in wind) that could confuse the augmentation system leading to unstable dynamic oscillation and eventual crash or bad data collection.
Validation: The system is simulated with a multiple disturbances. The system response is then measured and the data is search for any high frequency undamped oscillations.

DR 3.10: The aircraft must be waterproofed such that water/snow entering the aircraft do not damage the electronics.

Motivation: Possible flights in precipitation and possibility of snow melting on aircraft.
Validation: All external hardware and the vehicle itself will be subjected to a submersion test to look for leaks.

DR 3.11: Safety due to loss of signal, loss of power to the propeller, or loss of control to the control surfaces.

Motivation: The aircraft must be able to be brought down to the ground in such a manner that in a critical error, no person (ski patrol or other) can be put in danger. This means auto home for lost signal, 10:1 glide ratio or more or autorotation. Worst case scenario, aircraft must be as light as possible for complete loss of control to the control surfaces
Validation: Failure in some form is inevitable. Therefore, flight tests are with dummy payload are conducted to record how the vehicle responds to different failure modes TBD.

DR 3.11.1: Ground station/vehicle impediment on the ground.

Motivation: In a ski resort, crashes due to vehicle impediment could result in severe injury.
Validation: The final system and ground station footprint is compared to the area of interest. Any physical impediment with the vehicle in operation that makes it not possible to navigate the area is recorded.

DR 3.11.2: Loss of thrust

Motivation: Loss of thrust is a possible due to manufacturing trouble, user error, etc. Depending on the vehicle could make loss of thrust mission termination or at worst a falling projectile.
Validation: A flight test with dummy payload is conducted where at 400 ft AGL the throttle is brought to 0 and the aircraft is attempted to be landed.

FR 4: Data must be stored onboard for the flight duration and transferred to an existing computer system after the flight.

Motivation: This will facilitate data collection and processing post-flight in order to display snow depth.
Validation: A fully integrated flight test is conducted. The data measured will be transferred to a Copper Mountain computer. The data will then be scanned for bit loss and other data storage/transfer errors.

DR 4.1: Data storage must be large enough to store 100 acres of data until the vehicle returns to its launch point.

Motivation: Data storage capabilities must be large enough to store data collected from the minimum collection area. 100 acres represents the minimum collection area with some tolerance.
Validation: The data storage space is measured and compared against the required space to store 100 acres of data.

DR 4.2: Data must be able to be transferred to a computer for post-processing using available interfaces via a cable, preferably a USB.

Motivation: Data collected needs to be transferred to the computers found at Copper Mountain in order to be processed and displayed. To enable this transfer, a common interface must be used such as USB.
Validation: Flight test data will be transferred using a cable to a computer utilizing the same software.

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.

Motivation: This will allow the staff at Copper mountain to run a good quality, efficient, and accurate analysis of any avalanche threats with ease.
Validation: A full system flight test is conducted and the data will be processed and the delivered snow depth data is compared to manual snow depth measurements.

DR 5.1: System must be able to take in data from a datalogger.

Motivation: This will allow the program to overlay the data onto a map for the staff to use for their analysis.
Validation: Check to see if the software is compatible with the the output file of the datalogger.

DR 5.2: System must be able to process data type output by the datalogger.

Motivation: If the system cannot process the data type output by the datalogger, then data collected will not be able to be interpreted and will be useless.
Validation: Check to see if software processes data.

DR 5.3: Software must be able to return the depth of snow at given locations at a given time

Motivation: The raw data is not useful unless the snow depth is calculated at each specific location and time.
Validation: Check to see if the software overlays data onto a geophysical map.

DR 5.4: When post-processing, the software must generate a visual representation of the data.

Motivation: This is customer preference because they believe this type of visualization will provide the most information to them and their team.
Validation: Check if the software can output a readable map or graph of the data.

DR 5.5: System must be able to input and display processed data into a computer or other device owned by the ski patrol quickly.

Motivation: This allows for easier integration into the staff's (at Copper Mountain) computer systems.
Validation: If the software can run on a Mac or a Windows, this would be sufficient for the software.

DR 5.5.1: Post-processing must be easy enough for a non-technical employee to use

Motivation: This allows for wide usability.
Validation: Test this by allowing a staff member at Copper Mountain to use the system and we will analyze the difficulty in use of it.

DR 5.5.2: Data visualization must be easily read and understood by our customer.

Motivation: Provides quality data without the user having any background information on the post-processing.
Validation: Check to see if the output has good quality visuals as well as data. Also make sure that the output is easy enough to read (graphs are labeled, legends and keys are present, etc.)

DR 5.5.3: Data processing must be quick (a few minutes not a few hours).

Motivation: The staff needs to analyze the data as quickly as possible to highlight any threats from avalanches. Therefore the data they will analyze needs to be processed quickly.
Validation: Record the time it takes for the software to compile its output.

FR 6: The system shall collect location data accurately in order to navigate and assist with snow depth mapping.

<u>**Motivation**</u>: It will not be possible to collect useful snow depth measurements without the aircraft location relative to the ground.
<u>**Validation**</u>: Perform a flight test and compare location data accuracy to ground based position measurements.

DR 6.1: The system shall be able to locate itself laterally with an accuracy of 6m x 6m

<u>**Motivation**</u>: The lateral location accuracy is used to match up terrain maps with each other to compare snow depth at different times. The 6m x 6m is the customer's desired resolution
<u>**Validation**</u>: The subsytem in charge of measuring lateral position is tested in a variety of setting and the accuracy and precision is reported and compared against the required values.

DR 6.2: The system shall be able to locate itself vertically with an accuracy ±10cm.

<u>**Motivation**</u>: Vertical position is important for data processing in three axis.
<u>**Validation**</u>: The vertical position subsystem will be tested in a variety of locations of known altitude. The measured positions accuracy and precision will be recorded and compared.

FR 7: The system shall be compliant with the appropriate Federal Aviation Requirements and avoid flying over populated regions of the ski resort

<u>**Motivation**</u>: Failure of the system to meet USA laws will force the system to be ground.
<u>**Validation**</u>: The final system will be compared to FAR 107 section in detail to insure no section is violated. Same goes for the communication system with FCC regulations.

DR 7.1: The system shall be compliant with FAR section 107 and FCC rules that deals with small unmanned aircraft.

<u>**Motivation**</u>: Must comply with the law so Copper does not get sued
<u>**Validation**</u>: The final system will be compared to FAR 107 section in detail to insure no section is violated.

DR 7.2: The aircraft should avoid flying over populated regions of the ski resort in order to ensure safety.

<u>**Motivation**</u>: Won't want a customer to get hit, again avoiding lawsuits.
<u>**Validation**</u>: Potential flight paths are explored and then compared to populated areas.

III. Key Design Options Considered

A. Data Processing Software

To make the data that will be gathered by the system have worth, it needs to be processed and presented in a useful and understandable manner. To do this, software with terrain mapping capabilities are required. Raw, unfiltered and unprocessed data from a flight does not mean anything to the Ski Patrol; they need to know where and when the data was taken. Beyond that, they also need to compare the data to previously collected sets of data (i.e. a dry mountainside in the summer to a snow-covered one in the winter) to determine how the snow depth has changed over time. Finally, the data is much more useful and quicker for a person to process if it is presented in a visual manner (in this case some kind of map). Software post-processing of the data needs to be able to fulfil all of these requirements in a reasonable amount of time.

*1. **Python 3***

One option for software data processing is Python 3. Python has many libraries that could be used to complete the required data processing and visualization requirements (**FR 5**), like the matplotlib, mplot3d, and basemap libraries.

The main advantages of using Python are its flexibility and availability. Python is a free and open-source programming language, meaning it is usable for free even by commercial entities. It is also used widely, so there are many free support forums and open-source libraries for all sorts of different problems (including terrain mapping). Python downloads are also available for most computer devices and operating systems, so the Ski Patrol's devices should not have any issue using a program developed in Python (**DR 5.4**). Another advantage is that the design team has some experience using Python in the past, so the learning curve would be small.

A major disadvantage is that 3D rendering tends to be very slow in Python, and the 3D mapping/graphing libraries are less refined than some other programming languages. Another disadvantage is that most (if not all) members of the ski patrol will not have familiarity with the software (**DR 5.4.1**). This disadvantage could be minimized by developing a GUI to interact with, but this an additional load on the team. Finally, Python is not a programming language that is focused on 3D terrain mapping, so while there are many libraries for Python, the design team would likely have to create some of the terrain mapping elements from scratch. [17]

Advantages	**Disadvantages**
Free and open-source	3D Rendering slow and not well-optimized
Widely available and plenty of support	Unfamiliar to Ski Patrol
Some members have proficiency in Python	Python not focused on terrain mapping

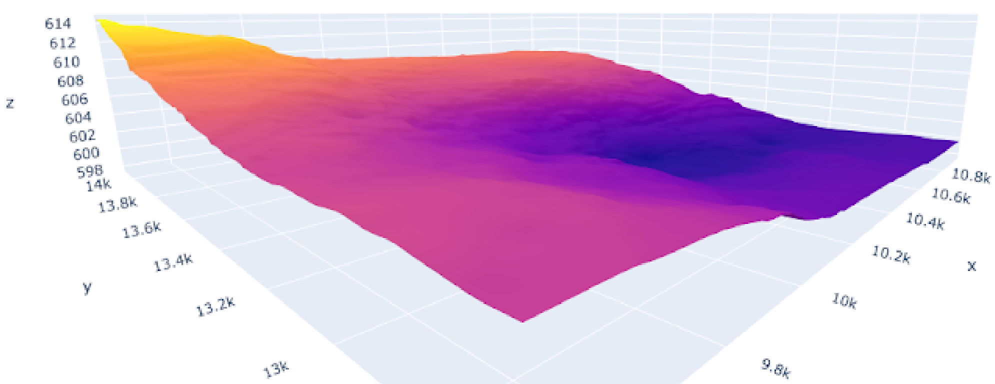

Fig. 3 An example of Python's 3D data visualization capabilities

2. *Matlab*

Matlab is a computer programmed used in the University of Colorado School of Engineering and is a capable data processing tool. Matlab is capable of fulfilling the data visualization required by this system (**FR 5**), but is not commonly used for our data visualization needs.

The main advantage of Matlab is that all members of the team are proficient in it. This is not true with the customer. Some training would be required to operate Matlab even if a fairly robust GUI was made.

The main disadvantages are the limited and somewhat clunky data visualization capabilites of Matlab, the training required in order for the Copper Ski Patrol to operate it, and the cost. Matlab is not a program that Copper Mountain currently owns and licensing costs $860 annually or $2,150 for a perpetual license. [25]

Advantages	**Disadvantages**
Familiar to the design team	Training required for Copper Mountain
Large-scale data analysis	Data visualization
	Cost

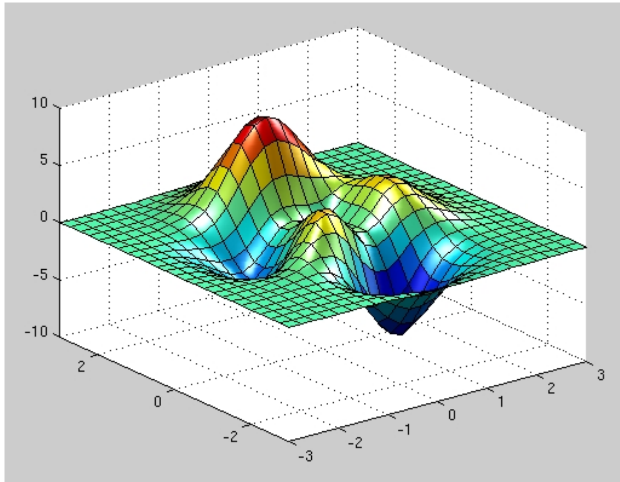

Fig. 4 An example of Matlab's 3D data visualization capabilites

*3. **ArcGIS***

ArcGIS is a desktop application that overlays physical data on top of geophysical features. One major appeal of this application is the fact that it accepts a large variety of data types which means that there would be a good chance that its robust ability in file intake would not hamper other design choices. So this would satisfy the requirement for the application to be able to read in datalogger data (**DR 5.1**) and process it (**DR 5.2**). In terms of data visualization, ArcGIS has a a large amount of mapping interface options and geophysical maps, satisfying our previous design requirements as well. It also has a large amount of 3D mapping options which directly satisfies **DR 5.3.1**. One con is our team is unfamiliar with ArcGIS's libraries so we are unfamiliar of the quality of geophysical data. If there is no library containing quality grid data in ArcGIS then it would hamper the quality of our data and put our team at risk of not meeting resolution requirements specified by the instrument package. Another con is that the training and tutorials for the program cost money. However, it is available to CU students for free, and is currently used by Copper Mountain's ski patrol, establishing familiarity. Any extra training necessary can be done by the design team.

In discussing the team's ability to build a program for the user so that post-processing is easy enough for a non-technical employee use (**DR 5.4.1**) and a program that outputs an easy to read graphic (**DR 5.4.2**), ArcGIS allows multiple methods to complete this requirement. To further explain, ArcGIS has multiple application programming interfaces (API) available to use. This allows our team a variety of languages they are comfortable coding in to create a program for our end user. However, if our team finds that building a program for the end user is too timely, there are user-friendly interface programs readily available so we could provide instructions on how to use these programs. However, this might require some training from the staff at Copper Mountain which could fit into the 40 hour training period that customer has allotted for their employees. [2]

Advantages	**Disadvantages**
No experience in coding is necessary if we build a program	Not an intuitive program without an interface
Training is available for user-friendly APIs	Training directly from ArcGIS costs money outside of CU.
A large variety of interactive mapping options	Experience is necessary to make quality maps
There are multiple APIs including Java and Python	The APIs will take some learning
Large suite of applications for user interface	This interface would take some training
Overall good quality package options and customization	Not sure if there are libraries with geophysical data
Has a large variety in 3D mapping options	
Large variety of data types ares supported	

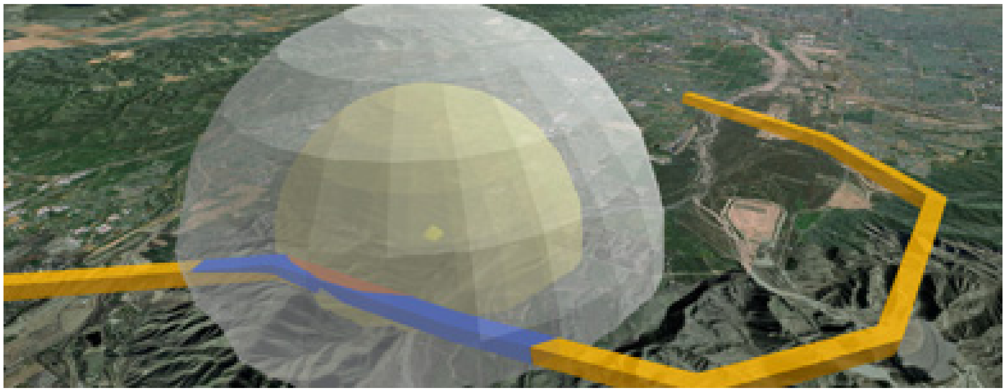

Fig. 5 Image showing an example of a 3D model of LiDAR data taken over a mountainous terrain which was processed by ArcGIS

*4. **Google Earth Engine***

Google Earth is a software suite that focuses on providing high-resolution images and maps of the Earth's surface. Google Earth Engine is the component of the software suite that focuses on data processing and customizing 3D images.

The main advantage is that Google Earth has a huge volume of preexisting data about the Earth's surface. Also, the graphics developed in Google Earth are the best looking out of all of the options considered (**DR 5.4.2**).

The main disadvantage is that Google Earth Engine is not free for commercial groups. Also, the data input types in Google Earth Engine are extremely limited. The design team currently has no experience with Google Earth Engine, so there will be some learning curve. Finally, the programs developed in Google Earth Engine are not very user friendly (**DR 5.4.1**). [26]

Advantages	**Disadvantages**
Allows data input to be overlayed	Input file types are limited
Geophysical has good quality that would meet resolution standards	Google Earth Engine is expensive outside of CU
Allows developers to make user-friendly interface	Making user friendly interface is time-consuming

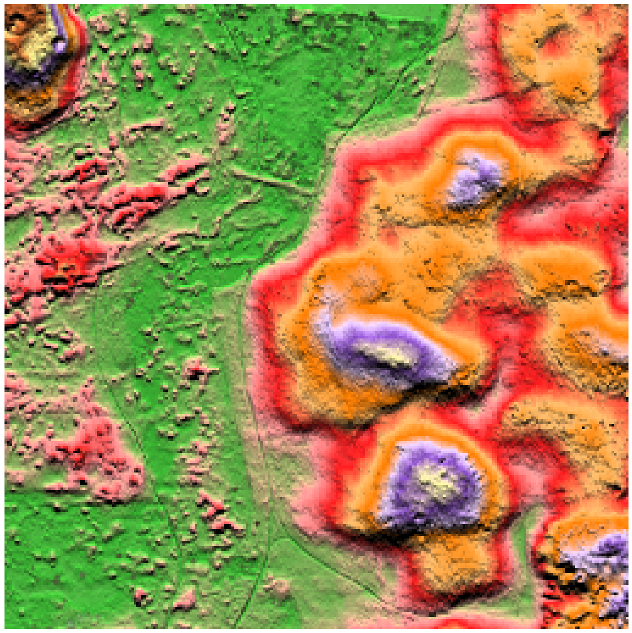

Fig. 6 Image created from LiDAR data from the Netherlands between 2007 and 2012. Contains ground level samples with all items above the ground removed.

B. Vehicle/Platform Design

In order to compare each aircraft option, an estimation of aircraft takeoff weight and fuel/battery weight was obtained for the following parameters:

- 1.5 kg payload
- 60 minute endurance

The fraction of takeoff weight for payload and fuel/battery is then compared. Using this method allowed the team to account for differences in takeoff weight of different aircraft, even though the actual endurance and payload may be different.

*1. **Fixed wing UAV***

Some key data used in airplane performance sizing follows. Note that the full list of parameters and values used in analysing the aircraft is in the appendix.

- m_{PL} = 1.5 kg. Mass of payload. This is subject to change based on the chosen sensor package and its mass.

- ηc = 200000 J kg^{-1}. Product of propulsion system efficiency and LiPo capacity in cold conditions. More data is needed to determine what a reasonable value for this parameter is.

- t = 3600 s. Required endurance. This value may change depending on the sensor package.

- v_{crs} = 10 m s^{-1}. Cruise velocity. Subject to change depending on sensor requirements.

- ρ = 0.8 kg m^{-3}. Air density. Based on standard atmosphere for 14,000 ft.

An equation for the takeoff weight and the battery weight was derived (see appendix). This equation results in a takeoff mass of 8.65 kg and the aircraft would require approximately 1.5kg of batteries. In turn, both the payload and the batteries would make up approximately 17% of the aircraft's takeoff weight.
In order to determine the appropriate ranges of wing loading and thrust-to-weight ratio, the aircraft performance sizing plot must be generated. All data is taken at a standard atmosphere altitude of 4,267 m (14,000 ft) which results in an air

density of 0.8 kg m^{-3}.
The following parameters are considered:

- Stall speed. While there are no explicit stall speed requirements for the aircraft to meet, a stall speed of 8 m/s is chosen to ensure that the aircraft is not flying unduly fast during landing which would make manual flight difficult.
- Landing distance. While the design requirements do specify the required landing distance, it is suspected that, due to uneven terrain and the expected low friction coefficient between the aircraft's landing gear and the snow, the aircraft will need to be landed on an uphill slope, which does not lend itself easily to being modeled by takeoff distance equations.
- Takeoff distance.
- Climb.
- Maneuvering.
- Speed. The assumed cruise speed of 10 m/s and the dash speed of 30 m/s are used to ensure that speed requirements are met.

See the appendix for the corresponding constraint curves that apply to each of these criteria.

Using all constraint curves, the performance sizing plot is generated:

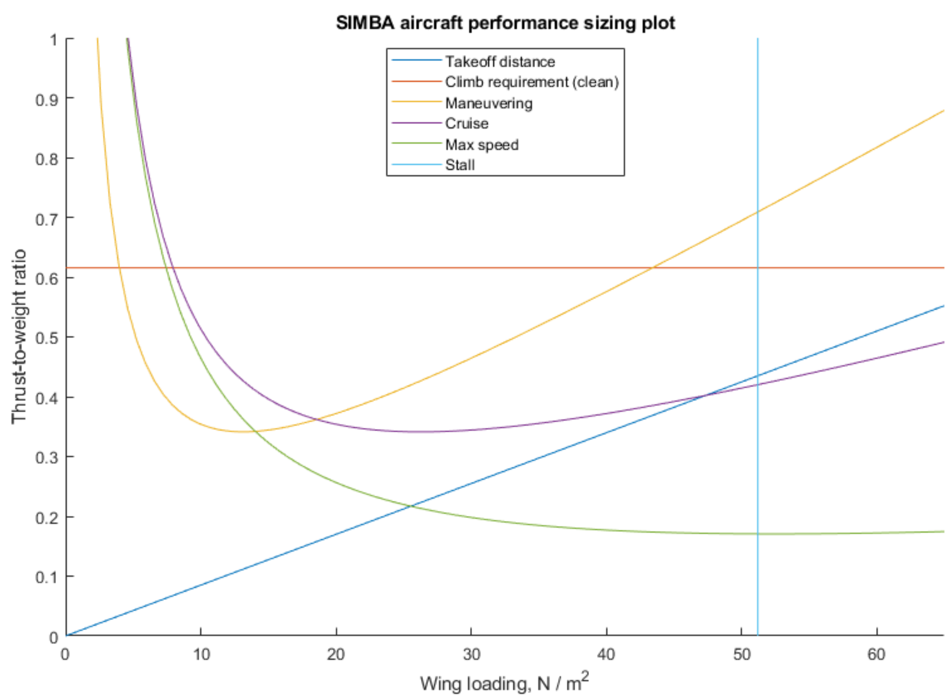

Fig. 7 SIMBA performance sizing plot. The acceptable design area is the area above the climb requirement line and bounded by the cruise, maneuvering, and stall speed curves.

While the wing area does not need to be immediately determined, the climb requirements generally set the required thrust-to-weight ratio; a value of approximately 0.62 is required. This isn't surprising: a UAV this small climbing 305 m/min (1,000 ft/min) is significant. For the sake of determining an estimate of the wetted area, the wing loading is chosen as the wing area associated with the intersection of the climb and maneuvering lines, which calls for a wing area of 44 N m^{-2}. This results in a wing area of 1.93 m^s. The wetted area is estimated as $S_w = 4S = 7.71$ m^2. In turn, the parameter m/S_w takes a value of ≈ 1.12 kg m^{-2}.
This analysis provides the data required to assess weighting matrix points to the airplane solution.

Advantages	Disadvantages
Significant endurance advantage over multirotors	More pilot training required
Better payload weight fraction than multirotors	Novel methods needed to slow aircraft on landing
Can design for very fast airspeeds to escape strong winds	
Can be flown to safe landing in event of propulsion system failure	

*2. **Multi-rotor UAV***

Multi-rotor UAVs are widely used for surveying and geo-mapping in many different situations. There are whole technology companies such as Action Drone USA that develop custom drones for the users specific needs. The custom drone needed to fit the requirements of this project however would be quite expensive and beyond the scope of this project's budget. Multi-rotor UAVs offer their advantages when it comes to safety, still being able to fly or allow the user to make a controlled emergency landing if one or more motors fail. If one fails the other motors can increase speed and therefore thrust output so the UAV can remain airborne. However, this does hinder the rover's performance with stability with the loss of a rotor making it more difficult for angular momentum to be conserved. This would require the rotor with the same rotational motion as the fail rotor, to increase its speed to conserve angular momentum. If the UAV is a hexa or octocopter then even more motors could fail and the rover will still work and make effective emergency landings.

The UAV does not preform well with endurance especially in extreme conditions. On average most UAVs that would be within the cost range of this project's budget could last for about 35 mins. This flight time is also under ideal conditions and not under the cold and wind that would be experienced flying at such altitudes. A sensor could be designed to where the sensor can collect all the data in this flight window. Although, this would limit the possible sensors that could be used and places a hindrance on accuracy. It is also possible to have the ski patrol bring extra batteries that can replace the dead ones when needed, however this adds complexity to the drone and the drone systems.

Advantages	Disadvantages
UAVs are already in use for this purpose	Expensive and most are out of range of budget
Increased stability and safety even with motor failure	Inefficient in power sources and short time of flight

*3. **Ground Effect Vehicle***

Fixed wing vehicles flying in ground effect can greatly reduced the induced drag of equal aircraft flying outside of ground effect. If parasitical/skin friction drag C_{D0} is small relative to over all C_D, reducing induced drag from flying in ground effect can bring down overall drag dramatically. Reducing overall drag maximizes L/D increasing endurance substantially. Flight velocity V will be less for ground effect vehicles due to practical operational concerns. Therefore range is less for vehicles flying in ground effect vs equal aircraft flying outside of ground effect since VL/D will be less. Equation 1 shows the reduction in induced drag [6].

$$\phi = \frac{(16h/S)^2}{1 + (16h/S)^2} \tag{1}$$

For calculating the vehicle sizing for the given arbitrary mission for fixed-wing ground effect vehicle flying 9% of the wing span above the ground, the following values are used.

- $h = 0.09S$
- $M_{PL} = 1.5$ kg
- $c = 200000$ J kg^{-1}
- $(L/D)/\phi = 15$
- $t = 3600$ s
- $\frac{W_e}{W_{TO}} = 0.65$
- $v = 10$ m s^{-1}

Assuming no parasitical drag, flying 9% of the wing span above the ground increases results in L/D=15. Using equation 3 to calculate the take off mass, whole aircraft weight is 6.45kg. The resulting battery weight is 0.8kg. Since ground effect tend to have large empennage and non-prismic wings, the estimated wetted area is four times the wing projection. If wing loading is 43 N/m^2, the wing area is 1.4715 m^2, resulting in a total wetted area of 5.886 m^2. This results in a $\frac{M_{TO}}{A_{wet}} = 1.10$ kg/m^2.

A multi-rotor aircraft hovering in ground effect will see a larger decrease in induced drag vs fixed wing flying in ground effect for the same normalized height. However, a multi-rotor translating in ground effect will quickly see a loss in ground effect, increasing induced drag levels to normal flight levels. Specifically, horizontal flight speeds above 8 m/s see all ground effect lost. An airspeed below 8 m/s is too slow since the vehicle could not meet design requirement 3.3 and potentially fail to meet functional requirement 2. Therefore, a multi-rotor vehicle will be not viable and will not be explored in the trade study. Only the fixed wing ground effect vehicle will be explored in the trade study (see reference [11].

For this project, the ground effect vehicle would have to fly on uneven snow. Ground effect becomes less effective over porous material. Depending on snow conditions this could result in a significant increase in induced drag. Also, rough ground decreases the effectiveness of ground effect further. If the terrain is rolling (hills, slopes, etc), a larger power plant is needed to pull the vehicle over the terrain. This could lead to a larger power plant then an equivalent aircraft flying outside of ground effect. Therefore, flying in ground effect over snow could ultimately lead to larger power plant and potentially larger batteries/more fuel, (see reference [20].

Advantages	**Disadvantages**
Potential to significantly increase endurance	Ineffective over porous surfaces (snow)
Reduced weight vs comparable fixed-wing/multi-rotor	Ineffective over rough surfaces

*4. **Lighter than Air***

Blimps, zeppelins, balloons, and plimps (plane blimp combination) have all been used for aerial surveillance and data sensing. Lighter than air vehicles offer a stable platform and long endurance's. Balloons offer very high endurance and the least amount of complexity at the sacrifice of mobility and wind resistance. Most envelopes for lighter than air vehicles are made of 3-10 mm polyester. These envelopes can be easily pierced and are worn out by UV rays. Blimps, zeppelins, and plimps are mobile while balloons are not. Zeppelins have an internal frame while blimps do not.

Dry air has a density of 1.29 g/L at STP and an average molecular mass of 28.97 g/mol. Helium has a density of 0.179 g/L at STP and an average molecular mass 4.003 g/mol. The buoyant force is equal to the weight of the displaced air. To lift a payload mass of 2 kg 10 m^3 of helium is required. The total mass of a blimp system that can lift 2 kg of payload would be approximately 5 kg. The payload, motors, and batteries account for 96 percent of the mass. A commercial remote controlled blimp that is 6 meters long and holds 10 m^3 of helium has a max speed of 5-6 m/s. The front profile area of a 6 meter long blimp is 1.666 m^2 and the side profile is 3.43 m^2. The large cross sections and low mass of lighter than air vehicles make them vulnerable to wind.

Advantages	**Disadvantages**
Potential to significantly increase endurance	Cost prohibitive (Helium)
Very stable platform	Largest vehicle option
Lift is not effected by temperature and altitude	Cannot fly in mild winds

*5. **Stationary ground based platform***

An alternative to an aerial approach is a ground mounted sensor/camera. The sensor/s would be mounted on poles or trees. A ground based sensor would eliminate the need for a UAV, cutting costs and complexity. The ground based sensors could impose a safety risk to skiers if they are mounted on poles. The sensor/s would need to be weathered proof more so than the aerial sensors as it be exposed all winter. The ground based sensor/s would need to be avalanche proof. A DSLR camera at the bottom of the bowl with a calibration pole in the field of of view would be able to measure snow accumulation all season. In order to measure snow at six snow pit locations multiple sensors or a rotating sensor may be needed, increasing the cost significantly.

Advantages	**Disadvantages**
Lowest unit cost	No mobility
Super stable platform	Avalanche/weather danger
	Possible safety risk to skiers

C. Sensor Package

The sensor package is critical to mission success and will be selected based on its ability to perform in cold weather conditions, meet our accuracy requirements, and optimal vehicle endurance. Five different options will be considered. We will look for sensors that are available for purchase as developing our own would require complex fabrication and testing techniques not possible given our resources and time.

1. LiDAR

Light Detection and Ranging, or LiDAR, initially started in 1970's for applications in terrain mapping. The system calculates distance by measuring the time it takes for an emitted laser pulse to travel from its origin to a surface and back as shown in figure 8.

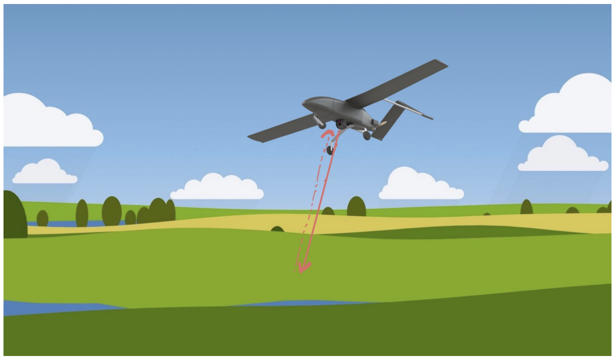

Fig. 8 Solid line is the emitted pulse the dotted line is the return signal. Both are equal are equal in length.

The time of flight of the laser beam is then multiplied by the constant speed of light and divided by two to get the distance between the sensor and the surface. Concurrently, the position and orientation of the sensor is taken by a Global Navigation System(GNS) and Inertial Navigation System(INS) respectively to calculate the X,Y,Z coordinates of a surface for input in terrain generation modeling.

The main advantages for a UAV LiDAR include higher point densities and its large max range. A higher pointing density allows the sensor to pick up finer details for improved resolution while also flying at higher altitudes. LiDAR can also be flown at night allowing for low light operating conditions. Furthermore, LiDAR has the capability of penetrating vegetation for accurate snow depth measurements in vegetated areas.

The main disadvantage is the cost of a survey grade LiDAR sensor, often quadrupling the cost of other sensor packages and easily exceeding our budget. In addition, precise calibration between the laser and GNS/INS is required to minimize positional error.

Advantages	**Disadvantages**
High point density for finer detail/resolution	Exorbitant Cost
High maximum operating ranges	Requires Precision Calibration
Operations in any lighting	
Canopy Penetration	

2. Photogrammetry

Structure from Motion (SfM) is a photogrammetric technique for high-resolution topographic surveying. Digital single-lens reflex (DSLR) cameras capture two dimensional still-images of the visible environment. Photogrammetry is the use of photography in surveying and mapping. For snow-depth measurement, careful photogrammetry yields digital models accurate to within centimeters[31].

Accurate photogrammetry requires many photos, and camera sensors are not as fast as other sensors considered. This leads to longer flight times and introduces concerns about endurance. Recent technological advances make photogrammetry possible. The image quality of relatively cheap digital cameras has increased the popularity of photogrammetry. As a result, there are many free and commercially available software programs available for photogrammetry. The post-processing software compiles the photos to output digital surface models and elevation models. Photogrammetry is easier when using a UAV platform, as a UAV can cover a large area of remote and variable environments from an aerial perspective.

Using a DSLR camera is cost-effective and reliable as it has been used in similar conditions and os proven to work. Because DSLRs are commercially available, equipment and solutions for most problems of camera operation can be diagnosed and fixed. Low-voltage differential signaling (LVDS) based cameras are also considered. LVDS cameras are small and consume minimal power [38]. However, the small sensor reduces quality and information within an image signifcantly. A complete sensor package by SenseFly also satisfies our objectives. The S.O.D.A. Photogrammetry Camera is optimized for UAV use that produces digital elevation model with a precision of up to 3 cm. It has additional sensors including thermal imagery and collects GPS data within the sensor package [37]. The proprietary nature of the camera and software included may introduce difficulties when attempt to optimize, adjust, or troubleshoot this camera system. This is likely as the S.O.D.A has not been tested on surfaces covered by snow. The cost of the system, close to half our budget, further discourages this method.

Advantages	**Disadvantages**
Low cost & high heritage use	Larger processing resources & time needs
Hardware available and easy to use	Longer flight times
Open-source & COTS software available	Susceptible to changing weather

*3. **Radar***

Radar is a technique for remote sensing that has the main advantage of being ground penetrating. The sensing not only measures distance to the surface of the ground, but can display what is underneath the surface. For our purposes, radar could be used to measures the distance to ground level as well as the distance to the top layer of snow. This would provide accurate snow depth measurements without relying on knowing the location of the vehicle to extreme accuracy. The range of complexity of radars varies greatly. Some more advanced systems can identify layers or objects in the ground and classify them based on how the radar waves reflect or are absorbed [33]. Simple systems, like altimeters, also exist that simply give a distance measurement. This can be useful, but does not overcome the need for a very accurate vehicle location measurement.

Radar has been utilized for surveying over many application before, including proving accurate in determining depth of snow. However, in most applications the radar sensors are fixed to a stationary object or are ground based systems that are on the surface of the ground and measure what is below it. This is especially the case for accurate ground penetrating radar systems, which unfortunately is not susceptible to this project. From a COTS stand point, most options are intended for construction or measuring snow on roadways. Many are heavy, are only accurate when stationary, or are intended to be used on the surface. This makes many radar sensors poor options when considering mounting them to a UAV.

Advantages	**Disadvantages**
Potential to ease UAV position accuracy requirements	High weight
Gives instantaneous depth (no need to compare to previous data)	COTS intended for ground or stationary use
Sensing can differentiate between ground and snow	

*4. **Ultrasonic***

Ultrasonic sensing is a method used to measure distances by measuring propagation times of ultrasonic waves. The sensor will emit a wave towards an object and it converts the reflected wave into an electronic signal.

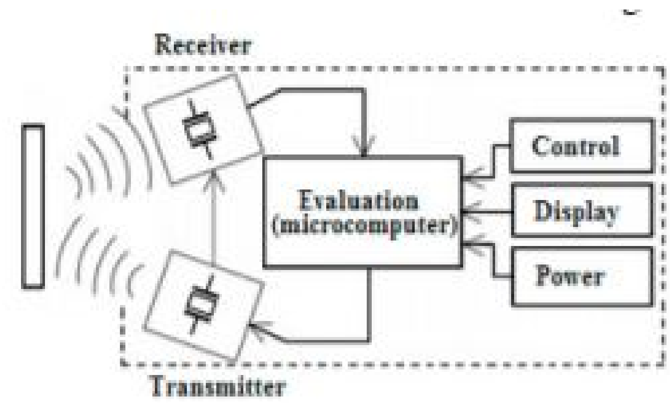

Fig. 9 Ultrasonic Sensor Diagram

This diagram shows a separate transmitter and receiver, but in many cases the two are combined into one sensor component. The same equation is used to measure distance as in LiDAR, however, in this case, C, is the speed of sound. The advantages of using ultrasonic sensors are they are inexpensive, have low power consumption, and most can operate in low temperature environments. Ultrasonic sensors have been utilized to measure snow depth on the ground by attaching the sensor to a beam and pointing the sensor straight down. Another application for ultrasonic sensors is object detection for aircraft. The use of ultrasonic sensors on an aircraft for surveying is limited mainly due to inaccuracy of measurements.

There is dramatic fall off to reading accuracy as distance increases, and past applications have found that 10 meters is the maximum range for these sensors. This will require a longer flight time by having to fly so close to the ground. The ultrasonic sensor also requires the aircraft to remain still until the transmitted signal is received. Other sources that can also impact the performance of these sensors are high wind speeds that can attenuate ultrasound and vibration of the aircraft while recording data. There is very little heritage of ultrasonic sensors being attached to a moving aircraft for accurate distance measuring, mostly due to these sources of error. To account for this, the precision and accuracy score in the trade study has been deducted by one point to factor this effect.

Advantages	**Disadvantages**
Low power and lightweight system	Maximum range of 10 meters
Works well in cold conditions	COTS intended for ground or stationary use
Low cost	Precision accuracy affected by flight

D. Georeferencing System

1. Pressure Altimeter

Pressure altimeters (also known as barometric altimeters) use a reference pressure at ground level to calculate the current altitude given the current current pressure. Pressure altimeters also account for the current weather conditions to create a more accurate reading of its current altitude. The equation used to calculate the altitude z is

$$z = cTlog(\frac{P_o}{P}) \tag{2}$$

where c is a constant that depends on at the acceleration of gravity as well as the molar mass, T is the absolute pressure, P is the pressure at altitude z, and P_o the pressure at sea level or a reference pressure. Pressure altimeters tend to work better at lower heights (heights lower than approximately 70m to 80m) with an error of about 2%. However this error is far too large to provide an accurate reading of snow depth. Barometric altimeters tend to be cheaper and typically come in a form of a chip so integration with this kind of georeferencing equipment should lack in complexity. Because they are so cheap, this option allows us the flexibility to purchase multiple barometric altimeters in order to find the most accurate one.

Advantages	Disadvantages
Low cost	Incredibly fragile
Accurate at lower altitudes	Inaccurate at higher altitude, limiting flying options
Very low energy costs	Inaccuracy is typically on a scale of over 100cm

*2. **Traditional GPS***

The Global Positioning System uses four or more satellite signals in order to determine geolocation and time information for a satellite receiver. GPS is used by a multitude of systems including smartphones in order to locate the device in space. GPS can typically provide location data that is accurate to within 2 or 3 meters, but accuracy can be increased through ground control points. Ground control points are known way points used to calibrate the GPS receiver and improve accuracy. Although, even with the use of ground control points GPS data will not be accurate to within 10cm.

One big advantage of traditional GPS is cost. GPS receivers can be bought off of the shelf for cheap, under 100 dollars. These GPS units are fairly simply and have been used extensively on UAVs. This means that implementation of a traditional GPS unit in our vehicle should not be difficult. The accuracy means that it could not be used as a reference for our sensor to get snow depth measurements, but it could be used to collect latitude and longitude data for use in snow depth mapping.

Advantages	Disadvantages
Low Cost	Low Accuracy
Widely used/Easy implementation	Accuracy can be affected by surroundings

*3. **PPK GNSS***

PPK GNSS, or Post-Processed Kinematic Global Navigation Satellite System, is a technique which gathers raw GNSS positional logs from a rover and a base station and applies correctional algorithms to account for satellite signal errors. The rover in this case would be our designed aircraft and would require the purchase of an on-board PPK GNSS receiver. The base station, also known as a reference station, is used as a baseline for the data collected from the rover and is a required component to this technique. Cost can be reduced with the use of existing, publicly available reference stations such as CORS (Continuously Operating Reference Station) offered by NOAA. It is recommended the base station be located, at most, 15 km away from the rover to reduce signal attenuation that may occur due to differing atmospheric conditions between the rover and base. Figure 10 shows the nearest available CORS, stationed between 8.7-13 km away from Copper Mountain in nearby Breckenridge.

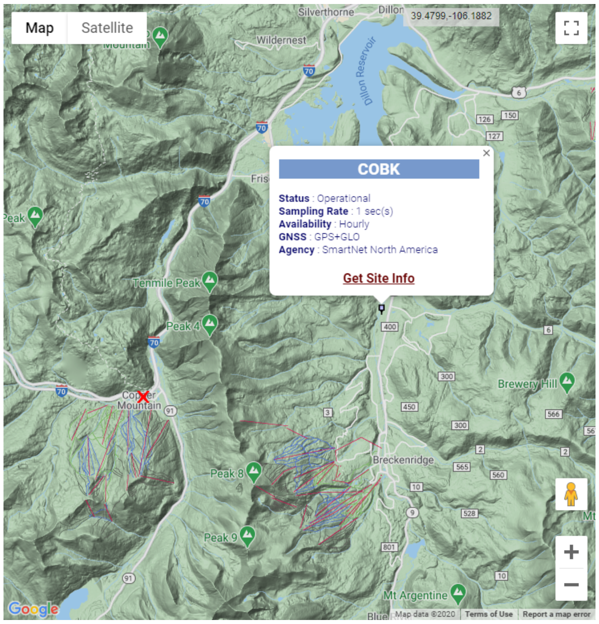

Fig. 10 Closest Available Base Station (Copper Mountain marked in red)

The main advantage to using PPK GNSS is the centimeter level accuracy it is able to achieve, allowing the system to meet the vertical error budget of 10 cm. In addition, the availability of a nearby ground station makes PPK GNSS a cost effective solution for georeferencing sensor data. The biggest detractors for PPK GNSS is the additional post-processing time needed to perform correction algorithms and purchasing software to perform these algorithms. Fortunately, access to software is often included when purchasing PPK GNSS receivers and open source software is a possibility.

Advantages	Disadvantages
Positional Accuracy to within Centimeters	Requires additional software
Existing Base Station Available	Increased post-processing times
Easy to setup and maintain	

4. Ground Control Points

Ground Control Points (GCP) are physical markers that are placed on the area to be surveyed. The exact locations of these markers is measured and is used as tie points to increase the accuracy of a GPS system. These only improve surveying with other GPS systems and are not a stand alone geo-referencing system. GCP are only applicable to image based surveying such a photogrammetry and LiDAR and they help with the stitching process of the images in post processing. They locations of the GCP must be measured with real time kinematic (RTK) or PPK GPS systems to ensure the measurement is precise which requires additionally equipment. Using around four or more GCP can increase the accuracy of the maps measurements from a few meters to a few centimeters [12]. The main issues for using GCP for this project is that the markers would need to be placed and measured in the snowfield. If using permanent GCP, there must be a way to keep the points clean and clear of snow. If using temporary GCP, personnel would have to go into the snowfield to place and measure them which defeats the purpose of a UAV.

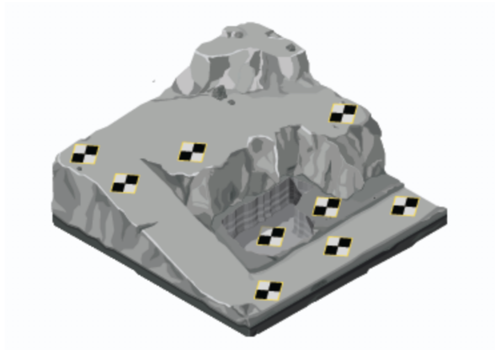

Fig. 11 A terrain map with GCP distributed throughout [1]

Advantages	Disadvantages
Increases positional accuracy of GPS to within centimeters	Only applies with photogrammetry and LiDAR
Can improve measurements on hilly terrain	Points placed must remain visible
	Points must be measured very accurately

IV. Trade Study Process and Results

A. Software

1. Software Criteria and Weighting

Criteria	Driving Requirements	Weight	Reasoning
Perpetual or Permanent Cost	**PAB REQ.**	0.3	The project has many different aspects to it, all requiring a portion of the allocated $5,000 budget. It is likely that both the vehicle and sensor systems will be costly, and the more money that can be spent on those systems, the more effective they will be. Therefore, it is of great importance to save money on the software system, so that already places cost as an important metric in the software trade study. Next, with costs varying so much for different software packages that provide similar utility, (free for Python, more than $2,000 for Matlab) the cost becomes the main distinguishing factor. Thus, the cost is one of the most important factors for the trade study and is assigned a weight of 30%, equal in importance to the ability to integrate with the sensor package.

Data Visualization Quality	**DR 5.3**, **DR 5.4**	0.1	The data collected from the sensor needs to be conveyed to the Copper Mountain Ski Patrol in a useful way. The quality of the data visualization produced will directly relate to how well they understand the data and, in turn, how useful the data is to them. While poor data visualization does not make the data useless to ski patrol, better data visualization will make the data accessible to more people. The 10% weight assigned to data visualization quality reflects the fact that poor data visualization will still work for our purposes but is not desired.
Integration with Sensor Package	**FR 1**	0.3	The software's ability to integrate with the sensor selected to collect data is critical to the function of our system. If the two are unable to interface, then each becomes useless and our system is not able to complete the minimum requirements of our project. The easier it is to integrate our sensor and software, the more time we can spend dialing in our sensor to collect accurate readings and tweaking our vehicle to provide a better platform for our sensor. The weight of 30% was decided because of how necessary software integration is to our project.
Ease of Use by Predicted Training Time	**DR 5.4**	0.2	This metric highlights the interfacing capability of our system. This is important to our customer because they do not want their team spending too much time dealing with a complicated system. Ideally a staff member should little interaction with the software in order to get the information they need to assess avalanche factors. However, this does not have a direct impact on the functionality of the software and therefore is not a critical of the software.
Data Processing Speed	**DR 5.4.3**	0.1	This has a low weight because it is not critical to the functionality of the software nor was it requested. This just provides quality user experience and a baseline for the time of the processing process.

2. Software Trade Study Scoring

Criteria	1	2	3	4	5
Perpetual or Permanent Cost	$2,000+	$1,500-$1,999	$1,000-$1,499	$500-$999	$0-$499
Data Visualization Quality	unusable	low	readable	high	pristine
Integration with Sensor Package	incompatible	requires extreme effort	requires moderate effort	requires low effort	integration is seamless
Ease of Use by Predicted Training Time 80 Hours+	40-80 Hours	40 Hours	20-40 Hours	10-20 Hours	10 Hours or less
Data Processing Speed	1-hour+	30-60 minutes	10-20 minutes	1-10 minutes	1 minute

Note: Higher scores are better.

3. Software Trade Study

Criteria	Weight	Python 3	Matlab	**ArcGIS**	Google Earth Engine
Perpetual or Permanent Cost	30%	5	1	5	3
Data Visualization Quality	10%	4	2	5	5
Integration with Sensor Package	30%	3	4	3	3
Ease of Use by Predicted Training Time 80 Hours+	20%	4	3	5	4
Data Processing Speed	10%	4	5	5	5
Total:	100%	4	3	**4.4**	4

Note: Higher Scores are Better

Python 3

Perpetual or Permanent Cost: Python 3 is a free program and running its software is also free.
Data Visualization Quality: Python 3 has a few geophysical libraries with good quality imagery with high resolution. Python also has multiple options for displaying 3D data. However, Python requires that we create our own user interface.
Integration with Sensor Package: Depending on the sensor, there may be some programs that are built in Python that come with the sensor which would make integration seamless. However, if there is no built code, then we will have to design the code requiring at minimum a moderate amount of integration. Python also allows for a large variety of file inputs to read so there is practically no limit on which files the sensor package can output in.
Ease of Use by Predicted Training Time: The interface that is created will take some training in order to use it. There would also be some training require in order to customize and personalize the output data to the users preference.
Data Processing Time: Because Python is a base language, processing time should take no longer than a minute. However, with large data sets and especially when printing 3D images, Python can take more than a minute to output its

figures. [17]

Matlab

Perpetual or Permanent Cost: Matlab's perpetual license costs $2,150, which could prove to be prohibitive. For our project, this cost would take up close to half of our budget leaving a small amount of money to purchase a sensor and vehicle.
Data Visualization Quality: Matlab is designed to handle large data sets organized into matrices. It is very good at performing computations on these large data sets but it's data visualization capabilities are limited. It will not be able to display the data required in this project in a way that will be easy to interpret for the Copper Mountain Ski Patrol.
Integration with Sensor Package: Matlab will integrate with the sensor package well. It is capable of inputting many standard file formats including common file formats for scientific data. Matlab is also capable of interfacing with other coding languages such as C/C++ which could help with sensor integration
Ease of Use by Predicted Training Time: Matlab will not be a program that is familiar to the Copper Mountain Ski Patrol. It also lacks a user friendly interface or a way to build an all encompassing GUI. Even if a GUI is built, knowledge about the structure of the code will need to be conveyed in case errors are encountered down the road. This will require a moderate amount of training.
Data Processing Time: Matlab should not have an issue processing the amount of data we will collect in a timely manor. An optimized program should be able to return a visualization of the data well within the time required. [25]

ArcGIS

Perpetual or Permanent Cost: The actual program itself will cost $700 and the training can cost over $500. However, the staff at Copper Mountain already have access to ArcGIS, so for the purposes of this project, the software is free.
Data Visualization Quality: ArcGIS specializes in outputting data overlayed onto geophysical maps and is packed with geophysical libraries that can provide high resolution imagery and grids. It also has multiple options for user interface; either already built interfaces or we can design one ourselves. It even has different coding APIs such as Python and Java.
Integration with Sensor Package: Similar to Python 3, this would take some coding and preparation to integrate with the output data of our software. However, even worse than Python, it only accepts a limited number of file types which heavily impacts the options of the sensor package.
Ease of Use by Predicted Training Time: There are already available training to use this application and also has multiple user interface options so we can choose from the best!
Data Processing Time: ArcGIS has shown to have processing speeds for large projects as quick as 5 seconds showing me that it would be capable of producing an image of estimated snow height on a mountain in under a minute. [2]

Google Earth Engine

Perpetual or Permanent Cost: Google Earth Engine is free to use for research, academia, or personal uses. There is a cost for commercial use but it is not disclosed on their website. We have requested a quote but have not heard back from Google.
Data Visualization Quality: Google Earth Engine allows access to images taken from space of the Earth. You can overlay data on to these images leading to great data visualization. A heat map could be created indicating snow depth overlayed on an actual image of Copper Mountain Ski Resort.
Integration with Sensor Package: Google Earth Engine is somewhat limited in the file types that can be used. The engine can input CSV, Shapfile, GeoTIFF, and TFRecord file types. While the options are limited, these file types should not be prohibitive for our projects purposes. Regardless of what file type our sensor outputs data in, conversion to a CSV file should not be difficult.
Ease of Use by Predicted Training Time: Training would be required in order for an program to be created for use by the Copper Mountain Ski Patrol using the Google Earth Engine. The code editor uses JavaScript. which is not a language anyone on our team is proficient in. There is some experience with JavaScript on the team but not extensive use. The Google Earth Engine does have a user interface API, meaning the final product delivered to Copper Mountain should be easy to use.
Data Processing Time: Data Processing time should not be an issue. Google Earth Engine was built to display data on

top of images of the earth, so it is well optimized for our use case. [26]

B. Aircraft Design

It is decided that to conduct an accurate and thorough trade study of the various vehicle design options, two trades studies will be conducted and the resulting scores are multiplied together for the final weight. The first trade study is a standard weighted trade study. The second trade study is the critical criteria made up of critical features the vehicle must possess. If the vehicle does not meet these requirements the entire mission is a failure. The scoring for the critical criteria is binary; either the vehicle meets the requirements or it does not. Each critical criteria score is multiplied against the final weighted criteria score. If any critical criteria is not met for a given vehicle, the vehicle's composite score is driven to zero. If the vehicle passes each critical design requirement, its weighted criteria score will be unaffected.

To more accurately compare vehicle types to each other, a generic vehicle of each vehicle is sized to an arbitrary mission with a 1.5 kg payload for 1 hour endurance. To see the calculations of the parameters for each vehicle, see the respective vehicle section in section III.B.

1. Aircraft Design Criteria and Weighting

Standard Parameter Weights

Criteria	Driving Requirements	Weight	Reasoning
Payload mass fraction: $\frac{M_p}{M_{TO}}$	**DR 3.6.1 3.6.2, 2.1.1**	0.1	A vehicles with a larger payload faction is able to carry more payload of less vehicle weight. Low payload fraction will result in heavy vehicles. Aircraft weight and size will impact both project cost, maintenance and usability by the user resulting in an intermediate weighting.
Fuel/battery weight mass fraction: $\frac{M_b}{M_{TO}}$	**DR 3.6.1 3.6.2, 2.1.1**	0.1	For the same payload mass, a vehicle with a smaller fuel/battery weight fraction is able to either have a smaller power plant or longer flight time. This then would cascade in overall aircraft weight and dimensions. Since the aircraft is operating at high altitudes in cold conditions, meeting the required endurance without a large vehicle is a critical design point. Aircraft weight and size will impact both project cost, maintenance and usability by the user resulting in an intermediate weighting.
Total takeoff weight	**DR 3.6.1 3.6.2, 2.1.1**	0.05	Heavy vehicles tend to have large dimensions. A large, heavy vehicle will create logistical challenges for Copper Ski patrol moving the vehicle to the area of interests. The customer has expressed the wish that the vehicle be transported preferably by human skier, then snow mobile and lastly by snow cat. Since this parameter overlaps with payload weight mass fraction, the weighting is reduced. Since aircraft takeoff weight has been represented in both payload mass fraction and fuel/battery mass fraction, the final aircraft weight is weighted less.
Expected maximum airspeed	**DR 3.3**	0.05	The aircraft is desired to be able to operate in 18 m/s wind speeds. If the aircraft is unable to fly above 18 m/s air speed, the vehicle will be unable to overcome the wind conditions and could be lost. The larger the vehicle air speed is compared to wind speed the better the vehicle will be able to overcome steady wind conditions. Also, high vehicle air speeds will be able to better fly the require flight path for the sensor package in high wind speeds. While the customer would prefer a high wind capable aircraft, it is more important to have a smaller and functional aircraft, hence the lower weighting.
Safety due to loss of thrust	**DR 3.11**	0.16	If the vehicle experiences some failure to the power plant system during flight, the ability of the aircraft to still be controlled and landed safely will vary between vehicle type. An uncontrollable vehicle is a major safety hazard. Since safety is a largest design concern, this is the most weighted section.

Standard Parameter Weights cont.

Safely due to ground impediment	**DR 3.11**	0.15	Ground based vehicles/stations could create impediment to freedom of motion on the ground. Since the vehicle will be used in a ski resort, it is expected that people will occasionally be occupying the same space as the vehicle. Since skiers and snowboarders move quickly, especially on steep slopes, collision and crashing at these speeds can be extremely dangerous. Therefore, if the vehicle is on the ground, ground impediment is a serious concern. Since safety is a largest design concern, this is the next most weighted section.
Effect of gust: $\frac{M_{TO}}{A_{wet}}$	**DR 3.3, 3.4**	0.12	For the vehicle to operate it must be able to be controlled in gusting winds. Even if the vehicle is unable to provide the sensor with the required stability in gusting winds, the vehicle must still be controllable and landable else the vehicle will become a safety hazard. Therefore, $\frac{M_{TO}}{A_{wet}}$ is decided to be a good measure for a vehicle's ability to resist gusting winds. If the vehicle has a large enough $\frac{M_{TO}}{A_{wet}}$, the vehicle will be able to provide the sensor package with the needed stability to collect accurate data. Providing a stable platform such that accurate sensor measurements can be collected is a vital to the mission, hence the higher weighting.
Thrust-to-weight ratio: $\frac{T}{W}$	**DR 3.1.2, 3.5, 3.8**	0.12	Since the vehicle is operating in mountainous conditions, high climb rate is essential for avoiding collision with the ground. This can take the form of rapidly rising ground or significant downdrafts formed from the high mountain ridges and winter conditions. A high thrust-to-wait ratio is expected in order to meet these requirements. Reducing vibration is an important goal, and thrust-to-weight ratio is a proxy for vibration. So the aircraft which requires the lowest thrust-to-weight ratio (and consequently less vibration) is desired. Since the aircraft is operating in mountainous terrain, it is vital to keep the vehicle from crashing, hence the higher weighting.
Turing radius requirement met	**DR 3.7**	0.05	With the coarsest measurement grid set to 20m x 20m, if the vehicle is flying laps of the area of interest, a turning radius of 10m is a minimum requirement. If the payload package is able to create a finer measurement grid, it is deemed acceptable if the vehicle must perform dog legs. Since this is a binary parameter, either it is met or not, scoring is 1 or 5. Since turning radius is not critical to mission, the criteria is weighted less.

Standard Parameter Weights cont.

Density altitude requirement me	**DR 3.1**	0.05	For the vehicle to be usable most days, a density altitude of 4,267 m (14,000 ft) has been set. If the vehicle is unable to operate below this density altitude, the total number of usable flight days drops. While poor density altitude flight is acceptable since mission could still be occasional flown, to meet the customer's expectation of being able to take measurements most days, a vehicle capable of getting good density altitude is important. Since this is a binary parameter, either it is met or not, scoring is 1 or 5. Since high density altitude is not as common in cold winter conditions it is considered not critical to mission, hence the criteria is weighted less.

Constraint Weights

Criteria	**Driving Requirements**	**Weight**	**Reasoning**
Navigate over uneven terrain	**DR 2.1**	1	Since the vehicle must operate in mountainous, snowy terrain, if the vehicle is unable to operate over, or maneuver around rough terrain, the vehicle will be both unable to operate without significant risk of crashing and a significant safety hazard. Therefore, the vehicle being unable to operate in rough, snowy terrain is a mission failure case.
Cost	**PAB req.**	1	Since there other project expenses like the sensor package, data processing, etc, the vehicle can only use a fraction to budget. Some vehicle configurations inherently have significant expenses. For example, large volumes of helium can quickly run into many thousands of dollars, exceeding project budget and being too expensive to operate for the costumer. Neither the vehicle, power plant consumables, (electricity, fuel, etc) or other operations expenses can be prohibitively expensive for constructing or continued operation. Exceeding reasonable building/operational costs results in a mission failure case.
Takeoff/landing distance	**DR 3.5 3.1.2**	1	If the vehicle type is unable to safely become air born on the maximum takeoff area of 20m x 20m, the vehicle could either crash or put people in danger. This is a mission failure case.

2. *Aircraft Design Trade Study Scoring*

Weighted Criteria Scoring

Criteria	1	2	3	4	5
Payload weight mass fraction: $\frac{M_p}{M_{TO}}$	<0.075	0.075-0.15	0.15-0.225	0.225-0.3	0.3<
Fuel/battery weight mass fraction: $\frac{M_b}{M_{TO}}$	0.3<	0.225-0.3	0.15-0.225	0.075-0.15	<0.075
Expected maximum airspeed	<8 m/s	8-16 m/s	16-24 m/s	24-30 m/s	<30 m/s
Total takeoff weight >15kg	15-12.5kg	12.5-10kg	10-7.5kg	7.5-5kg	5kg<
Safety due to loss of thrust	Losses thrust, can't maintain flight	Loss of thrust means aircraft is uncontrollable or cannot be effectively navigated	Losses thrust, can be maneuvered to avoid obstacles	Losses thrust, can be maneuvered to avoid obstacles and can glide to a specified location	Can't loose thrust (stationary)
Safety due to ground impediment	Area being measured is impassible safely	Multiple ground impediments	One ground ground impediment	Ground vehicle is able to avoid collisions	No ground impediment
Effect of wind: $\frac{M_{TO}}{S_{wet}}$	<0.75 kg m^{-2}	0.75-1.5 kg m^{-2}	1.5-2.25 kg m^{-2}	2.25-3 kg m^{-2}	3< kg m^{-2}
Thrust-to-weight ratio: $\frac{T}{W}$	>1.5	1.03-1.5	0.56-1.03	0.1-0.56	<0.1
Turing radius requirement met	Requirement not met	N/A	N/A	N/A	Requirement met
Density altitude requirement me	Requirement not met	N/A	N/A	N/A	Requirement met

Critical Criteria Scoring

Criteria	0	1
Operate over uneven terrain	Requirement met	Requirement not met
Cost	Requirement met	Requirement not met
Takeoff/landing distance	Requirement met	Requirement not met

Note: Critical criteria must be met. Failure to meet these requirements leads to the vehicle type receiving a score of zero

3. *Aircraft Trade Study*

Since it was not possible to find an commercial vehicles that could meet the required flight profile for the given budget, it is expected that a custom vehicle will be designed and built either from scratch or possibly modifying an existing platform. Therefore five vehicle types were explored to see which type would most inherently be able to meet the mission requirements.

Standard Criteria Trade Study

	Weight	**Fixed-wing**	Multirotor	Airship	Ground effect vehicle	Ground Stations
Payload weight mass fraction $\frac{M_P}{M_{TO}}$	10%	3	3	**5**	4	**5**
Fuel/battery weight mass fraction: $\frac{M_b}{M_{TO}}$	10%	3	2	1	4	**5**
Takeoff weight, total	5%	4	3	1	4	**5**
Expected maximum airspeed	10%	**5**	4	1	3	5
Safety due to loss of thrust	16%	4	4	2	3	**5**
Safety due to ground impediment	15%	**5**	5	5	4	2
Effect of gusts: $\frac{M_{TO}}{S_{wet}}$	12%	2	3	1	2	**5**
Thrust-to-weight ratio: $\frac{T}{W}$	12%	4	2	**5**	3	5
Turing radius requirement met	5%	5	4	5	5	5
Density altitude requirement met	5%	5	5	5	5	5
Sub Total	100%	**3.91**	3.54	3.04	3.43	4.55

Constraints

	Fixed-wing	Multirotor	Airship	Ground effect vehicle	Ground Stations
Able to navigate over uneven terrain	1	1	1	0	1
Prohibitive Cost	1	1	0	1	0
Takeoff/landing distance	1	1	1	1	1
Resulting Product	1	1	0	0	0

Combined Trade Study Score

	Fix-wing	Multirotor	Airship	Ground effect vehicle	Ground Stations
Composite Score	**3.91**	3.54	0	0	0

Fixed wing

The above trade study values for the aircraft vehicle were calculated and explained in section III.B.2 with a diagram in Appendix B.

Multirotor

The above trade study values for the multirotor vehicle were calculated and explained in section III.B.2 with a diagram in Appendix B.

Airship

The above trade study values for the airship were calculated and explained in section III.B.4.

Ground Effect Vehicle

The above trade study values for the ground effect vehicle were calculated and explained in section III.B.3.

Ground Stations

Since the ground station does not fly, none of the trade study criteria based around flight and wind/gusts are pertinent. Therefore the ground station gets a 5 for each of these categories. The ground station gets a 2 for safety due to ground impediment since multiple ground stations will be required to measure all the terrain resulting in multiple ground impediments.

C. Sensor Package

We will be looking into 4 types of sensor options represented as 4 different matrices in the trade study. Each matrix will compare 3 commercially available sensors for a combined total of 12 sensors. Note, matrices are filled out based on available manufacturer data sheets either found online or requested via email.

1. Sensor Package Criteria and Weighting

Criteria	Driving Requirements	Weight	Reasoning
Temperature Sensitivity	**DR 3.2**	0.25	System will most likely operate in below freezing temperatures where electronics are susceptible to performance degradation.
Maximum Range for Measurements	**DR 1.4**	0.25	The higher the vehicle can fly above the ground and still get measurements, the less measurements need to be taken and decreasing mission times. Higher flight also allows for avoidance of obstacles such as trees.
Precision/Accuracy	**DR 1.1**,**DR 6.1**,**DR 6.2**	0.25	Measuring snow depth within ±10cm is the main requirement of the system and depends on the sensor itself as well as any GNS/IMU systems to track sensor location and attitude.
Power Budget	**DR 3.2.1**	0.1	The more power efficient a system is, the smaller the battery is needed. This can lead to lower aircraft payload weight and consequently longer flight times.
Weight	**DR 3.6**	0.1	The weight of the combined system must be below the 25kg limit as required by FAR 107.3. Reducing weight also helps with flight times.
Cost	**PAB REQ.**	0.05	The project must remain $5000 as a whole. The cheaper the sensor, the more budget remaining for other subsystems of the project.

2. ***Sensor Package Trade Study Scoring***

Criteria	1	2	3	4	5
Temperature Sensitivity	15°C	0°C	-10°C	-25°C	-40°C
Maximum Range for Measurements	10m	15m	25m	50m	75m
Precision/Accuracy	25cm	20cm	15cm	10cm	5cm
Power Budget	10W	5W	3W	2W	1W
Weight	<2,000g	<1,000g	<600g	<400g	<200g
Cost	$4,000	$3,000	$2,000	$1,000	$500

Note: Higher scores are better.

3. ***Sensor Package Trade Study***

LIDAR	Weight	**Quanergy M8 Core**	Velodyne Puck	Pheonix Scout-16
Temperature Sensitivity	25%	4	3	3
Maximum Range for Measurements	25%	5	5	5
Precision/Accuracy	25%	5	5	5
Power Budget	10%	1	1	1
Weight	10%	2	2	1
Cost	5%	1	1	1
Total	100%	**3.85**	3.65	3.3

Note: Higher scores are better.

RADAR	Weight	LUFFT Snow Depth Sensor SHM31	**US-D1 Radar Altimeter**	SDMS40
Temperature Sensitivity	25%	5	5	5
Maximum Range for Measurements	25%	2	4	1
Precision/Accuracy	25%	4	5	5
Power Budget	10%	3	4	1
Weight	10%	3	5	2
Cost	5%	2	4	Requested (assuming 5)
Total	100%	3.45	**4.6**	3.3

Note: Higher scores are better.

ULTRASONIC	Weight	NovaLynx 260-700	USH-9 Snow Depth Sensor	**MB1340 XL-MaxSonar-AE4**
Temperature Sensitivity	25%	5	5	2
Maximum Range for Measurements	25%	1	1	1
Precision/Accuracy	25%	4	4	4
Power Budget	10%	3	4	5
Weight	10%	3	1	5
Cost	5%	2	2	5
Total	100%	2.83	2.76	**3.62**

Note: Higher scores are better.

Photogrammetry	Weight	**DSLR** Camera	LVDS Camera	eBee SODA
Temperature Sensitivity	25%	4	5	5
Maximum Range for Measurements	25%	5	2	5
Precision/Accuracy	25%	4	1	4
Power Budget	10%	4	3	2
Weight	10%	3	5	2
Cost	5%	4	5	2
Total	100%	**4.15**	3.05	4.00

Note: Higher scores are better.

LiDAR

Temperature Sensitivity: Both the Puck and Scout-16 have a minimum operating temperature of -10°C which can severely limit operational availability in cold climate environments such Copper Mountain. The M8 has operational ability at -20°C is significantly better, however, more leeway is preferred.

Maximum Range for Measurements: Maximum range measurements were used when the surface is assumed to be 80% reflective, which is a reasonable estimate for snow. All sensor have a maximum range of at least 75m while also falling under FAR 107

Precision/Accuracy: All sensors can achieve accuracy of ±3cm. Note these are estimates are based on terrestrial surveys. Aerial surveying systems come with inherently more error due to sources stemming from GNS and INS positional setup and collected data accuracy in addition to the sensor itself.

Power Budget: All sensors scored low in terms of power consumption, with the Puck consuming the lowest with 8W. The M8 and Scout-16 consume 16W and 40W respectively. The high power consumption means a compromise with flight times or system mobility.

Weight: All sensors scored relatively low on weight given the assumption the aircraft must carry at least 1.5kg. This is of high concern as the Puck and M8 do not come with an integrated INS and GNS, hitting the 1.5kg limit.

Cost: It is important to note that cost is varies by how the system is sold. For example, the Scout-16 includes an integrated GNS and INS and is sold with proprietary data handling software. Although very appealing, the starting price comes out to $35,000. Cheaper LiDAR's such as the M8 Core and Puck start at $4,000, leaving little room for other sub-teams.

Radar

Temperature Sensitivity: All radar options operate down to -40°C which is colder than conditions typically found on Copper Mountain.

Maximum Range for Measurements: The LUFFT SHM31 [34] has a maximum range of 15m and the SDMS40 [36] has a maximum range of 5m. The 15m is a reasonable distance but doesn't allow for flexibility in flight patterns. The 5m is a very small distance and would likely put the UAV in danger of hitting ground obstacles. The US-D1 radar altimeter[35] can operate at a range of 50m which gives lots of flexibility in the height the UAV flies.

Precision/Accuracy: The LUFFT SHM31 has a accuracy of about 8 cm which gives little leeway on the snow depth accuracy requirement for the project. This sensor is more precise when flying closer to the ground as well. The US-D1 is accurate to 5cm and is intended for UAV use. The SDMS40 is accurate to 3mm. Unfortunately, the SDMS40 is intended for stationary use near the ground and this accuracy is unlikely when flying from a UAV. The LUFFT SHM31 is also intended to be stationary so accuracy may degrade when attached to a UAV.

Power Budget: The LUFFT SHM31 requires 3.4W. The US-D1 uses 2W. The SDMS40 uses over 24W. The first two valus are acceptable while the SDMS40 likely requires too much power to be used on this project.

Weight: The LUFFT SHM31 and SDMS40 are intened to be mounted to a pole and are rather heavy at 2.3 and 1.8 kg respectively. The US-D1 is only 110g which is very condusive to a UAV sensor.

Cost: The LUFFT SHM31 sensor is about $ 2500, the US-D1 is about $600, and the SDMS40 has an unknown price currently as the manufacturer has yet to respond with a quote. For analysis purposes, it was assumed to score a 5.

Ultrasonic

Temperature Sensitivity: The NovaLynx 260-700 and USH-9 Snow Depth Sensor are capable of operating to -40°C which gives significant leeway. However, the MB1340 is serviceable to 0°C which severely limits operational use.
Maximum Range for Measurements: Almost all ultrasonic sensors will have a max range of about 10 meters, making flight measurements difficult.
Precision/Accuracy: All three ultrasonic sensors have precision below 1 cm, however this value is from data specification sheets for ground based systems. There are many factors explained in key design options considered that reduce accuracy. As a result, the scores were reduced by 1.
Power Budget: The NovaLynx has the highest power budget of 3.3W and the USH-9 uses 1.08W. The MB1340 has the lowest power output at .02W but once again will require integration that may increase the power budget.
Weight: The NovaLynx 260-700 has a weight of .6kg, the USH-9 has a weight of 1.2kg and the MB1340 is very lightweight, but it would require some integration that may increase the weight.
Cost: The quote for the USH-9 is $2,278 and the quote for the NovaLynx 260-700 is $2,682. The MaxSonar sensor itself is only $150 but would once again require integration that will factor into cost.

Photogrammetry

Temperature Sensitivity: The operational limit of both the SODA Camera and the LVDS sensor is -40°C. DSLRs are operational to -25°C but solutions exist for improving cold weather performance of the DSLR cameras.
Maximum Range for Measurements: Previous studies that used DSLRs for snow depth imaging were on average conducted at 50 m. This is standard for aerial DSLR imagery as using a short focal length forces the camera to be close to the terrain while capturing larger areas. The SenseFly SODA's recommended altitude is 43 m above ground level. The size of sensor on the LVDS camera means it has to be closer to gather useful information in an image.
Precision/Accuracy: The SODA photogrammetry camera has produced digital elevation maps with 3 cm precision. Using DSLRs, the models were between 3 and 10 cm, but quantified information is limited. The LVDS camera is not viable due to its small sensor size, 1280 by 800 pixels.
Power Budget: The low-voltage differential signaling camera is operational nearly 3 W. The SODA and the DSLR have removable batteries. While the S.O.D.A's battery cannot be modified, it may be possible to connect the DSLR camera to the aircraft's central power.
Weight: The LVDS sensor and its wires are less than 10g. The DSLR is 575g with a lens. The SODA unit with mounting hardware is 750g.
Cost: The LVDS camera sensor is $275. The advanced DSLR in question with a lens is approximately $750. The SODA camera with integrated GPS and thermal capabilities is upwards of $2,000.

D. Georeferencing

The importance of a georeferencing trade study is critical in meeting our allowed vertical error budget. Positional data is taken in tandem with the sensor package to provide accurate X,Y,Z coordinate data for post processing. In this trade study we will be comparing three systems, each with a respective trade matrix with three commercially available options for each matrix. Note, matrices are filled out based on available manufacturer data sheets either found online or requested via email.

1. ***Georeferencing Criteria and Weighting***

Criteria	Driving Requirements	Weight	Reasoning
Vertical Accuracy	**DR 1.1**	0.20	Vertical Accuracy is required because in order to obtain the snow depth, you need the vertical position of the aircraft as well as the distance to the ground. With this information you can get data on the ground level, which can be compared to the ground level when there is no snow in order to obtain snow depth. If the vertical position of the vehicle is not known with extreme accuracy, then the depth of the snow will not be able to be obtained to within 10cm as is required. The crucial role that vertical accuracy plays in our project justified the 20% weight.
Cost	**PAB REQ.**	0.20	Cost is important because we are constrained by a hard budget of $5,000. This money needs to be split between the vehicle, the sensor package, and the software so only a portion can be used to get a georeferencing system. The weight of 20% was decided because it is crucial that we get a system that is within our budget.
Weight	**DR 3.6.2**	0.20	The weight of the georeferencing system is critical for the function of our system as a whole. The vehicle selected must be able to carry this sensor as well as other components in order to operate. Weight is critical to vehicle operation so it was weighted 20%.
Lowest Operating Temperature	**DR 3.2**	0.15	Temperature is a large concern when operating any device at the top of Copper Mountain. Extremely cold temperatures are somewhat normal so any device used in this project will need to be able to sustain cold temperatures. This criteria was only given 15% weight because a separate thermal solution could be used to heat the sensor if necessary.
Power Budget	**DR 3.2.1**	0.15	The device needs to draw a reasonable amount of power in order for it to be usable for this project. The power required by this device needs to be small enough to allow all other devices to operate without requiring a prohibitively large power source. The weight of 15% was given because this is important but can be a tradeoff between all devices needing power.
Complexity	**DR 5.4**, **Time Constraints**	0.1	Since the georeferencing system is only one part of this project, it must be sufficiently simple in order to implement it in our vehicle. A large portion of time cannot be spent figuring out the georeferencing system if it prohibits us from completing other portions of the project. It was given a weight of 10% because more time could always be dedicated to the project by the group.

2. Georeferencing Trade Study Scoring

Criteria	1	2	3	4	5
Vertical Accuracy	25cm	20cm	15cm	10cm	5cm
Cost	$2,500	$2,000	$1,500	$1,000	$500
Weight	<1000g	<800g	<600g	<400g	<200g
Lowest Operating Temperature	15°C	0°C	-10°C	-25°C	-40°C
Power Budget	10W	5W	3W	2W	1W
Complexity	extremely complex	very complex	moderately complex	somewhat complex	low complexity

Note: Higher scores are better.

3. Georeferencing Trade Study

PPK GNSS	Weight	Tersus UAV PPK Solution	RTKITE Receiver	**Seagull GPK2**
Vertical Accuracy	20%	5	5	5
Cost	20%	3(Estimate)	4	5
Weight	20%	5	5	5
Lowest Operating Temperature	15%	5	5	5
Power Budget	15%	3	3	3
Complexity	10%	4	4	3
Total	100%	4.2	4.4	**4.5**

Note: Higher scores are better.

GPS	Weight	Hornet ORG1410 [27]	**Adafruit Ultimate GPS** [28]	Copernicus II [29]
Vertical Accuracy	20%	1	1	1
Cost	20%	5	5	5
Weight	20%	5	5	5
Lowest Operating Temperature	15%	5	5	5
Power Budget	15%	4	3	3
Complexity	10%	3	5	4
Total	100%	3.83	**4**	3.83

Note: Higher scores are better.

Pressure Altimeter	Weight	BMP388	SEN-11084	**29124-ND**
Vertical Accuracy	20%	1	1	2
Cost	20%	5	5	5
Weight	20%	5	5	5
Lowest Operating Temperature	15%	5	5	5
Power Budget	15%	5	5	5
Complexity	10%	3	3	5
Total	100%	4	4	**4.4**

Note: Higher scores are better.

PPK GNSS

Vertical Accuracy: It is evident that the achieved accuracy (to within ± 1.5 cm) of PPK GNSS is significantly higher than those of other techniques. Furthermore, all three sensors scored a 5 in this category.
Cost: The Seagull GPK2 is the most cost effective solution of the three coming in at $600. The RTKITE Receiver comes in around $1,200 with the Tersus being an estimate of around $1,500 until they respond to our inquiry. The cost disparity being the addition of proprietary software used to perform algorithms with the RTKITE whereas the Seagull comes with the receiver only.
Weight: All receivers with antennas weigh less than 200g. This is true for all georeferencing equipment compared in the trade study.
Lowest Operating Temperature: All receivers can operate in as low as -40°C, which exceeds our operational temperature requirements.
Power Budget: All receivers operated around the same wattage with a typical power consumption of 2.8W
Complexity: All receivers are relatively easy to operate as all three can connect to the same dual band GPS and GLONASS satellite constellation tracking used by the nearest base station. None were given above a score of 4 as integration between base station, receiver, and the sensor is still needed. Seagull was given a 3 as the cost does not include PPK correction software.

Adafruit Ultimate GPS

Vertical Accuracy: The positional accuracy listed on the Adafruit provided data sheet is 1.8m. This will not allow us to collect accurate snow depth measurements and is not viable for vertical geolocation. This could be viable for location data in the other two directions because our accuracy constraints are much less strict.
Cost: The Adafruit Ultimate GPS costs just under $40. This easily fits within our budget for the project.
Weight: This GPS unit weighs 8.5g. This amount of weight should pose no problems and be light enough to cause no issues.
Lowest Operating Temperature: The working temperature range listed in the data sheet is -40°to 85°C. Temperature should not cause problems for this GPS unit for our use case.
Power Budget: The wattage required by this device to operate is 3-5.5W. While this is not ideal, it does not prohibit its use in our project
Complexity: The complexity of this device is not an issue as it has a fairly extensive user manual. The manual includes all relevant information including common wiring setups and example code for parsing and data logging. [28]

29124-ND

Vertical Accuracy: This chip has a vertical accuracy of ±20cm.
Cost: This chip is fairly cheap at $30 with options to buy in bulk (which doesn't seem necessary for this project, but could come in handy).
Weight: This chip is very light weighing about 2g
Lowest Operating Temperature: This chip can operate well in temperatures as low as -40°C.
Power Budget: One reason why this chip is so good is combined with its accuracy, it also does not need a lot of power to function. This chip needs less than a watt to function.
Complexity: This chip is not very complex to integrate because it comes with pins already attached and a pretty large user manual. However, it will take some wiring in combination with the on-board sensor package.

V. Selection of Baseline Design

ArcGIS was the software selected for our baseline design. This choice made a lot of sense since it is a software package that the Copper Mountain Ski Patrol already owns and uses. ArcGIS has all of the capabilities required by this project, including 3D mapping. It inputs a wide variety of data types which makes the software/hardware interface more user friendly. The University of Colorado Office of Information Technology also offers ArcGIS licensing to University of Colorado students for free. The one downside to ArcGIS is that no one on our project team has experience with the program. More time will have to be dedicated to learning the program to make it feasible for our project. After weighing the pros and cons, we decided that the extra time investment was worth all of the advantages that come with ArcGIS.

A radar altimeter was selected as the sensor package for our baseline design. This was the leading choice out of the trade study. LiDAR systems proved to meet our accuracy requirements, however, the cost either takes up too much of our budget and requires the purchase of additional systems or is simply not feasible given our budget. Ultrasonic sensors are deemed insufficient given our system specifications. This is due to the vibrations and movement of the UAV and its motors, causing significant errors and interference. Photogrammetry is a close second to a radar altimeter in the trade study, but was ultimately not chosen due to uncertainty in performance on featureless surfaces such a snow. These surfaces make stitching together photographs challenging and would likely provide results that are unacceptable in terms of error for the depth measurements of the snow. Photogrammetry would likely have won due to the nice 3D surface model it produces and the high amount of data points produced, but the concerns with error were too high for featureless terrain. A radar altimeter is selected for the baseline design because they are lightweight, accurate, and have a high sample rate which should overall allow for precise and high resolution measurements of snow depth.

For the georeferencing system, a PPK GNSS (Post Processing Kinematic Global Navigation Satellite System) receiver was chosen. Specifically the Seagull GPK2 reciever. Of all the options for locating the aircraft, (standard GPS, PPK GPS, and altimeters) the PPK receiver afforded the best accuracy without too much extra cost. PPK receivers scored the highest in the most heavily weighted categories (Accuracy, cost, and weight). The main downside of the PPK receivers is some added complexity in setting them up, but the manufacturers provide instructions and offer technical support. PPK requires a base station nearby to be used effectively. Fortunately, there is a NGS-run base station in Breckenridge, CO that is open for public use and is within the required range to use PPK systems accurately. Overall, the PPK receivers offer the accuracy required to make the necessary positional measurements without significant trade offs in other criteria.

For the vehicle platform, a fixed-wing aircraft is chosen. This option is chosen due to several factors: (a) airplanes can be glided to a safe landing in the event of powerplant failure, (b) airplanes can be designed to achieve high airspeeds which will help escape strong headwinds, and (c) airplanes provide for the best payload weight fraction and battery weight fraction of the aircraft we studied which didn't violate the constraints. One downside of the airplane is that, due to its expected light wing loading, it will be more susceptible to gusts so the team will have to design for very stable natural dynamics. The team will conduct further investigation to size the aircraft weight, wing loading, and thrust-to-weight ratio to ensure all performance requirements are met. The team will also select an airplane configuration and overall airplane concept in order to meet requirements.

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VI. Appendix

A. Airplane sizing and performance estimation analysis

Note that the following data is used in analyzing the performance of a fixed-wing UAV:

Summary of data used in airplane performance analysis:

- $m_{PL} = 1.5$ kg. Mass of payload. This is subject to change based on the chosen sensor package and its mass.
- $\eta c = 200000$ J kg^{-1}. Product of propulsion system efficiency and LiPo capacity in cold conditions. More data is needed to determine what a reasonable value for this parameter is.
- $\frac{L}{D}\Big|_{max} = 10$. Maximum lift-to-drag ratio. This information can be found more precisely during more detailed design, but this value is fairly conservative for the purpose of initial analysis.

- $t = 3600$ s. Required endurance. This value may change depending on the sensor package.
- $\frac{W_e}{W_{TO}} = 0.65$. Empty weight fraction. Estimated based on experience with UAVs. Subject to change depending on aircraft construction techniques; i.e. use of composites could lower this value.
- $v_{crs} = 10$ m s^{-1}. Cruise velocity. Subject to change depending on sensor requirements.
- $v_{max} = 30$ m s^{-1}. Maximum velocity. Value chosen to escape strong headwinds.
- $\rho = 0.8$ kg m^{-3}. Air density. Based on standard atmosphere for 14000 feet.
- $S_{to} = 12$ m. Takeoff ground roll length. From design requirements.
- $g = 9.81$ m s^{-2}. Gravitational acceleration.
- $C_{L_{max_{to}}} = 1.8$. Conservative estimate for maximum lift coefficient with flaps in takeoff configuration. Subject to change based on wing design.
- $V_{climb} = 5$ m s^{-1}. Required climb rate from design requirements.
- $n_{man} = 2$. Load factor for maneuvering. Value is chosen to avoid extreme bank angles.
- $C_{D_0} = 0.028$. Parasite drag coefficient. Estimated based on $\frac{S_{wet}}{S} = 4$ and $C_{fe} = 0.007$ which is a high value for drag typical of single engine airplanes. Subject to change depending on aircraft drag properties.
- $AR = 7$. Aspect ratio of wing. Reflects estimated/desired aspect ratio.
- $e = 0.7$. Oswald efficiency factor. Conservative estimate for Oswald efficiency.
- $\frac{T_{TO}}{T_{man}} = 2$. Ratio of takeoff thrust to maneuvering thrust. Very rough estimate.
- $\frac{T_{TO}}{T_{crs}} = 4$. Ratio of takeoff thrust to cruise thrust. Very rough estimate.
- $\frac{T_{TO}}{T_{max}} = 1$. Ratio of takeoff thrust to thrust required for maximum speed. Assume that full thrust is used for maximum speed.
- $r = 10$ m. Turning radius. From design requirements.
- $V_{S0} = 8$ m s^{-1}. Stall speed in landing configuration. Value is chosen to not create undue pilot difficulty.
- $C_{L_{max_{ldg}}} = 2$. Conservative estimate for maximum lift coefficient in landing configuration. Subject to change based on wing design.

The takeoff weight is to be estimated first to guide further analysis into the performance of the airplane. Takeoff weight is the sum of empty weight, battery weight, and payload weight: $W_{TO} = W_E + W_{BATT} + W_{PL}$ [8]. The weight of the payload is specified as 1.5 kg for the sake of this trade study, and the empty weight can be estimated as a fraction of the takeoff weight based on typical values for fixed-wing UAS. So $W_E = 0.65 W_{TO}$.
Estimating the weight of the batteries requires a determination of the thrust used by the aircraft: based on a free body diagram, the trust of the aircraft must counteract drag and in turn must take a value of $T = \frac{m_{TO}g}{(L/D)}$. The power required is simply the thrust T times velocity v. The energy required is the power times the required endurance t: $E = \frac{v m_{TO} g t}{(L/D)}$. Now the energy content of typical RC aircraft batteries, such as Lithium Ion Polymer (LiPo) batteries, needs to be considered. Typical LiPo batteries have an energy density of 125 Wh kg^{-1}. In order to account for performance degradation due to cold temperatures and inefficiencies in the propulsion system, this value will be taken as a little bit under half of the typical value, or 200000 J kg^{-1}. It is assumed that this value accounts for the inefficiencies in

the propulsion system since the estimate for LiPo capacity is very rough anyway. This value is named ηc. The mass of the battery then can be expressed as $m_{batt} = E/c = \frac{v m_{TO} g t}{(L/D)} \frac{1}{\eta c} + m_{PL}$. Having formulated expressions for each contribution to the aircraft's takeoff mass, the following expression can be written:

$$m_{TO} = 0.65 m_{TO} + \frac{v m_{TO} g t}{(L/D)} \frac{1}{\eta c} + m_{PL} \tag{3}$$

In order to solve for m_{TO}, the following values are used:

- $M_{PL} = 1.5$ kg
- $\eta c = 200000$ J kg^{-1}
- $L/D = 10$
- $t = 3600$ s
- $\frac{W_e}{W_{TO}} = 0.65$
- $v = 10$ m s^{-1}

Solving for the corresponding takeoff mass of the aircraft and mass of batteries, the aircraft would weigh approximately 9kg and require approximately 1.5kg of batteries. In turn, both the payload and the batteries would make up approximately 17% of the aircraft's takeoff weight.

In order to determine the appropriate ranges of wing loading and thrust-to-weight ratio, the aircraft performance sizing plot must be generated. All data is taken at a standard atmosphere altitude of 14000 feet which results in an air density of 0.8 kg m^{-3}.

Stall speed. While there are no explicit stall speed requirements for the aircraft to meet, a stall speed of 8 m/s is chosen to ensure that the aircraft is not flying unduly fast during landing which would make manual flight difficult. The stall speed constraint curve is defined by the following equation [9]:

$$\left(\frac{W}{S}\right)_{TO} = \frac{1}{2} \rho v_{S_L}^2 C_{L_{max_L}} \tag{4}$$

Landing distance. While the design requirements do specify the required landing distance, it is suspected that, due to uneven terrain and the expected low friction coefficient between the aircraft's landing gear and the snow, a supplemental system will be needed to stop the aircraft upon landing. One such concept is a sort of deployable anchor which drops down from the aircraft upon landing, digs into the snow, and stops the aircraft. The aircraft can also be landed uphill. Later design work and modeling will be needed to ensure that landing distance requirements are met, but there are feasible options to ensure that an airplane can meet these requirements.

Takeoff distance. Assuming that thrust forces are significantly greater than drag and friction forces, the following equation holds for takeoff distance [10]:

$$\left(\frac{T}{W}\right)_{TO} = \frac{1.44}{(S_{FL}/1.66) \rho g C_{L_{max_{TO}}}} \left(\frac{W}{S}\right)_{TO} \tag{5}$$

Climb. It is desired that the aircraft can escape a 1000 ft/min (5 m/s) downdraft. Note that CGR is the climb gradient: $CGR = \frac{V_{climb}}{V_\infty}$. The constraint curve for this requirement is [10]:

$$\left(\frac{T}{W}\right)_{TO} = CGR + \frac{1}{L/D} \tag{6}$$

Maneuvering. A 10-meter turn radius is desired. A maximum load factor for the maneuver of 2 is set. In order to verify that the turn radius requirements can be met at normal cruise speed, the required airspeed to meet the 10-meter turn radius requirements is calculated: $V_{\infty,turn} = \sqrt{rg\sqrt{n^2 - 1}}$. The required airspeed is greater than the specified 10 m s^{-1} cruise speed, so these maneuvering requirements are met. Having established that these requirements can be met, the performance sizing curve for maneuvering is defined by[10]:

$$\left(\frac{T}{W}\right)_{TO} = \frac{q C_{D_0} (T_{TO}/T_{man})}{(W/S)_{TO}} + \frac{n^2}{q \pi A R e} \frac{T_{TO}}{T_{cr}} \left(\frac{W}{S}\right)_{TO} \tag{7}$$

Speed. There are two constraint curves related to speed: one for normal cruise speed and one for a faster dash speed of 30 m s^{-1}. The governing equation for performance sizing is the same in each case [10]:

$$\left(\frac{T}{W}\right)_{TO} = \frac{q C_{D_0} (T_{TO}/T_{cr})}{(W/S)_{TO}} + \frac{1}{q \pi A R e} \frac{T_{TO}}{T_{cr}} \left(\frac{W}{S}\right)_{TO} \tag{8}$$

The final performance sizing plot is shown:

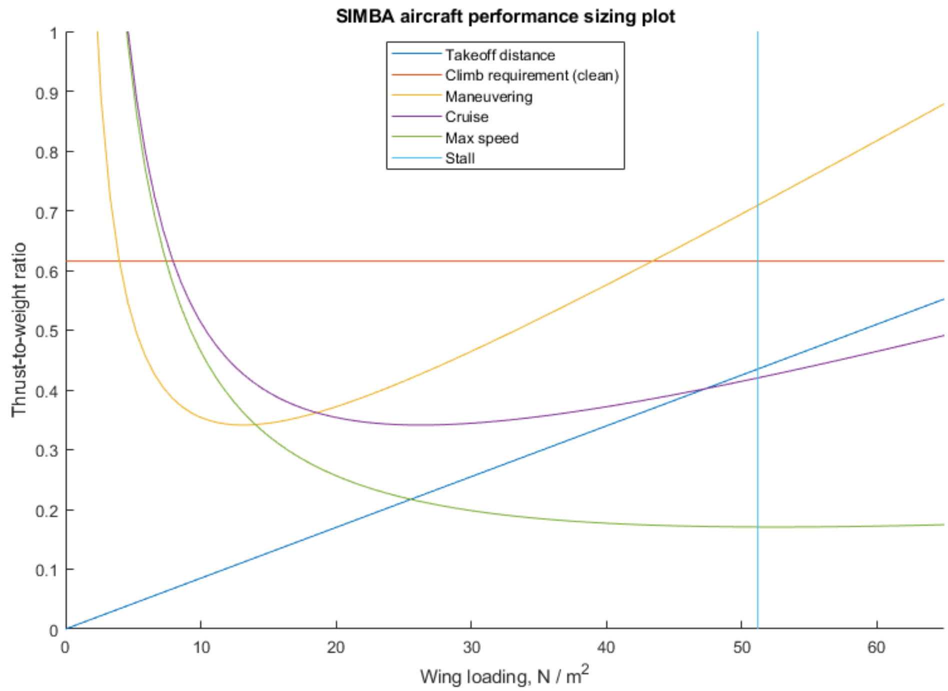

Fig. 12 SIMBA performance sizing plot. The acceptable design area is the area above the climb requirement line and bounded by the cruise, maneuvering, and stall speed curves.

B. UAV stability and Force

The equation for vertical thrust is simply $F_t = ma_y + mg$. Where a_y can be split into a $1x4$ matrix in order to solve for the thrust per motor.

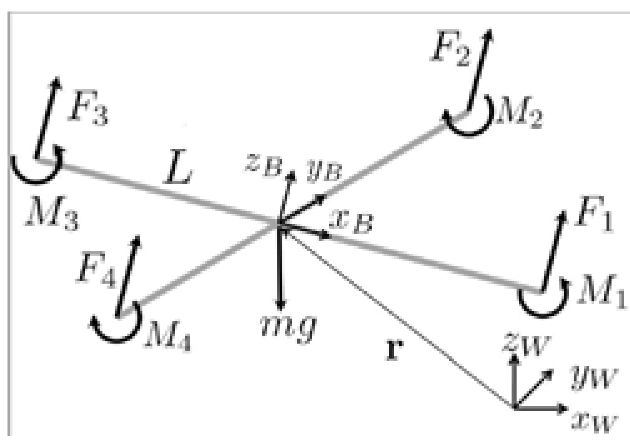

Fig. 13 Free Body Diagram of basic Quad-copter with Forces and Moments from internal and external factors