University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project B.L.I.S.S.
Boundary Layer In-Situ Sensing System
Conceptual Design Document

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1.0 Information

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2.0 Project Description

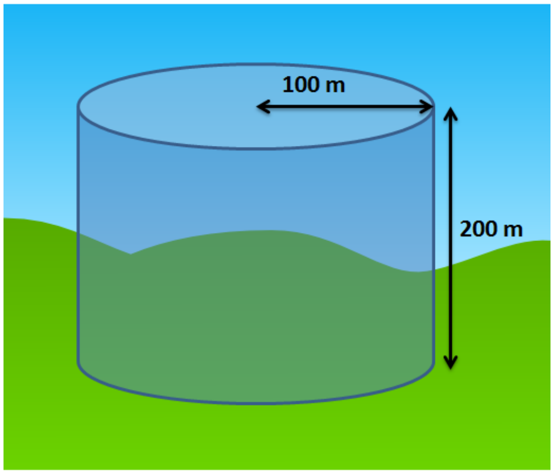


Figure 2.1: Measurement Cylinder

The motivation of this project is to collect in-situ wind data and atmospheric cloud observations to provide Northrop Grumman the ability to verify an atmospheric boundary layer model. The in-situ measurements are preferred to remote sensing due to the high cost of remote sensing equipment.

To accomplish this, three systems will be developed. The first, a measurement system, will collect in-situ relative wind data in a volume of airspace defined as a cylinder with a radius of 100 meters and a height of 200 meters above average ground level. A diagram of this airspace, situated in an undetermined type of location, can be seen in Figure 2.1.

The measurements will be post-processed to create a U-, V-, and W- inertial wind velocity vector field and will be accompanied by the temporal and spatial location of each measurement. Data will be recorded for 10 minutes duration, with the maximum radial distance between data points being 30 meters, distributed over the entirety of the cylinder. The measurement system must be able to collect data at an accuracy of 1 meters per second with a precision of 0.1 meters per second.

To transport the measurement system, a delivery system will be developed. The delivery system will transport the measurement system through the air volume, allowing the measurement system to take data at the required spatial and temporal locations within the measurement cylinder such that no two points are more than 30 meters apart one another. The measurement and delivery system will be integrated together.

The third system is a cloud observation system that will measure the base altitude of low-level clouds and image the clouds above the measurement cylinder in order output a cloud footprint. The cloud observation system will be separate of the integrated delivery and measurement system. As the Customer's only defined requirements are a cloud footprint and base altitude; further analysis was done to quantify the requirements for the system.

Early calculations indicate that the measurement error of cloud height increases as the cloud is higher in the atmosphere. As the scope of this project is boundary layer wind, clouds closest to the boundary layer were selected to be observed. NASA defines three levels of clouds, with the lowest being below a base altitude of 2 km, which includes cumulus and stratus clouds.

In order to define a functional requirement for sampling frequency with firm reasoning, a study of wind speed forecasts at 12,000 ft. above sea level (about 2km above ground level in Denver, CO) at Denver International Airport over a 1-week timeframe was performed. The study resulted in an average speed of 5.54 meters/second with a standard deviation of 2.89 meters/second. Assuming a normal distribution of wind speed, 2 standard deviations above the average will capture the 95th percentile strongest wind. This number comes out to be 11.32 meters/second and was used in calculations. At this speed, a cloud will take about 17 seconds for a cloud to cross the 200-meter diameter virtual measurement sphere. To insure that a cloud that passes through the bulk of the 100-meter radius cloud footprint is imaged multiple times, and clouds that pass through the edges are imaged at least once, a sampling frequency of ¼ Hz was selected.

The data collected by this project will be given to Northrop Grumman to provide them the ability to immediately verify their atmospheric boundary layer model. In the long term, Northrop Grumman plans to apply their model to environmental pollution monitoring, firefighting, and to facilitate soldiers in battle conditions.

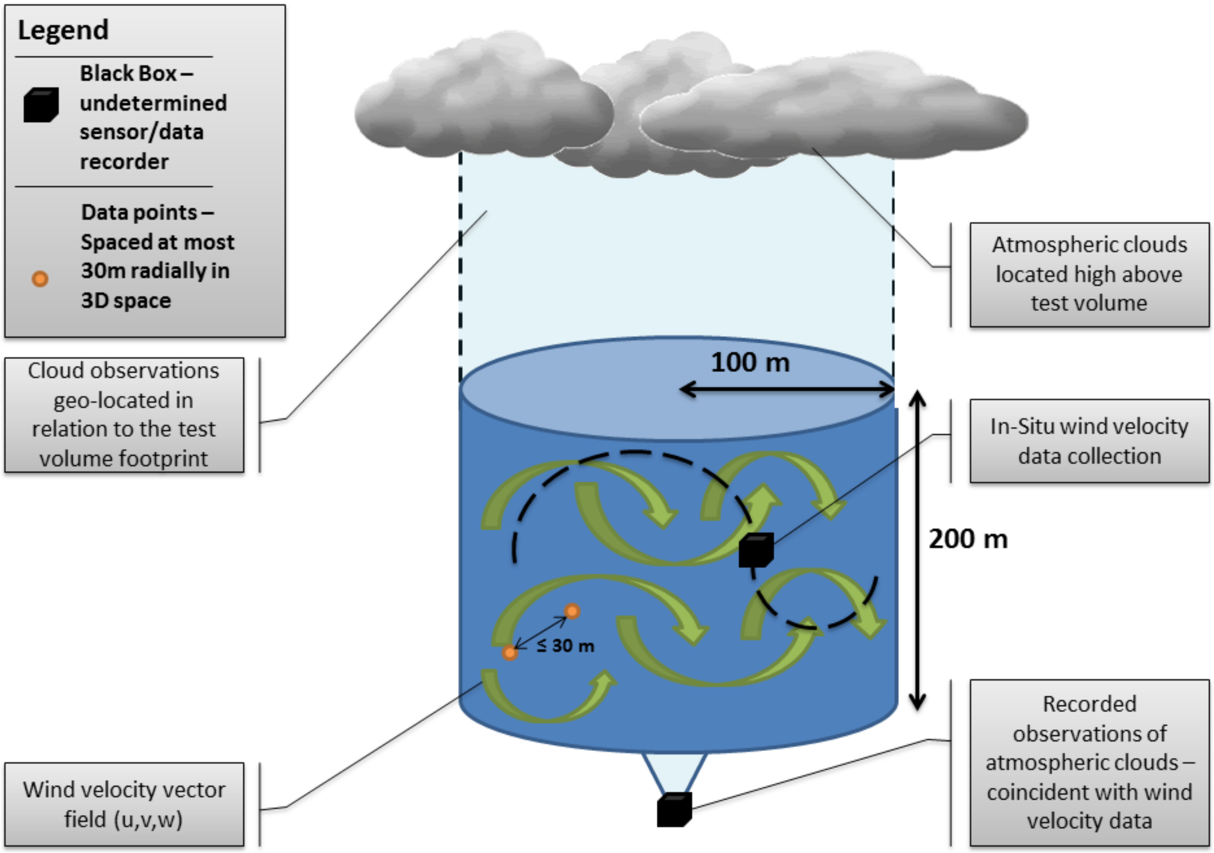


Figure 2.2: Experimental Method

Figure 2.2 depicts the same diagram of the test airspace volume as seen in Figure 2.1 to show Bliss' experimental setup. Included in this diagram is the natural wind velocity vector field present within the defined airspace, as well as the undetermined sensor/data recorder package which is to be moved throughout the volume in such a way that data points can be collected with a maximum resolution of 30 meters in 3D space. The cloud observation system, also included in this diagram, will operate independently to capture photographs of low level atmospheric clouds up to 2 kilometers above the test volume.

Figure 2.3 depicts the Concept of Operations diagrams. Five separate cylinders are shown in progression, where 1-5 represents the time frame of the project. Diagrams 1 and 5 are outside the scope of this senior project. Diagram 1 represents the results of Northrop Grumman wind model, which will be calculated for a defined airspace equal in size to the test volume described by Figure 1. Diagram 2 represents this physical airspace, complete with the physical wind vector which the Northrop Grumman model is attempting to predict. Diagram 3 depicts the data collection system capturing in-situ wind data through the test volume. When the in-situ wind velocity data has been collected, an inertial wind vector will be calculated from the data by post processing. The necessary post processing will depend on the type of data collection system used (i.e. pitot tube, anemometer, sonic, etc). These design options are considered in Section 4 of this document and results of a trade study are discussed in Section 5. Diagram 4 is the final stage of this senior project. Diagram 5 shows that Northrop Grumman will use wind data and cloud observations to verify their model results by comparing the predicted inertial wind vector field with the one determined from the in-situ data collection.

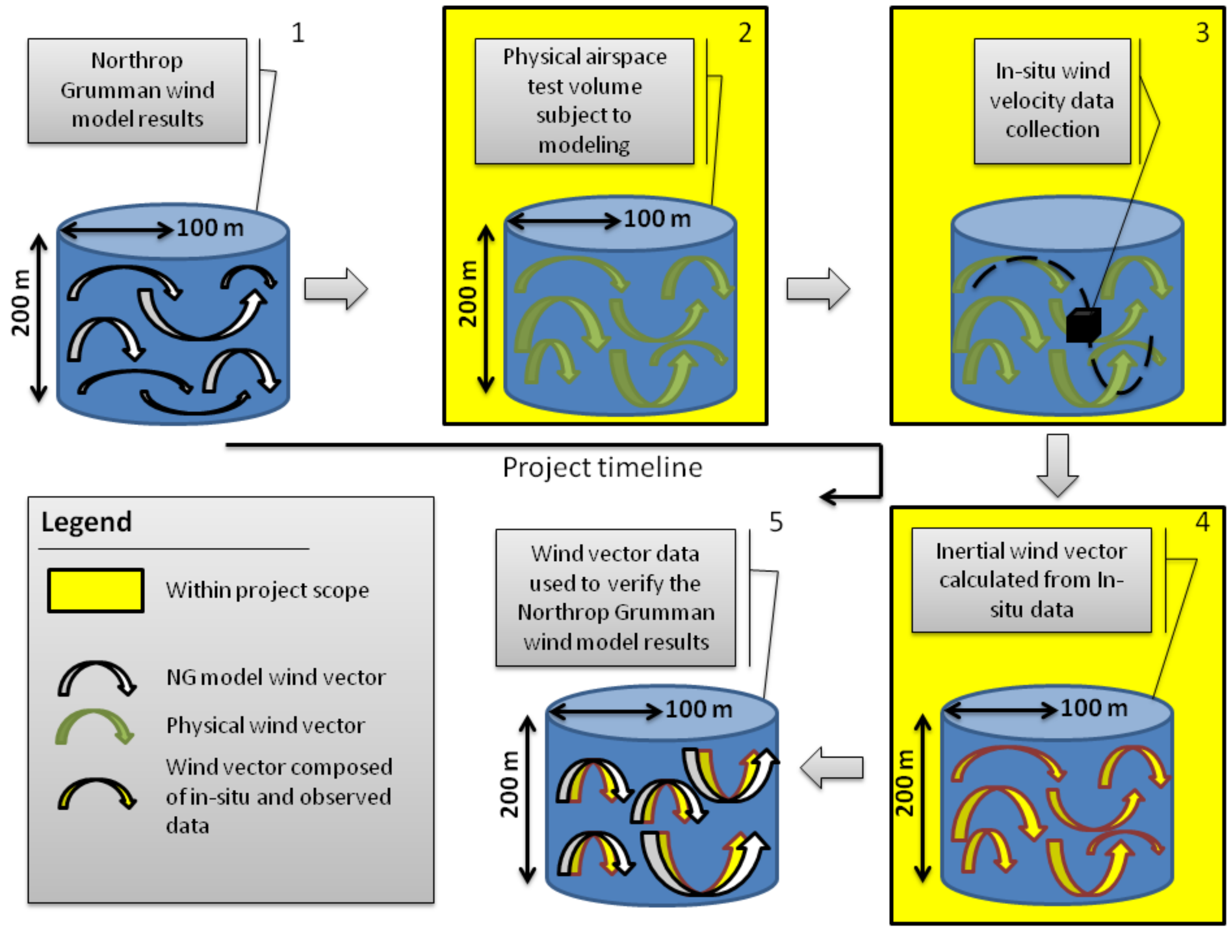


Figure 2.3: Concept of Operations

The functional block diagram (FBD) for the measurement and delivery system is shown by Figure 2.4 while the functional block diagram for the cloud observation system is shown by Figure 2.5. The FBDs were separated in order to emphasize that the measurement and delivery system will operate as an integrated unit while the cloud observation system operates independently from the ground. The diagram in Figure 2.4 begins with the wind velocity sensor of the measurement system, shown inside the green box, collecting measurements from incoming wind. Since the measurement system is unknown, the term “wind velocity sensor” was used to be clear on the motive of measurement while remaining ambiguous to the variety of sensors considered in the trade study. The processor queries the wind sensor for data, timestamps and sends this raw data to onboard storage to be post processed after the experiment.

The delivery system, shown in the red box of Figure 2.4, contains the electrical power system that will supply power to both the measurement system and delivery system. As the delivery system moves through the measurement cylinder, its location is recorded by a GPS, with coordinates sent to the onboard processor to be time stamped and sent to onboard storage. Avionics sensors send aircraft state data to the processor to be time stamped and sent to onboard storage. The GPS and avionics sensors also send the aircraft location and state to the flight controller, which determines the control commands necessary to follow the desired flight path. These commands are sent to control surfaces and propulsion mechanism.

After the experiment is completed, data will be offloaded from the measurement and delivery system’s onboard storage for post processing. The method of post processing will vary based on the final design choices, but will involve computing the relative wind vector to compare with the inertial orientation and velocity of the craft to determine the inertial wind velocity as a 3D U-, V-, W- vector field in the measurement cylinder throughout the experiment. The scope of the senior project ends at this point, when the vector field will be delivered to Northrop Grumman for use validating wind models.

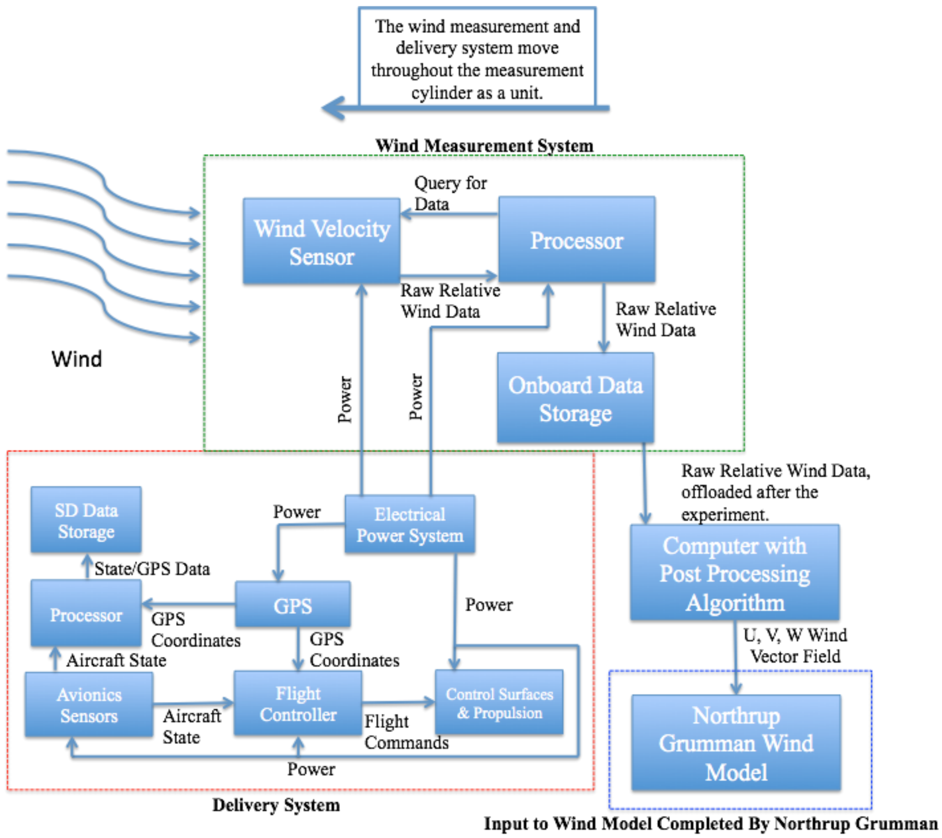


Figure 2.4: Measurement and Delivery System Functional Block Diagram

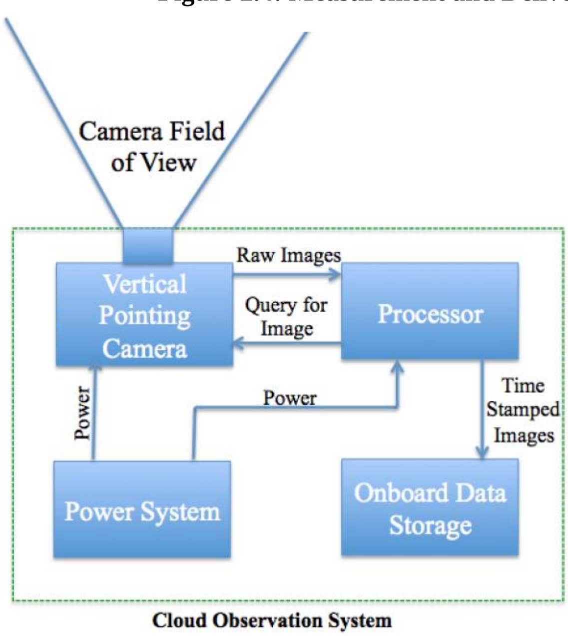


Figure 2.5: Cloud Observation System

The cloud observation system, shown inside the green box in Figure 2.5, operates on the ground inside the measurement cylinder wind data is being collected. The system images the clouds with a vertical facing camera or team of vertical facing cameras (design options are evaluated in the trade study) when queried by the processor. These images are time stamped by the processor and sent to the onboard data storage. After the experiment, images from the onboard data storage will be post processed to map the cloud footprint to the area above the measurement cylinder and determine base altitude.

3.0 Design Requirements

Index: FN - Functional Requirement, REQ - Requirement

FN1: A 3 dimensional in-situ U-, V-, W- inertial wind vector field shall be delivered to Northrop Grumman.

REQ 1.1: The vector field shall be a cylinder of airspace constrained by a cylinder with a 100-meter radius and 200 meter height.

REQ 1.1.1: Data points shall be collected throughout the entire measurement cylinder with no more than 30 meters radial spacing between adjacent points.

REQ 1.1.1.1: The delivery system shall transport the measurement system to location in order to collect this data.

REQ 1.2: The measurement system shall measure relative wind data accurate to 1 meter/second, with precision of 0.1 meters/second and variance of 1 meter/second.

REQ 1.2.1: Relative wind data shall be post processed in order to determine the U-, V-, W- inertial wind vectors at each point.

REQ 1.2.1.1: The delivery system shall record the aircraft state data necessary to determine the inertial wind vector from the relative wind vector.

REQ 1.2.2: The measurement system shall be tested in a wind tunnel to verify accuracy, precision and variance requirements.

REQ 1.2.2.1: The measurement system shall be tested in a wind tunnel to verify 3 dimensional measurement capability.

FN2: Cloud conditions above the measurement cylinder during the experiment shall be delivered to Northrop Grumman.

REQ 2.1: A cloud footprint above the measurement cylinder shall be recorded once every 4 seconds, or 1/4th Hz, throughout the experimental timeframe.

REQ 2.1.1: The footprint shall be an image of clouds above the measurement cylinder constrained by a 100-meter radius circle above the measurement cylinder.

REQ 2.1.1.1: Images taken during the test period shall be post processed to overlay a projection of the 100-meter radius circle above the measurement cylinder.

REQ 2.1.1.2: There shall be less than 10% error in radial distance in constraining the 100-meter radius circle above the measurement cylinder on the footprint image.

REQ 2.2: The cloud observation system shall measure the base altitude of clouds below 2 km for each cloud footprint image.

REQ 2.2.1: Cloud images shall be post processed after the experiment to determine cloud height.

REQ 2.2.2: There shall be less than 10% error in distance of cloud base altitude for clouds at 2 km.

REQ 2.2.2.1: The cloud observation system's error shall be tested by determining the distance of a fixed point known to be 2 km away.

FN3: Relative wind data and cloud conditions shall be collected over a 10-minute time frame.

REQ 3.1: The delivery system shall be able to continuously operate for a 15-minute time frame (1.5 safety factor).

REQ 3.1.1: The delivery system's electrical power system shall provide the delivery system and measurement system with power for at least 15 minutes.

REQ 3.1.2: The delivery system's onboard data storage shall be able to store at least 15-minutes worth of GPS and aircraft state data.

REQ 3.2: The measurement system shall be able to continuously operate for a 15-minute time frame (1.5 safety factor).

REQ 3.2.1: The measurement system's onboard data storage shall be able to store at least 15-minutes worth of wind measurement data.

REQ 3.3: The cloud observation system shall be able to continuously operate for a 15-minute time frame (1.5 safety factor).

REQ 3.3.1: The cloud observation system's electrical power system shall provide enough power to operate for a 15-minute timeframe.

REQ 3.3.2: The cloud observation system's onboard data storage shall be able to store at least 15-minutes worth of cloud images.

FN4: The experiment shall take place in a location specified by Northrop Grumman

REQ 4.1: Team Bliss shall coordinate with Northrop Grumman to determine a location where the experiment can be legally run and is approved by Northrop Grumman before the end of FY2014 to allow time for approval.

REQ 4.1.1: A Certificate of Airworthiness (COA) shall be obtained to operate any unmanned aerial system used to collect data during this project.

4.0 Key Design Options Considered

In order to thoroughly consider every possible design option, separate research was done on individual delivery and measurement systems. By studying delivery and measurement systems separately, an understanding of the union between systems can be more easily achieved. A thorough comprehension of a system's design and functionality will help determine which systems are worth exploring in a trade study. This was done by looking at specific qualities of delivery and measurement systems that relate to the overall goal of the project.

In order to rank delivery systems, it was considered how well a delivery system could traverse through the airspace, how much payload it could carry, and how stable such a system would be. Also considered was the cost and safety of the system, as well as how much the airflow interference of the vehicle would affect the measurement system. Interference, in this sense, refers to how the undisturbed airflow reacts to the operation of the system. Ideally, the desired system will have zero disturbances on the field of measurement. Because a delivery system with no disturbance is possible, airflow interference around each system must be considered. Further, the system must have the ability to efficiently maneuver about the cylindrical airspace, with some consideration being given to the measurement system. The tradeoff between system velocity and payload will be carefully studied. Based on this research, judgment can be made on which systems would be worth doing a trade study on.

In order to fully explore every possible measurement system, it was important to understand how wind is typically measured. Researching past work found that there were three main categories of wind measurement systems: anemometer, pressure sensing, and wind profiling. An anemometer, which literally means wind meter, is the most traditional way to measure wind. Pressure sensing typically uses pitot tubes to measure the pressure and converts that measurement into wind velocity. Wind profiling refers to the use of LiDAR and RADAR to remotely sense the velocity and direction of the wind. The most common form of this is Doppler radar. In the context of this project, radar was considered an observed measurement, not an in-situ measurement which is required to validate the Northrop Grumman atmospheric model. Therefore, only anemometers and pitot tubes will be studied. The qualities that are desired in a measurement system are data accuracy and resolution, cost, and system size and weight. Accuracy and resolution pertain to the specific measurement device, so it must be considered that a measurement system may need more than one sensory device to take accurate data in all three dimensions. In this case, the error might propagate through and be greater than it appears. Likewise, the size of the system was also looked at in terms of physical dimensions and weight. This is an important quality of a system because the payload can affect the speed of the delivery system, consequently resulting in less accurate and complete data.

The goal of looking at a multitude of independent systems is to characterize potential systems which may best deliver the measurement system to points within the cylinder. The matching of these two systems, within the requirements, will ultimately drive the baseline design.

4.1 Delivery System

4.1.1 Fixed wing UAV's

Figure 4.1.1: Images of Fixed Wing UAV's[1]

Fixed wing UAV's use a scaled down aircraft frame to carry a moderately sized payload. Fixed wing UAV’s are capable of long endurance flight because similar to airplanes, they use the lift provided by an airfoil to support the payload’s weight. Fixed wing UAV's encompass both traditional airframes scaled down and flying wings. Flying wings use only two control surfaces to combine the aileron and elevator and have no yaw control, however they are inexpensive and capable of carrying a large payload for their weight. A typical flying wing airframe costs between $130 and $150 without components and is constructed using foam. Flying wings typically have no landing gear and land by sliding on their belly. Flying wings often use an electric motor for power.

More traditional airframes use multiple control surfaces and have a vertical tail with rudder providing yaw control. Many scaled down aircraft also use tricycle landing gear reducing the wear and tear on the aircraft caused by belly landings. Using landing gear instead of a belly landing is also lower impact, reducing the stress on the sensor package. Typical scaled aircraft using an electric motor retail between $150 and $200, however, some more expensive gas powered aircraft sell for as much as $400. Fixed wing UAV's have low interference on the flow because they are using airfoils to provide lift instead of multiple propellers like a multi-rotor UAV. Mounting an airspeed sensor in front of the nose of a fixed wing UAV would minimize the disturbance on the airspeed measurement and allow for accurate collection of relative airspeed data. Fixed wing UAV's can fly between 20-25 meters per second, allowing for rapid data collection. After doing preliminary calculations of the flight path it was estimated that, with 40% extra flight distance due to turns outside the cylinder, a fixed wing UAV could collect data from the entire measurement airspace in 8.4 minutes flying at 20 meters per second. This extra distance was added to the fixed wing UAV to account for overshoot outside of the measurement cylinder when turning

Both flying wings and scaled aircraft would require the purchase of an autopilot, speed controller for an electric motor, control servos, a multi-channel remote controller, and other electronic components necessary for flight. These additional systems will push the cost of a fixed wing UAV to around $1500 dollars, or around 30% of the total budget. While this is not a large amount of the project budget, having a robust airframe is necessary so that tests can be repeated without buying multiple airframes. In the event of an airframe becoming damaged, replacing the fuselage is relatively inexpensive compared to the cost of the electronics on board.

Fixed wing UAV's have a smaller amount of exposed propellers than multi rotor UAV's and therefore pose less of a safety risk. Fixed wing UAV's pose the threat of bodily harm if one was to hit a person, however implementing good safety procedures when in flight will limit the exposure to injury for the ground control crew.

As with any in-situ airborne delivery systems, a fixed wing UAV may be susceptible to disturbances due to high winds. These disturbances threaten not only the flight worthiness of the UAV but also the flight path, which could affect the spacing of the data points.

Many fixed wing UAV's are designed with large payload bays capable of carrying cameras and transmission systems. An airframe with appropriate payload capacity for the sensor system could be utilized, providing ample space to carry the airspeed sensor and data recorder along with an autopilot and other relevant systems.

A fixed wing UAV is a viable delivery system solution for this project. It is a cost effective method for rapid, accurate data collection with limited safety concerns. A fixed wing UAV will ensure data is collected from the entirety of the measurement airspace within the 10-minute timeframe. The only concern is the robustness of the airframe selected, however, the flying wing could be reinforced or landing skids installed to increase the longevity of the aircraft.

Table 4.1.1: Fixed Wing UAV Pros and Cons

Pros	Cons
Low interference on data collection	Airframe susceptible to damage upon crash
Inexpensive	Aircraft prone to loss of control in high winds
High speed craft allows for high speed of data collection	
Large payload capacity	

4.1.2 Helicopter UAV

Single and multi-rotor helicopter UAV's use vertically oriented propellers to lift the vehicle, and adjustments of motor tilt angle and power distribution among multiple motors controls the translation of the vehicle. The distinction between single and multi-rotor vehicles is important as both types are suited to different applications and offer differing benefits to project objectives. Multi-rotor helicopter drones have recently been increasing in popularity as many of the commercially available designs are focused on aerial photography and are often easily controllable through phone apps or input of GPS coordinates. Single rotor helicopters are typically used for hobby purposes and models designed to carry custom payloads usually come in kits, not pre-built like most multi-rotor UAV's.

4.1.2.1 Multi Rotor Helicopter UAV's

Figure 4.1.2.1: Image of Multi-Rotor Helicopter UAV[2]

Multi-rotor helicopter UAV prices have a wide range from a few hundred dollars to upwards of $25,000, mostly dependent on payload mass capabilities and flight speed. While some models of multi-rotor helicopters are extremely expensive and used for professional aerial photography, others are meant for beginners and are significantly cheaper. The least expensive option researched still would use over 20% of the budget, while the most expensive was over five times the total budget. These vehicles can be flown manually or to individual locations through input of GPS coordinates. Due to their simple applications, autopilots do not come pre-installed and if an autopilot were used it would need to be integrated manually. Most models include a mount to attach cameras, which could be utilized for mechanically integrating the measurement system. Flight velocities are limited to under 15 meters per second and payload mass capabilities less than 5 kilograms. Due to the large number of radially mounted spinning propellers there will be a significant downwash that disturbs the air motion around the vehicle. There is an inherent danger from spinning propellers and flying vehicles, however, a crash from this type of vehicle would not pose a fatal threat to those on the ground. This type of vehicle is relatively light and the propellers are made out of a thin plastic that would not inflict fatal injury.

Table 4.1.2.1: Multi-Rotor Helicopter UAV Pros and Cons

Pros	Cons

Inexpensive	Downwash due to rotors would cause significant interference upon data collection.
Large payload capacity	Airframe might break upon crash.
	Low speed of UAV limits the speed of data collection

Cons of this delivery system by far outweigh the pros for multiple reasons. The largest disadvantage to using a multi-rotor helicopter drone is the interference on the data collection if collecting wind data based on pressures or actual wind velocities using an anemometer. The downwash from rotors will significantly change the airflow around the vehicle, limiting the precision to which the relative wind vectors can be measured. There are alternative methods to measuring the wind vectors with drone helicopters, however they are not accurate and would require more time to collect the data required. One such method is attempting to have the helicopter hover in a trimmed condition in a specific position. An estimate of the relative wind can be found by measuring the required thrust and in what directions adjustments are required. Robustness also made the cons list as these devices are typically made from weak plastics and likely to break beyond repair if involved in more than a minor crash. The repair is also significantly more difficult with this type of helicopter as they are typically purchased “Ready to Fly” and individual components are difficult to come by. Speed of data collection is also not optimal with these vehicles, as they fly slowly (5-15 meters per second), are susceptible to gusts of wind that would require corrections, and depending on the measurement system they would need to hover at each data collection point to obtain data, increasing the total time to collect all points. Payload capacity is listed under pro because with a 5kilogram payload capacity on some models, most measurement systems would be able to be carried, although with a heavier payload the flight velocity decreases.

As with the other delivery systems, the pros and cons can be slightly re-interpreted depending on the measurement system. For example if the data were to be taken by determining the thrust and direction required to keep the helicopter in a trimmed hover, the interference on data collection would have much less of an impact and could even be considered a pro. The interference on collection is listed as a con because it is a con for the majority of the considered measurement systems.

4.1.2.2 Single Rotor Helicopter UAV’s

Figure 4.1.2.2: Image of Single Rotor Helicopter UAV[3]

The more traditional looking helicopter design has been around for longer than the multi-rotor design and has a wider variety of uses. Typical single rotor helicopter UAV’s come in kits that are assembled by the user, and different configurations can be designed for different payload considerations. Sizes vary greatly from handheld to one meter in length and motors can be electric or gas powered. Payload capabilities are significant, as a $2,000, 16 kilogram gas powered model is capable of lifting an 11kilogram payload and flying at approximately 20 meters per second, less when at full payload capacity. These vehicles are designed to be flown by remote control, however most models are sold as skeletons where the user integrates flight control systems so using an autopilot would be on the same level of complexity as the multi-rotor design. As with the multi-rotor design, single rotors still have a significant downwash caused by the propeller, which would degrade the quality of data taken. A possible extendable boom carrying the measurement system could aid in reducing the effect of downwash on the data. This design is typically heavier than the multi-rotor design and blades spin faster making safety a larger issue with this design. Single rotor kits have similar costs to multi, around 20% of the total budget.

Table 4.1.2.2: Multi Rotor Helicopter UAV Pros and Cons

Pros	Cons
High speed of UAV allows for high speed of Data Collection	Downwash due to rotors would cause significant interference upon data collection.
Large payload capacity	UAV may break upon crash

Speed of data collection has been moved to a pro for the single rotor design as their larger, individual motor allows them to fly at faster speeds, while carrying a larger payload. Robustness is improved from the multi-rotor design as single rotor helicopter UAV's come as a simple skeleton/motor in which flight control systems and payload can be added. This more simplistic design is more robust to damages from crash and if components are broken they are more easily replaced. Interference on data collection is again listed as the largest disadvantage to this design, as the downwash from a gas powered engine would disrupt the surrounding air enough to significantly degrade the data. There are methods of getting around the interference, such as a boom, but they add to the complexity and price of the design.

4.1.3 Balloons

High altitude balloons have been used for weather and atmospheric experiments since the 18th century. Recently, high altitude ballooning has grown into an affordable way for many hobbyists to reach and photograph near-space altitudes. Because of the popularity and weight requirements of these activities, large weight capacity balloons can be found for affordable prices.

Due to the low price and simplicity of a single balloon system, balloons can be used in a system consisting of many subsystems, where each subsystem is made up of one tethered balloon at 200 meters altitude and 7 total sensor packages spaced 30 meters along the length of the tether. However, because the test cylinder is so large, 21 of these subsystems would be required along the circumference of the cylinder alone. A total of 46 subsystems would be required to take continuous data within the cylinder without spacing points more than 30 meters apart.

In order to support the required mass of 7 sensors, each of the 46 1.5 meter diameter balloons would need to be filled with 180 cubic feet of helium. Based on current bulk helium prices, the cost to fill 46 is roughly $6800. This does not account for the prices of balloons, sensors, tethers, or the wiring required to connect the airborne sensor packages to the ground.

Balloon systems are a viable option for collecting the most data points simultaneously, however, the size of the test volume as well as the spatial resolution restrictions add a large amount of cost and complexity to the system. Overall, the tethered balloon delivery system will either accomplish the spatial resolution of the data requirements and exceed the project budget, or meet budget requirements and violate the spatial resolution of the data requirements.

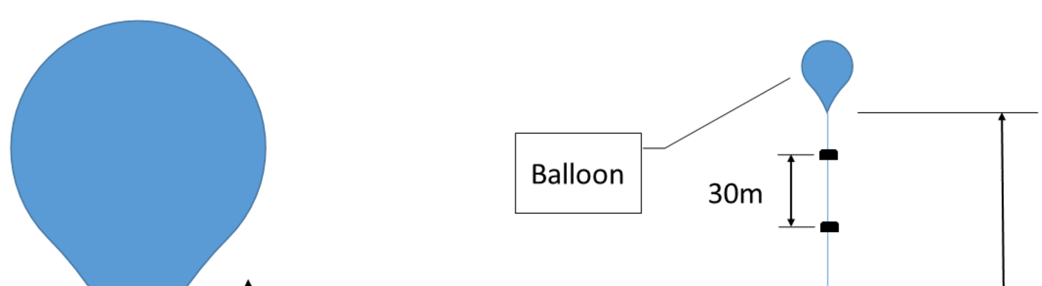


Table 4.1.3: Balloon Pros and Cons

Pros	Cons
High mass budget means one balloon can carry multiple sensors	Stationary and thus requires hundreds of sensors to operate within the design constraints
Relatively small tethered and balloon size means for relatively low interference from the system onto the wind field	Cannot be used with certain sensors (pitot tubes) due to low relative wind speed
	Tethered balloons are prone to drift due to wind which could cause data points to drift out of the 30m distance limitation
	30 meter requirement gets violated unless 46 balloons are used.
	Prohibitively expensive

4.1.4 Blimps

A blimp is an airship that derives its lift from a lifting gas that is lighter than air like a balloon, however, a blimp has propulsion capabilities. The main components of a blimp are: Envelope (Balloon), rudders, control system, and power plant. The envelope is often made of Polyurethane with reinforced welding to assure the minimum of helium loss. The rudders are for stability reasons and are made of lightweight materials. The control system, usually encased in Styrofoam or Fiber Glass, consists of the complete electronics used to control the blimp. The main difference from a tethered balloon, other than not being tethered, lies in the use of a power plant. The power plant consists of two battery-powered motors that can rotate. By using thrust vectoring with these motors along with rudders, the airship can be maneuvered via a remote control. Balloons, on the other hand, simply follow the wind. Remotely controlled blimps are mainly used for advertising purposes as well as aerial surveillance.

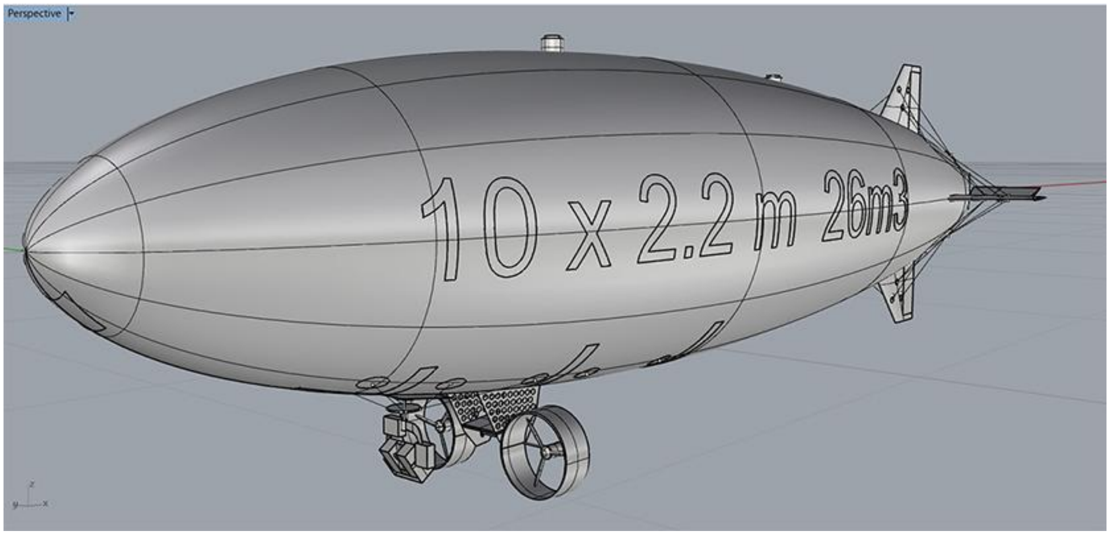


Figure 4.1.4: Blimp Image[4]

Blimps are effective because they can lift heavy payloads, fly for an extended duration, and can be controlled by a pilot. Typical outdoor blimps can lift payloads between 2.5 kilogram up to about 5 kilogram depending on the size of the blimp. Also, blimps can fly anywhere between 20 and 60 minutes depending on the weather conditions and pilot. A blimp would be ineffective as the delivery system for the design requirements for a few reasons. First, the flight speed of the airship would not be fast enough to traverse the cylindrical airspace within a reasonable time. The minimum velocity to navigate the entire airspace in the 10 minute timeframe would be about 12 meters per second using a perfect path. The Blimps fly between speeds of 25 and 30 km/hr or about 8 meters per second, meaning that at least two separate blimps would be required to reach the desired points in an acceptable amount of time. This leads to the next point, that blimps are relatively expensive. One blimp costs between \$2000 and \$4000 depending on length and volume. This does not include the cost of helium which would be needed for each flight. As the size of the blimp increases, the more the wind affects the airship which leads to increased power consumption for control. Another downside of a remotely controlled blimp is that a pilot would have to fly the craft through the airspace which would most likely not be accurate enough to meet requirements.

Table 4.1.4: Blimp Pros and Cons

Pros	Cons
Heavy Payload capabilities	Slow flight speeds

Long Flight duration	Must fill with helium each flight
Controllable	Expensive
	Remote controlled
	Large body interferes with flow
	Poor performance in high winds

4.2 Measurement System

4.2.1 Pitot tube

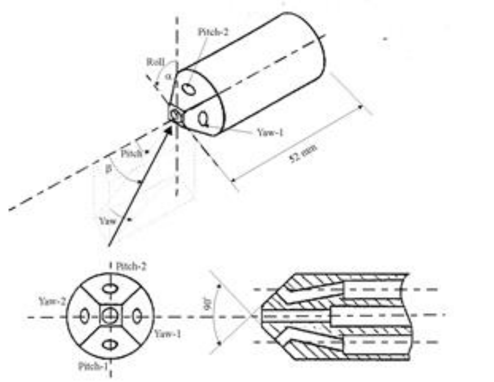


Figure 4.2.1: Image of Pitot-Tube[5]

Pitot tubes measure the both the static and total pressure of a flow in order to compute relative wind speed with Bernoulli's equation. A single pitot tube can only measure speed as the tube can only see the change in total pressure in one dimension. Multiple pitot tubes can be operate as a system called a multi-hole pitot tube, seen in Figure 4.2.1, in order to determine a 3D wind vector field. In a flow, wind will produce different pressure readings on each pitot tube depending on which direction the wind is coming from. By carefully calibrating the pitot tubes and combining the data with an aircraft's inertial velocity, known from GPS data, a 3D U-, V-, W- inertial wind vector can be produced.

In the scope of this document, the term "pitot tube system" refers to the pitot tube, pressure transducer, and any other necessary parts such as tubing and connectors. Standard multi-hole probes consist of three, five, or nine pitot tubes. Multi-hole pitot systems have a relatively small mass; the transducers weigh anywhere from 5 to 10 grams, while the actual pitot tube and associated tubing ranges from 20 to 100 grams. Error with pressure transducers depends on the total pressure being measured, therefore at low speeds error is much larger than at high speeds. As pre-made multi-hole pitot systems are not widely available on the market at low cost, the probe may need to be created by combining several individual pitot tubes which could increase error.

There is a large amount of published research that will aid in the design of such a system, as this is a well-established method of wind sensing. In addition, the RECUV project at University of Colorado - Boulder uses this method, which will provide a great source of in-house experience and advice on a complex problem.

Table 4.2.1: Pitot Tube Pros and Cons

Pros	Cons
A proven method of wind measurement (RECUV)	Requires precise calibration for accurate data
Low mass and volume, therefore easily applicable to a wide range of vehicles	Low speed vehicles (balloons) produce high inaccuracies with pitot tubes
Large selection of individual pitot tubes on the market	Multi-hole pitot tubes needs to be built using single-hole pitot tubes

4.2.2 Anemometer

One solution for a measurement system can be anemometers. Anemometers or wind speed measurement devices can measure the speed and, with a vane, can measure the direction, too. For the measurement system three different anemometers are examined. These are cup anemometer and vane, propeller anemometer and vane, and hot wire anemometers.

4.2.2.1 Cup Anemometer

This anemometer has three cups that spin to measure the wind speed. A vane mounted on top of the cups gives the direction of the wind. This system would only give the U and V wind vectors. A second system would need to be bought and mounted vertically to give the W velocity component. These systems weight about 2.3 kilograms each and take up about a square foot of space. Then there also is an electronics box that must be connected to each system. The system is very accurate for wind speed measurement. This system can meet the measurement quality as defined. Figure 4.2.2.1 shows the concept of this measurement system.

Figure 4.2.2.1: Image of Cup Anemometer[6]

Table 4.2.2.1: Cup Anemometer Pros and Cons

Pros	Cons

Accurate and Precise enough wind speed measurement and Direction	Large in size
Made of strong sturdy plastics	Heavy

4.2.2.2 Propeller Anemometer and Vane

This anemometer has a propeller mounted on the end of a vane. The vane aligns with the wind to provide direction and the propeller spins to measure the wind speed. Much like the cup anemometer, this system would only provide the U and V wind vectors. A second propeller anemometer would be needed and mounted vertical to provide the W velocity component. These systems are even larger than the cup anemometers. However they only weigh in the range of 1.1 to 2.5 kilograms. These systems also meet the accuracy and precision required. Figure 4.2.2.2 shows the propeller anemometer and vane concept.

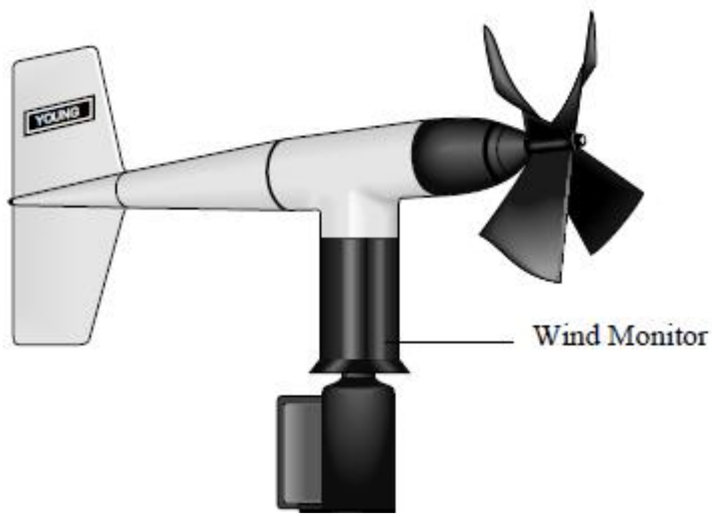


Figure 4.2.2.2: Image of Propeller Anemometer and Vane[7]

Table 4.2.2.2: Propeller Anemometer and Vane Pros and Cons

Pros	Cons
Accurate and precise Wind Speed and Direction	Large in size
Made of strong plastics and aluminum	Expensive

4.2.2.3 Hot Wire Anemometer

This anemometer consists of an electrically heated wire exposed to the wind. It measures the wind speed by measuring the current used to keep the wire at the same temperature. These systems are very accurate measurement devices for wind speed. However they do not provide the wind direction unless three are used together. They must be set up orthogonal and then the U,V,W wind vector can be found. The positives of this system is that they are lightweight, and small. They also meet the accuracy and precision wind speed requirements. However this option is the most expensive of the anemometer options.

Figure 4.2.2.3: Image of Hot Wire Anemometer[8]

Table 4.2.2.3: Hot Wire Anemometer Pros and Cons

Pros	Cons
Accurate and precise wind speed measurement	Cost
Lightweight	Complex
Small	Large Power Consumption

4.2.2.4 Sonic Anemometer

Sonic anemometers use ultrasonic sound waves between pairs of transducers to measure wind velocity and direction. Using a known distance between the

Figure 4.2.2.4: Image of Sonic Anemometer[9]

transducers and the known speed of sound, a calculation is done to yield a wind velocity vector. They come in one, two, and three axis systems and the velocity tends to be very accurate, on the scale of 0.001 meters per second. The resolution and directional accuracy is also very high, on the scale of 0.01 meters per second and 0.1 degree, respectively. The physical size and weight of a sonic anemometer could cause problems when selecting a system. They can weigh anywhere from 1 to 4 kilograms, with the largest system being 56 centimeters tall with a 25 centimeter radius. For the mission purposes, one 3-axis or two 2-axis sonic anemometers could be used. Durability of these systems varies depending on physical design, where some models have considerable robustness while others tend to be brittle. The more robust instruments happen to be cheaper. Whether a single 3-axis design or two 2-axis designs are chosen, the total cost for the measurement system would come out around $2500, which is roughly 50% of the total budget. In this case, a cheaper delivery system would have to be considered.

Table 4.2.2.4: Sonic Anemometer Pros and Cons

Pros	Cons
Accuracy and Resolution	Size and Weight
Simple Data Output	Cost
Ease of Integration	Robustness

4.3 Cloud Observation System

4.3.1 Stereovision

Stereovision is the use of a two camera imaging system to determine an object's location in reference to the camera system. The cameras are separated by a known distance and pointed at parallel fields of view, as can be seen by 4.3.1.1.

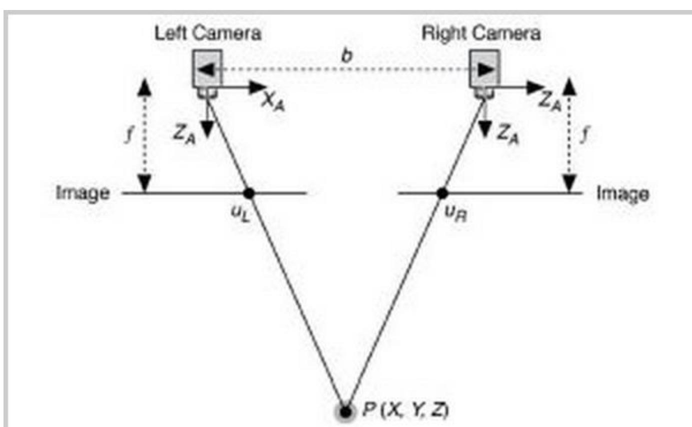


Figure 4.3.1.1: Stereovision Diagram[10]

Distance of a point on the image, in this case the cloud base, can be computed by overlaying images from each camera taken at the same instance in time. Since the cameras are separated by a known distance, they have a known difference in field of view. The distance between projected locations of a common point on the two images is known as disparity. The mathematical representation of disparity is shown by Equation 4.3.1.1 where u is the projection of the point of interest on the left and right image.

$$disp = u_l - u_r \qquad \textbf{(Eq. 4.3.1.1)}$$

Finally, the distance of the object can be computed using Equation 4.3.1.2, where Zp is the distance, f is the focal length of the camera, b is the distance between the cameras and disp is the disparity.

$$Z_p = \frac{f * b}{disp} = \frac{f * b}{u_l - u_r} \qquad \textbf{(Eq. 4.3.1.2)}$$

This is a simplified method for distance computation. More complex methods exist and take advantage of digital images and computer processing. Digital imaging with computer processing increases measurement accuracy as compared to distance measurement with a film camera. With film cameras, pictures have to be printed very large and disparity measurements of a common point made by a ruler while with digital imaging, disparity measurements can be made with software, down to the pixel of interest.

A system to locate the base of the clouds would have 2 vertical facing two cameras mounted on independent platforms spaced a large distance apart. The distance must be large in order to have a disparity between common points that may be up to 2 km away. The system will be able to define the measurement cylinder's circular projection on the clouds by comparing the delivery system's location throughout the test with its location in the images.

An error analysis was done in order to determine the feasibility of a stereovision system to image clouds at a height of 2 km. The horizontal accuracy of any point within a digital images field of view is based on the distance of the point, d, the camera's field of view, α, and the images number of horizontal pixels, p_h. The derivation of horizontal accuracy is shown by Figure 4.3.1.2. The final form of the accuracy equation is shown by Equation 4.3.1.3. Horizontal accuracy of any point on the image is equal to the projection error of the image, δu.

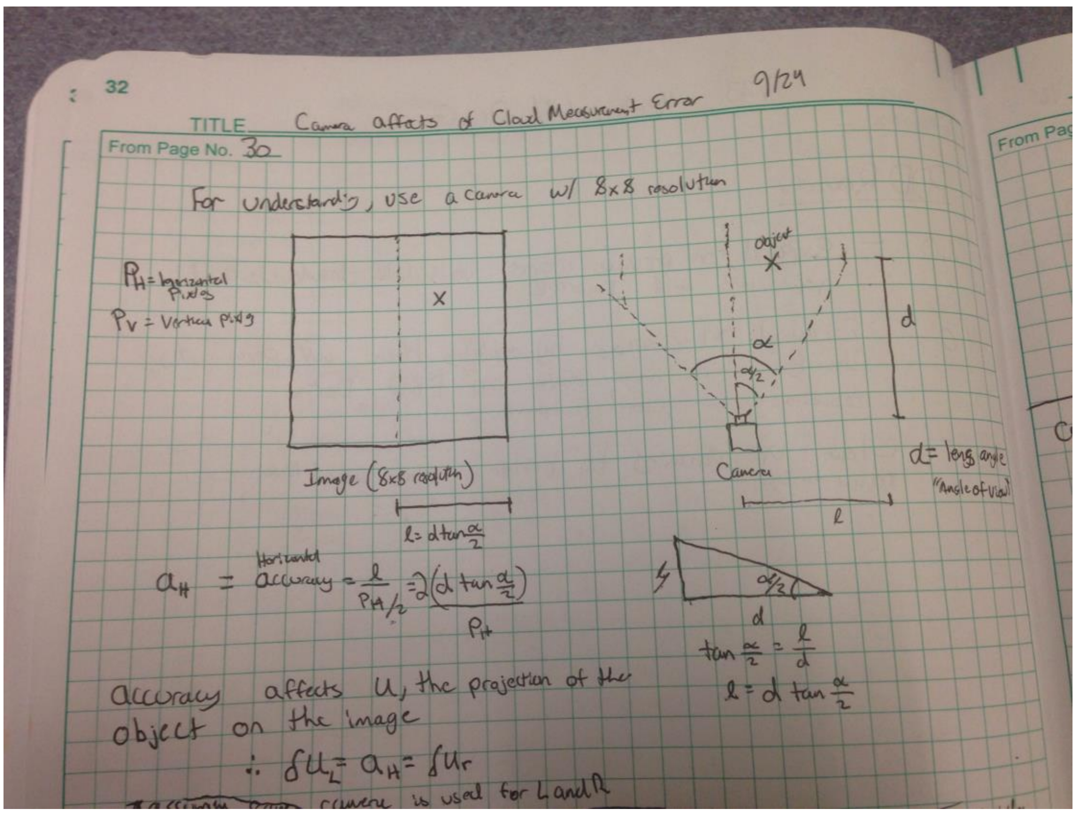


Figure 4.3.1.2: Digital Image Horizontal Location Accuracy

$$a_H = \delta u = \frac{2d\tan(\frac{\alpha}{2})}{p_h} \qquad \textbf{(Eq. 4.3.1.3)}$$

The error propagation of Equation 4.3.1.2 is shown by Equation 4.3.1.4. Error due to the focal length of the camera was omitted from this analysis, as it was shown to be significantly smaller than other sources of error.

$$dZ_p = Z_p\sqrt{\left(\frac{\delta b}{b}\right)^2 + 2\delta u^2} \qquad \textbf{(Eq. 4.3.2.4)}$$

A Matlab script was created to evaluate the error of cloud base measurement from heights between 1 and 2 km with a range of affordable camera resolutions and fields of view. Figure 4.3.1.3 shows the error due to the camera's field of view by holding resolution constant at 16 Megapixels. Figure 4.3.1.4 shows the error due to the camera's resolution by holding field of view constant at 11°.

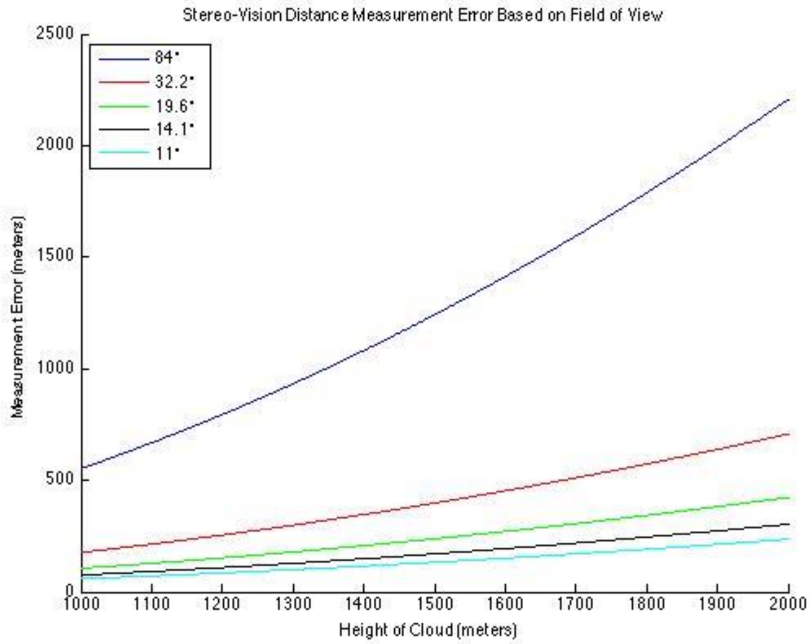


Figure 4.3.1.3: Cloud Base Measurement Error Due to Camera Field of View

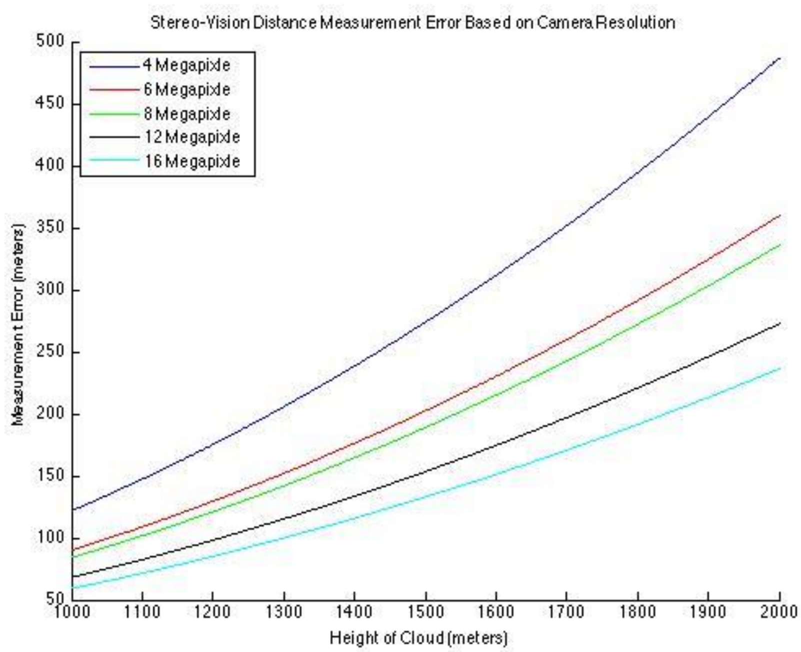


Figure 4.3.1.4: Cloud Base Measurement Error Due to Camera Resolution

Error analysis shows that higher resolution cameras with narrow fields of view decrease the error in cloud base measurement. A set of 16 megapixel cameras with an 11° field of view will have just over a 10% measurement error for clouds with a base of 2 km. Assuming that cloud height does not change between successive measurements will allow averaging of data to increase the accuracy. Cameras with these specifications can be found for under $200 on multiple online vendors.

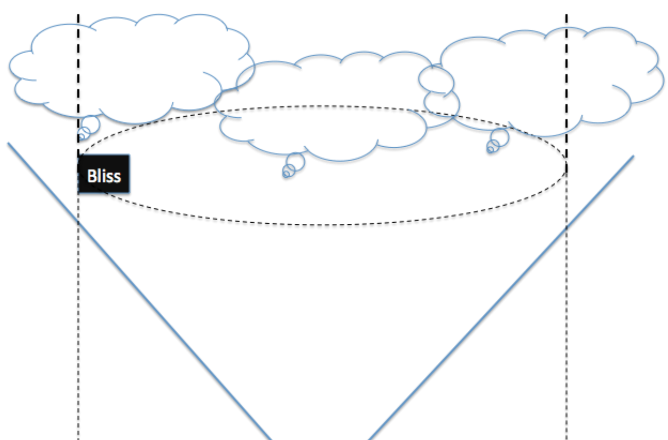
There are many software packages designed to process stereo pair's of images and compute distances. Matlab has one version of such software implemented in their computer vision systems toolbox, which available under a Matlab student license. A number of open source software projects are designed to do distance measurements and these libraries will be explored further along in the design process.

Table 4.3.1: Stereo Vision Pros and Cons

Pros	Cons
Distancing is Possible within accuracy requirements	Accuracy depends heavily on camera resolution and Field of View
Can determine cloud footprint	
Relatively inexpensive	

4.3.2 Monocular Vision

Monocular vision in this application is the use of one camera to determine the distance of an object in relation to another. Monocular vision for absolute distancing is a method plagued by high error and therefore its application is mainly non-critical distance estimation. Monocular distancing methods compare relative sizes of known objects to determine a ratio of actual size to imaged size that can be extrapolated to distances.



To attempt to distance clouds, the camera would be placed in the middle of the measurement cylinder oriented with the lens vertical. Images would be taken throughout the wind data collection period. After the test, the images would be post processed. To begin post processing the images, the projected size of the delivery system and clouds on the image would be measured. The projected size of the delivery system would be compared to the known actual size to determine the actual to imaged ratio. If the cloud size is known, its actual to imaged size ratio can be computed and distance can be extrapolated. The big downfall of this approach is that cloud size must be estimated to determine an actual to imaged size ratio. To our knowledge there is not a way to estimate the size of a cloud without already knowing its height. This eliminates the monocular vision as a solution to determining cloud base altitude. The method would be able to define the projection of the measurement cylinder on the clouds above by comparing the known location of the delivery system to the location in the images.

Table 4.3.2: Monocular Vision Pros and Cons

Pros	Cons
Can determine cloud footprint	Cannot determine cloud height
Relatively inexpensive	Accuracy depends on quality of camera

4.3.3 Ceilometer & Camera

A ceilometer is a device used to determine the height of clouds by recording the time it takes for a beam of radiation, usually a laser, to travel from the sensor, bounce off of the cloud and be captured by the sensor. These sensors give unprecedented resolution. The Vaisala CL31 can measure cloud base with a resolution of 5 meters at heights up to 7.6 km. Unfortunately, these systems are very expensive and outside of the budget of this project. The lowest price quote found was on the Model 8339 Ceilometer from AllWeather Inc., which was upwards of $19,000.

There are many do it yourself ceilometer tutorials available online, but they all rely on shooting visible light, such as a powerful laser, at the cloud base during the night and measuring the angle from an observation point on the ground to the laser. Knowing the distance between the observation point and laser source gives enough information to compute the height with right triangle geometry. Testing at night is an issue, since cloud the customer desires footprint images and these images would not come out at night. The legality of this method is also in question, as the FAA has issued sanctions to people who have shot lasers at commercial airliners. Between the lack of feasibility and legality issues, DIY ceilometers were not considered.

Table 4.3.3: Ceilometer and Camera Pros and Cons

Pros	Cons
Distancing is Possible	Price exceeds budget
Can determine cloud footprint	Legality issues

5.0 Trade Study Process and Results

A trade study was conducted for each system in order to appropriately analyze its feasibility and success potential. For every system, facets were broken down into five objective categories, each holding considerable weight in the success of the project. A scale from 1 to 5 was used to quantify each potential solution per facet, where 1 is the least satisfactory and 5 is the most desired. Each category was then weighted to account for its relative importance to the project's success, where a higher importance is represented by a higher weight. This was done for all three systems in the project, with each possible solution's scores being averaged. This trade study was used to aid in the selection of the baseline design for the project.

Table 5.1 shows the delivery system's chosen facets along with definitions of the ranking for each facet. Table 5.2 gives the weighting of each facet along with further explanation of the facet's ranking system.

Table 5.1: Delivery System Trade Study Score Breakdown

Ranking	Cost (Percentage of Budget)	Speed of Data Collection	Interference on Data Collection	Safety	Robustness
1	> 40%	> 20 min	Data cannot be collected due to interference	Chance of a fatality upon crash	Un-repairable upon crash
2	30-40%	15-20 min	Interference inseparable from data	Chance of serious injury upon crash	Able to fly again upon crash, major repairs required
3	20-30%	10-15 min	Known interference, separable from data	Low possibility of injury upon crash	Able to fly again upon crash, minor repairs required
4	10-20%	7-10 min	Measurement interference not noticeable	No injury upon crash	Cosmetic damage only upon crash
5	0-10%	5-7 min	No interference	No possibility of crash	Crash has no impact on system

Table 5.2: Delivery System Facet Explanation

Facet	Reasoning
Cost (25%)	The total cost of the delivery system, including all hardware, software, and accessories needed, is taken into account in this facet. This facet was designated a weight of 25% because the overall design relies heavily on what delivery system is chosen. This will probably take up a large portion of the total budget, thus why it has such a large weight.
Speed of Data Collection (25%)	The ability of the delivery system to reach every point in the measurement cylinder during the 10-minute experiment is a huge design driver for this project. The delivery system must be able to get through the whole flight space in an efficient amount of time, thus why the speed of data collection is weighted 25%.
Data Interference (25%)	The success of the project depends heavily on whether the measured data is accurate or not. The delivery system could present major issues if it has bad interference characteristics which could affect the measurement system, thus giving this facet a 25% weight. For this analysis, it is assumed that the measurement system is positioned such that it undergoes the least amount of interference from the delivery system for this analysis.
Safety (10%)	Any object moving through the air is going to have some measure of risk correlated with it. This facet is weighted 10% because each system considered holds its own risk and safety precautions to mitigate that risk.
Robustness (15%)	It is important to consider how well the delivery system will respond to a crash or other malfunction. The integrity of this system is a key part of the overall design. If a system were to crash during a test, it would need to be strong enough to withstand the shock, as well as protect its on board measurement system. A crash during testing is possible, so this facet has a 15% weight, implying it is a large design driver.

Table 5.3 lists the results of the delivery system trade study. Each delivery system facet is shown, along with the weight and score for each delivery system concept considered. The chosen weights are expanded upon in the paragraphs following the table.

Table 5.3: Delivery System Trade Study Results

Delivery System	Weight (%)	Blimp	Helicopter UAV	Balloon	Fixed Wing UAV
Cost	25	1	2	1	3
Speed of Data Collection	25	2	3	5	4
Robustness/Reliability	15	3	2	2	3
Interference	25	2	2	3	4
Safety	10	4	2	2	3
Total Score	100	2.1	2.25	2.75	3.5

A trade study was conducted exploring a remotely controlled blimp as the potential delivery system. Following the scoring breakdown for the delivery system trade study, the major concerns for the concept, such as cost, speed of data collection, and interference on data collection, were examined in depth. The rough cost of the blimp would immediately account for 50 to 70% of the budget in order to purchase a large enough blimp for a practical payload of 5kilograms. This cost would increase substantially as this does not include the helium for each flight. The high initial cost along with unknown variable expenses led to the score of a 1 in the cost section of the trade study. With a maximum flight speed of about 8 meters per second, a blimp could traverse the desired airspace in roughly 15 minutes with an optimal flight plan. This corresponds to the score of 2 for speed of data collection. However, the quality of data and the speed of the collection are both limited by the pilot's ability to remotely control the blimp through the airspace. This would be extremely variable depending on the pilot's skill and weather conditions leading to a lower score in the interference category of the trade study. A blimp is unlikely to cause major damage to anything other than itself leading to a safety score of a 4 in the trade study. The robustness of the blimp would vary depending on materials used, but a larger blimp would be susceptible to poor control in high winds as well as helium leaking over time. Repairs will have to be made if for some reason the blimp were to crash. These factors lead to a robustness and reliability score of 3. Ultimately, the low score achieved in the delivery system trade study can be attributed to the following factors. The high initial cost of a blimp plus the unknown per flight helium cost potentially would exceed the budget. The large shape of the blimp would interfere with the data quality too much to obtain reasonable wind measurements and present control problems in higher wind speed conditions. Despite being relatively robust and safe, the limited flight speed hinders the quality of the data and speed of the data collection.

The rankings assigned to helicopter UAV's are quantified in Table 5.1, and are further discussed here. The ranking for cost was a two, or between 30 and 40% of the $5,000 budget. This $1,500-$2,000 range was determined by research on helicopter UAV's. Many different models were found and those which had a payload capability were averaged to a value of approximately $1,700. Many options fell outside of the $1,500-$2,000 range, but only options within the budget were considered. Speed of data collection was determined by the vehicle's flight velocity and battery capabilities. The vehicles which could not fly at the maximum velocity listed in the specification sheet for the duration required to collect data at all points were not considered. The flight velocity of those that could fly for long enough was used to determine the flight time required to fly through 240 points spaced at 30 meters, the ideal situation for the flight path through the volume of potential data points. The highest flight velocity of a vehicle considered was 20 meters per second, giving the best case scenario to collect all data points of 6 minutes. While this is a low time, adding a payload to the vehicle will slow it down and the actual flight path will be longer than the ideal case considered here. Most vehicles have a top speed listed of 15 meters per second, and this is still an ideal case so for the trade study an average flight speed of 10 meters per second was used. At this speed it would take 12 minutes to fly the minimum distance to collect all data points, giving it a three for the trade study. Interference on data collection is the largest disadvantage to using a helicopter as there is a large disturbance on the surrounding air from the rotors. Some characterization would be able to be given to the disturbance but not enough to accurately take out the disturbance from the actual wind. For this reason, it was given a two on the trade study. Safety was also given a two because the vehicles considered weigh 1-14 kilograms and if during a crash were to hit someone, there would likely be injury due to both the weight of the vehicle and spinning rotors. Robustness of helicopter UAV's is low, as there would be damage to the vehicle even in a minor crash. Most crashes would be repairable with new components, however the repairs would be major, and robustness was given a rating of two.

The feasibility of the tethered balloon delivery system is dependent primarily on the number of balloon subsystems used, where each subsystem consists of one balloon, tether, and 7 measurement system packages. In order to space data points no more than 30 meters apart and meet the data collection requirement, 46 individual balloon subsystems must be used. By using the data collection requirement of 30 meters maximum distance between points, trade study scores were given to the tethered balloon system.

Based on the current average price of bulk helium, and neglecting the cost of measurements subsystems, the complete balloon delivery systems has an estimated cost between $12000 and $13000, thus scoring a 1 on the cost category of the trade study. With a measurement system sensor package capturing data at every required point within the volume, the balloon system would be able to achieve the best possible speed of data collection; a 5 in this category assumes no negative effects on the balloons due to wind, which would be detrimental to the reliability of measurements. Because wind can affect the ability of the system to collect measurements which meet the 30 meter requirement, the balloon systems scores a 2 in the reliability/robustness category. Another reason for the 2 in this section is because the weather balloons would need to be filled to near their volumetric capacity in order to carry a suitable amount of weight (4-6kilograms) without moving to larger and more expensive balloons; as the balloons approach their volumetric capacity they become increasingly fragile. The effects of 46 1-2 meter diameter tethered balloons being blown by the wind at 200 meters could also contribute negatively to the interference of the wind sensors. Ideally, the balloons are assumed stationary so that all wind measurements made along the balloon's tether are inertial wind measurements. The system scores a 3 in the interface section because the movement of the balloons due to wind will cause interference with the sensor packages along its tether. In regards to safety, the balloon system does carry a dangerous amount of weight at high altitudes. This in combination with its low robustness rating leads to a score of 2 in the safety category.

In order to conduct a trade study on fixed wing UAV's, multiple fixed wing variants were researched in order to give a good picture on the practicality of using a fixed wing UAV. The overall cost of the UAV was found using the average cost of an airframe, electronics, and autopilot. The fixed wing UAV was estimated to cost between $1000 and $1500 dollars after the purchase of an autopilot, motor, speed controller, batteries, airframe, and control servos, getting a three in the cost category. The fixed wing UAV got a four on speed of data collection after doing an estimation of the flight time required to obtain a complete data set in the measurement airspace. This calculation was done using an estimated airspeed of 20 meters per second, an average for most fixed wing UAV's. The flight distance was estimated to be 10,080 m, a 40% increase over the minimum distance between measurement locations, to include turning and overlap due to flight limitations of the fixed wing UAV. The flight time required to cover the measurement cylinder was found to be 8.4 minutes. The fixed wing UAV was given a three in robustness because a crash on takeoff and landing would necessitate repairs, however most on board systems could be reused even if parts of the airframe needed to be repaired. A crash due to loss of control at maximum altitude was not considered because this would destroy all on board systems regardless of the delivery system. The fixed wing UAV's interference on the measured wind speed was assessed to be minimal and not measurable because the flow in front of the fixed wing UAV is not affected, therefore the fixed wing UAV earned a four. The fixed wing UAV has a low chance of injuring ground personnel in the event of a crash. The only possible way for ground personnel to be injured would be in the event of the UAV striking the individual and making direct contact with the propeller. The possibility of this occurrence happening was deemed low and therefore the fixed wing UAV earned a three in safety.

Table 5.4 shows the measurement system's chosen facets along with definitions of the ranking for each facet. Table 5.5 gives the weighting of each facet along with further explanation of the facet's ranking system.

Table 5.4: Measurement System Trade Study Score Breakdown

Ranking	Cost (Percentage of Budget)	Quality of Measurement	Reliability/Robustness	Pow er	Size	Weight
1	> 40%	Accuracy,	Crash results in	>5	At least one	> 3

		precision and variance requirements defined by Req.1.2 are not met	catastrophic damage	Watts	delivery system eliminated due to size constraints	kilograms
2	35-40%	Either accuracy, precision or variance requirements defined by Req 1.2 are met	Crash results in severe damage with possibility of repair	2.5-5 Watts	Possibility of delivery system elimination due to size constraints	2.25- 3 kilograms
3	30-35%	Two of the three requirements defined by Req. 1.2 are met.	Crash results is repairable damage	1-2.5 Watts	Considerable changes to delivery system necessary	1.5 - 2.25 kilograms
4	20-30%	Accuracy, precision and variance requirements defined by Req.1.2 are all met	Crash results solely in cosmetic damage	0.5-1 Watts	Alterations of delivery system necessary for mounting measurement system	0.75 - 1.5 kilograms
5	0-20%	Accuracy, precision and variance requirements defined by Req.1.2 are met or exceeded	Crash does not affect measurement capabilities	<0.5 Watts	Fits on all delivery systems	<= 0.75 kilograms

Table 5.5: Measurement System Facet Explanation

Facet	Reasoning
Cost (30%)	This facet takes into account the cost of the total sensor system, including all necessary hardware that is required by the actual sensor, e.g. pitot tube and tubing for a pressure transducer. This facet carries a weight of 30% as this is one of the major systems of the project, and is likely to take a large amount of budget to achieve the desired accuracy and resolutions.
Quality of Measurement (30%)	This facet takes into account three aspects: sensor accuracy, resolution, and variance defined by Req. 1.2. The weighting of 30% is derived from the customer requirements in order to verify the Northrop Grumman model.
Reliability/Robustness (10%)	Reliability and Robustness describes the ability of the sensor to perform after testing abuse. This was given a weight of 10% because a crash is possible during testing and crash may prove detrimental to the ongoing functionality of the measurement system.
Power (10%)	This facet describes the maximum power consumption of the sensing system. This was given a weight of 10%. Power consumption can impact which delivery systems are capable of carrying certain measurement systems.
Size (5%)	The size of the sensing systems impacts the type of delivery system that is viable, but it is not predicted to be a major design driver, so it was given a weight 5%.
Weight (15%)	This facet describes the physical weight of the sensing system. It was given a weight of 15% because extremely heavy measurement systems may not be usable with certain delivery systems.

Table 5.6 lists the results of the measurement system trade study. Each measurement system facet is shown, along with the weight and score for each measurement system concept considered. The chosen weights are expanded upon in the paragraphs following the table.

Table 5.6: Measurement System Trade Study

Measurement System	Weight (%)	Cup Anemometer	Propeller	Hotwire	2-axis Sonic	3-axis Sonic	Pitot Tube
Cost	30	3	1	1	1	1	5
Quality of Measurement	30	3	4	4	5	5	4
Reliability/Robustness	10	3	4	2	3	1	3
Power	10	3	3	1	3	4	5
Size	5	1	1	4	3	3	4
Weight	15	1	1	3	2	3	5
Total	100	2.6	2.4	2.45	2.8	2.9	4.45

The scoring for the anemometers was done by examining many easily purchased systems online. The price for the cup, propeller, and hot wire anemometers are $1600, $2100, and $2600 respectively. These prices were for systems that met the quality of wind speed measurement. The cup anemometer met all the wind speed measurement qualifications but the error was rather large for the direction. Therefore it was given a 3 in quality of measurement. The maximum power of each system was considered by the standard given in the respective data sheet. The cup anemometer needed 1.2 Watts of power and received a score of 3. Likewise the propeller anemometer received a score of 3 because it needs 2.4 Watts. The hot wire anemometer must dissipate a lot of power to keep the wire at a constant temperature, so it received a 1 for using over 30 Watts of power. The cup anemometer and propeller anemometer are very large systems and take up about 1858 square centimeters. Therefore they both receive a one for size. The hot wire anemometer however is smaller with three 7.5 centimeter probes and 3 electronic boxes which are 6 centimeters by 8 centimeters by 12 centimeters, so it was given a four for this reason. The cup, propeller, and hot wire anemometer systems weight 4.5, 3.18, and 1.36 kilograms respectively and were scored a 1, 1, and 3.

2-axis and 3-axis sonic anemometers were scored very closely after extensive research on each. This stems from the fact they are fundamentally very similar. Both styles of anemometer need the same voltage range to power them, take the same quality of data, and tend to be very close in size and weight. The one obvious difference between the two is the robustness. The 3-axis design involves six transducers supported by a thin metal structure. This structure, upon a crash, would no doubt be damaged. Since the transducers need to be perfectly aligned, this would then qualify the instrument as useless, so it received a 1. The 2-axis system offers options with a more robust design. Instead of the thin arms holding the transducers, each one is mounted directly to a solid, bodied design with a slit in it allowing air to pass through across the transducers. While this design is much better than the 3-axis sonic anemometer, it still is quite fragile. Upon crash, there is a chance it may encounter unfixable damage, but that chance is much less than the 3-axis system so it received a 3. Both of these systems are quite expensive, with the 3-axis having cost upwards of $2,700 and the 2-axis anywhere between $800 and $1500, depending on quality of measurement. In order to measure in three dimensions, two 2-axis anemometers would be required, so they both got 1's. Both systems can measure wind velocity and direction well within the parameters of the project, so each received a 5. In order to use these systems, they would need to be mounted and carried around the airspace. Each can weigh up to 3 kilograms and be as tall as 40 centimeters, spanning a 25 centimeter radius. It may be hard to attach either of these to a delivery system due to their sheer size. The 2-axis anemometer got a 3 and 2 for size and weight, while the 3-axis sonic anemometer got a 3 and 3. The power required for each anemometer is around 0.6 Watts. Therefore the 3-axis system got a 4, and since it would require two 2-axis systems, it got a 3. While the measurement benefits of sonic anemometers may be great, it is unclear whether these are even feasible options due to the budget and payload potential of delivery systems.

In order to score the trade study for the pitot tube system, various off the shelf pitot tubes systems and pressure transducers were researched and a baseline product was chosen in order to complete the trade study. It was also assumed that five individual pitot tube systems would be required to build a five hole pitot tube. A five was awarded in the cost category because the baseline cost of a single pitot tube and transducer was $55. For a five-hole pitot system, the total price would be $275, well below the $1000 threshold for a five. Quality of measurement was given a four because the baseline system exceeded all requirements except for accuracy, which met the required 1 meter per second but did not exceed it. A three was assigned for robustness because in the event of a crash on take-off or landing, even if a pitot tube had to be replaced, the rest of the measurement system could still be used. The baseline transducer requires 15 milliwatts of power to operate fully. All transducers can be powered by just 75 milliwatts of power, so it was given a five. Size was given a four because the transducer is small, around 5 millimeters by 3 millimeters, but the tubing and pitot tube require more room. The system weight was scored a five because one pitot tube system weighs 38 grams, so a total of 190 grams for all five, which is still a very low weight.

Table 5.7 shows the cloud observation system's chosen facets along with definitions of the ranking for each facet. Table 5.8 gives the weighting of each facet along with further explanation of the facet's ranking system.

Table 5.7: Cloud Observation System Trade Study Score Breakdown

Ranking	Cost (Percentage of Budget)	Cloud Base Altitude Measurement Error	Footprint Image Quality
1	> 40%	>40%	Cloud footprint image is unrecognizable and projections of 100-meter radius circle above the measurement cylinder onto the clouds are undefined
2	30-40%	30-40%	Cloud footprint image is recognizable however projections of the 100-meter radius circle above the measurement cylinder onto the clouds are undefined
3	20-30%	20-30%	Cloud footprint image is recognizable and projections of the 100-meter radius circle above the measurement cylinder onto the clouds have a radial distance error greater than 50%
4	10-20%	10-20%	Cloud footprint image is recognizable and projections of the 100-meter radius circle above the measurement cylinder onto the clouds have a radial distance error between 10% and 50%
5	0-10%	<10%	Cloud footprint image is recognizable and projections of the 100-meter radius circle above the measurement cylinder onto the clouds have a radial distance error less than 10%

Table 5.8: Cloud Observation System Trade Study Score Breakdown

Facet	Reasoning
Cost (30%)	This facet takes into account the cost of the entire cloud observation system including all necessary hardware such as cameras, microcontrollers etc. This facet carries a weight of thirty percent to emphasize the importance of remaining within the projects budget.
Cloud Base Altitude Measurement Error (40%)	Cloud base altitude measurement is a very important requirement of Northrop Grumman, and therefore the error of this measurement was weighted very highly. REQ 2.2.2 defines that the cloud base altitude measurement error must be less than 10% for clouds at a height of 2km. This requirement was used to determine the ranking system for the facet.
Footprint Image Quality (30%)	Discussions with the customer show that the cloud footprint image quality is an important facet, however it is not as important as the altitude measurements. REQ 2.1.1.2 defines that there shall be less than 10% error in radial distance in constraining the 100-meter radius circle above the measurement cylinder on the footprint image. This requirement was used to determine the ranking system for the facet.

Table 5.9 lists the results of the cloud observation system trade study. Each cloud observation system facet is shown, along with the weight and score for each cloud observation system concept considered. The chosen weights are expanded upon in the paragraphs following the table.

Table 5.9: Cloud Observation System Trade Study Results

Cloud Observation System	Weight (%)	StereoVision Camera System	Monocular Vision Camera	Ceilometer and Monocular Vision Camera
Cost	30%	4	5	1
Cloud Base Altitude Measurement Error	40%	4	1	5
Footprint Image Quality	30	5	5	5
Total	100%	4.3	3.4	3.8

The stereo vision camera system scored a 4 on cost because it will cost about $500 or 10% of the budget. The system would use two cameras in the range of $150, a less than $70 microcontroller to command the imaging, an SD card and power source. The stereovision system scored a 4 for height measurement error, as the error computations for an affordable camera system result in about a 10% error for a 2km cloud base altitude. As the delivery system will be operating very close to the bounds of the virtual cylinder, any affordable camera system will be able define the cylinder with less than 20% error therefore all three systems scored a 5.

As the monocular vision camera system will only need one less camera than stereovision, it will cost less than 10% of the budget and scored a 5. As the system will not be able to compute a cloud base with any confidence or certainty, the monocular vision system scored a 1 for height measurement error.

The Ceilometer alone is outside of the budget for this class therefore it scored a 1 on cost. With resolution of 5 meters at any cloud base altitude below 7.6 km, the ceilometer clearly scores a 5 on height measurement error.

6.0 Selection of Baseline Design

The trade studies conducted in section 5.0 were utilized to determine a winner for the delivery, measurement, and cloud observation systems based on system requirements and design facets. The delivery system trade study showed that a fixed wing UAV is the most viable option because of its high speed of data collection, low interference on data taken and reasonable cost. The results from the study show that some delivery systems could be eliminated without further analysis. The balloon, blimp, and helicopter UAV systems were removed from consideration because of their poor scores in critical areas such as cost, speed of data collection, and interference on data. The helicopter UAV was removed from further analysis because of the large interference on data collection while the blimp and balloon would require multiple systems to meet spatial and temporal measurement requirements. This would then exceed the budget allotted for BLISS when considering that multiple measurement systems would be needed as well.

The measurement trade study showed that the pitot tube scored the highest by a considerable margin and scored well in the two highest weighted facets, cost and quality of data. Therefore the pitot tube system was the selected measurement system. The third highest scoring option for the measurement system was the 2-axis sonic system. This system would be a viable option on any of the delivery system and delivers high quality data, however it had a prohibitively high cost and therefore was dropped from contention. Cup and propeller anemometer systems did not score as highly because they need to be stationary for accurate data to be taken and are heavy. Hot wire anemometers would need a considerable amount of power and costs over 50% of the budget so these were not a viable solution either.

A stereovision camera system was determined to be the best cloud observation system as it is priced within the project's budget, is able to determine the cloud base altitude, and output a cloud footprint image to the requirement defined by REQ 2.1.1.2 and 2.2.2. If cost were not a driving factor, the use of a monocular vision camera to define the cloud footprint with a ceilometer to determine cloud base height would be the clear winner of the trade study as it provides unprecedented accuracy in height and cloud footprint. The monocular vision camera alone will not accomplish the requirement of measuring cloud height within 10% and is the clear loser of the trade study.

The fixed wing UAV delivery system and pitot tube measurement system will integrate well together. Pitot tubes are consistently used on aircraft to determine airspeed. Pitot tubes and transducers are small in size and do not weigh much so the payload capacity of the fixed wing UAV will be sufficient. The fixed wing UAV and pitot tube combination will create a fast moving system that is capable of hitting the required spatial resolution within the cylinder while delivering the required data at the necessary accuracies.

7.0 References

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