University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

Functional **L**iDAR-Based **A**ssessment of **S**tructural **H**ealth (**FLASH**)
Conceptual Design Document (CDD)

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1. Information

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2. Project Description

2.1. Project Purpose & Background

There is a growing and persistent need for monitoring and inspection of critical infrastructure around the country and the world. In the United States alone, there are more than 600,000 bridges, one third of which are over fifty years old. These critical infrastructures require surveillance and maintenance in order to ensure they are structurally intact and not prone to failure. Traditional infrastructure inspection process, with an estimated industry value of USD 1.78 billion in 2019 and is projected to reach USD 5.38 billion by 2027 [1]. In the US, physical infrastructure is overseen by state governments, and as such many long-term partnerships between various states' departments of transportation and infrastructure construction corporations have been formed. Ongoing maintenance of the structures and handled both by the original contractors and dedicated infrastructure monitoring companies. However, traditional inspection methods can be slow, costly and infrequent. Moreover, in remote areas, where there is a lack of GPS-location systems, or rough terrains in which the strenuous accessibility has led to infrequent examinations, there is a need for an autonomous mapping system for remote access and efficient methods of evaluation.

ASTRA, LLC. is a local producer of ground-based and space-based instrumentation. Located in Louisville, CO, they employ several CU Boulder Aerospace Engineering graduates. Their mission statement reads, "We are scientists, researchers, engineers, and business people dedicated to solving global problems that affect how human-kind lives, works, and plays on our planet and in space through applied science backed by empirical knowledge. We turn science into data, and data into knowledge for our customers." [2] ASTRA is emerging as a leader in LiDAR-based applications, and their most recent interest is to utilize LiDAR to detect structural faults in varying forms of infrastructure. They have tasked this CU Senior Projects team with designing a system which can fulfill this mission requirement. With such an innovative system, ASTRA could solve many of the traditional infrastructure inspection problems presented in the preceding paragraph.

2.2. Mission Objectives

FLASH, or the Functional LiDAR-Based Assessment of Structural Health, is a vehicle-based system that shall be designed, built and deployed to continuously gather raw, 3D point cloud data of specified transportation infrastructure. The objectives of this mission are to provide accurate, 3D point cloud data to ASTRA, convert the registered point cloud data into usable 3D maps/models, and to deliver those maps/models to ASTRA for infrastructure fault analysis. This will be done by utilizing a specified "mission vehicle" to which a mounting structure will be attached. This mounting structure will contain the LiDAR system, as well as auxiliary sensors (GPS receiver, IMU, etc.), a power supply, and a hard drive for data storage. An objective of this mission is to minimize driver interaction with the system, making the data collection system as autonomous as possible. The team will also explore the concept of Simultaneous Localization and Mapping (SLAM) algorithm implementation, with the objective of making the 3D point cloud data collection process compatible with SLAM.

2.2.1. Critical Project Elements

From the project objectives, four critical project elements (CPEs) were established. The CPEs were then separated into three distinct levels of success, with each increasing level requiring more functionality out of the CPE. These designations were included in the Project Definition Document (PDD) and are reflected in the formation of the system's functional and design requirements below (see Section 3). The identified critical project elements are as follows:

2.2.1.1. Sensor Package

The success of FLASH depends upon the selection of a capable light detection and ranging (LiDAR) system. The use of LiDAR is a customer requirement, but the particular LiDAR system was not specified by ASTRA. The sensor package must be able to scan infrastructure while in motion and collect data to a 5cm accuracy from a 50m range to allow for 3D mapping and model generation. Acquiring a reliable LiDAR system will likely be the highest project expenditure. Thus, a rigorous trade study was conducted for selecting a reasonably priced system while adhering to functional requirements.

2.2.1.2 Data Processing Software

In order to transform the raw LiDAR data into a useful form, a robust software solution must be implemented, likely as part of an embedded system. This will require point cloud processing/registration so that detailed 3D maps/models of infrastructure can be created. Localization of the mission vehicle will be imperative to mission success and determining point cloud data accuracy. In relation, the software shall be compatible with a simultaneous localization and mapping (SLAM) algorithm to work in conjunction with the selected LiDAR system. Software implementation is a critical component of the project because it will likely require the most time and effort. Insightful damage assessment and infrastructure analysis cannot occur without operational software architecture.

2.2.1.3 Vehicle Platform

The LiDAR system shall be mounted onto a motor vehicle to allow for autonomous “drive-by” surveying of infrastructure. The mounting fixture must secure all hardware to the vehicle and the structure must incorporate housing to protect hardware from adverse conditions (rain, wind, snow, etc.). Additionally, since FLASH will often operate around other vehicles, the fixture must ensure that the system does not pose a safety concern. A poorly designed vehicle mount may obstruct system performance; hence, this aspect of the project is critical and it presents a challenge in material selection and structural design.

2.2.1.4. Data Transmission

The system shall be capable of transmitting point cloud data and supplementary information (date/time, position, unit number) to ASTRA headquarters. This wireless transmission shall be possible up to a 70 meter range from the ground station to ensure effective and timely data processing. This aspect of the project poses a challenge because the size of the point cloud data may be substantial and the LiDAR system may not be compatible with transmission hardware straight "out-of-the-box".

2.3 Concept of Operations

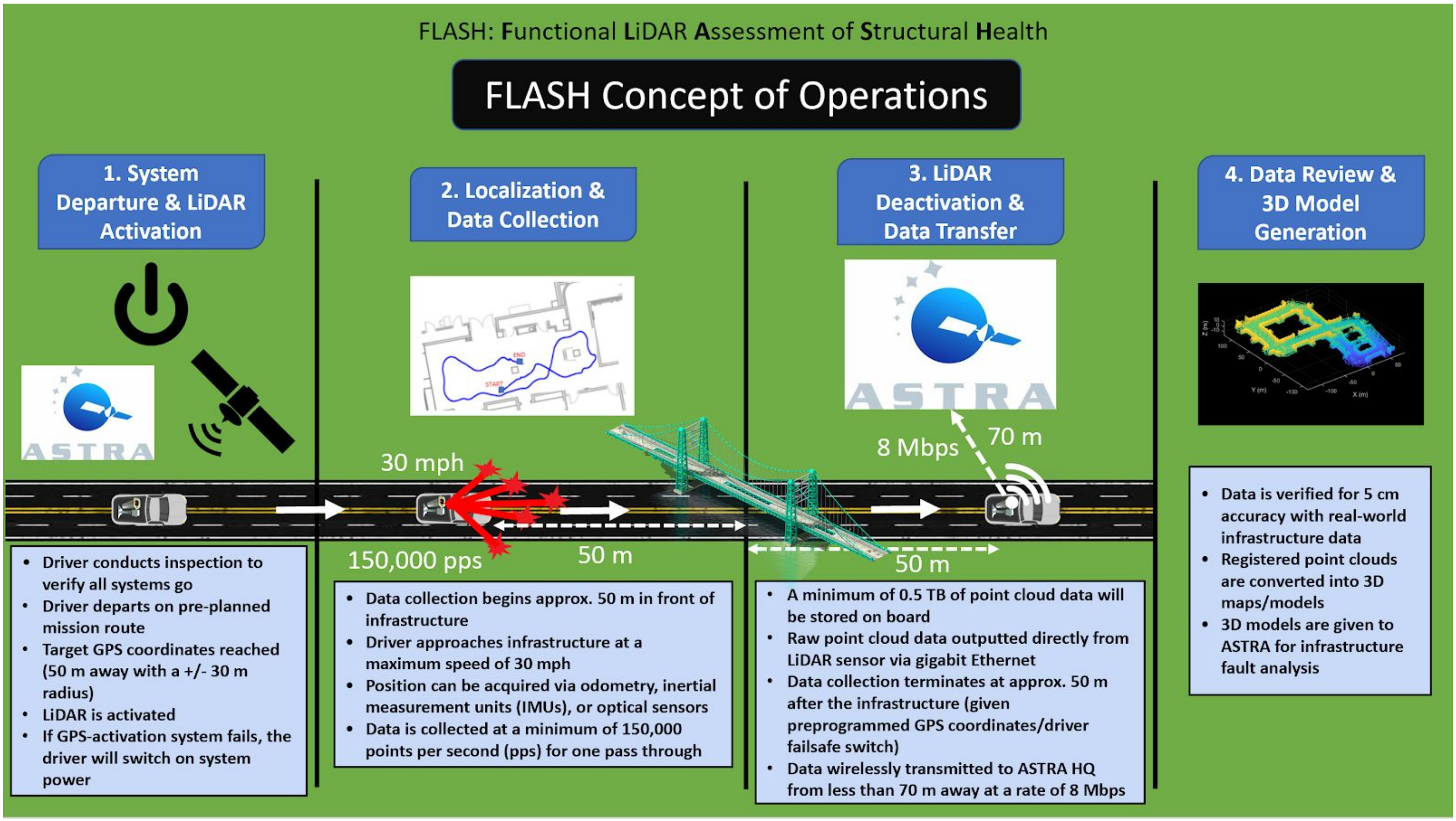

Figure 1: *FLASH Mission Concept of Operations*

The Concept of Operations for FLASH is outlined in Figure 1. The notional, Level 3 Success FLASH mission will begin at ASTRA headquarters with a driver inspection of the vehicle-mounted system to ensure all necessary interfaces are accounted for and to ensure structural integrity. The driver will depart on their pre-planned mission route. Once the vehicle reaches the mission preloaded GPS target coordinates (notionally 50 m away from the start of the target infrastructure, with a +/- 30 m radius), the LiDAR system will be activated and begin data collection. If the automatic activation sequence fails (as indicated by an LED), the driver will have a physical failsafe power activation switch. This switch will begin data collection. Upon activation, the LiDAR system, Internal Measurement Unit, and GPS tracker will begin collecting data to be stored onboard for later transmission and analysis. During the data collection period, the driver will maintain a speed of no more than 30 mph (as the system is further defined, this speed limit may increase). Localization data will be gathered via an IMU and/or GPS data (assuming GPS services are still available). The LiDAR system will collect data at a minimum of 150,000 points per second (pps). This raw point cloud data will be transferred directly to the system hard drive via gigabit Ethernet.

This CONOPs plans for a single pass-through of the infrastructure (this may be increased in the future to account for the amount of needed data). Once the vehicle is 50 m away from the infrastructure (using driver "switch" input), the LiDAR system will cease data collection and will deactivate. The localization, activation, and data collection processes will be repeated for each infrastructure inspected. The system will have a minimum 0.5 TB data collection capacity for raw point cloud data. Each form of data collected (LiDAR 3D point cloud data, IMU data, GPS coordinates) will be combined into one output data package for easy results extraction. Upon return to ASTRA headquarters, the collected data will be wirelessly transmitted to ASTRA. This process will occur no more than 70 m away from the receiver and at a rate of 8 Mbps. The raw point cloud will be registered and then compared to known infrastructure measurements for accuracy verification. This registered point cloud data will then be converted into 3D maps/models. These 3D maps/models will be delivered to ASTRA for their infrastructure fault analysis.

2.4 Functional Block Diagram

The Functional Block Diagram shows the major components, interfaces, and processes of the FLASH system, seen in Figure 2 below:

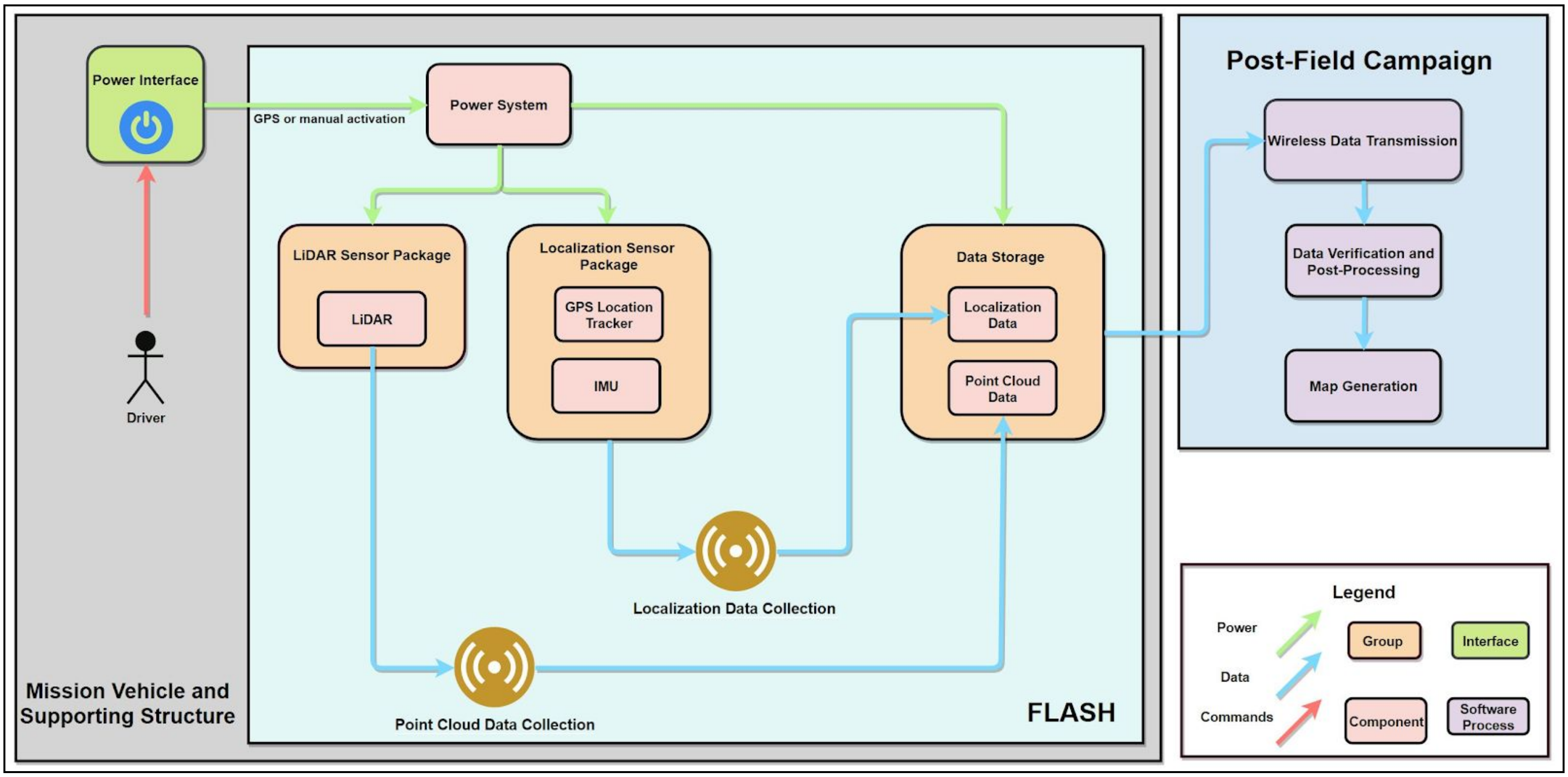

Figure 2: *FLASH High-Level System Functional Block Diagram*

Recognition of the target infrastructure GPS coordinates (or the physical failsafe driver switch) shall power on the system when approaching critical infrastructure to begin gathering data. The FLASH mission is contained inside the supporting structure on top of the vehicle. Inside, the power system supplies power to all sensors and onboard data storage devices. When the power is turned on, the *LiDAR* sensor, *Internal Measurement Unit* (IMU), and the *GPS Location Tracker* all gather data simultaneously. The GPS and IMU data are stored in *Localization Data*, while the *LiDAR Data* is stored separately. Once the data collection is complete, the mission vehicle makes its way to ASTRA headquarters, whereupon it shall wirelessly transmit the Localization and LiDAR data to ASTRA. Here, the data shall be verified to be accurate compared to ground-truth data gathered at the critical infrastructure. Furthermore, the data shall undergo post-processing, whereupon the 3D point cloud data is ready to be used to generate a model or map of the critical infrastructure. After all these steps have successfully taken place, FLASH will have executed its full mission successfully.

2.5 Summary of Functional Requirements

FR 1	The system shall utilize a 3D LiDAR sensor to survey infrastructure of interest.
FR 2	The LiDAR sensor shall collect and output usable 3D point cloud data.
FR 3	The system shall be capable of localizing itself even when GNSS services are not readily available.
FR 4	The on-board processing unit shall be capable of data storage, handling, and interfacing between components.
FR 5	The system shall be capable of mounting onto a vehicle and operating while the vehicle is in motion.
FR 6	The system shall incorporate a power source that is capable of continuously supplying power to all applicable components.
FR 7	The point cloud and localization data shall be consolidated and post-processed into an interactive digital 3D map/model to quickly identify structural faults.
FR 8	The on-board communications unit shall be capable of wirelessly transferring point cloud and localization data directly to a designated headquarters.
FR 9	The system shall be capable of initiating and terminating data collection with minimal driver interaction.
FR 10	The system shall conform to all relevant safety regulations and guidelines.

Table 1: *FLASH System Functional Requirements*

3. Design Requirements

FR 1 The system shall utilize a 3D LiDAR sensor to survey infrastructure of interest.
Motivation: Current technologies for infrastructure fault detection are expensive and inefficient in terms of time and resources. Creating a 3D point cloud gives structural engineers an effective alternative to detecting faults within infrastructure of interest. The proposed non-stationary terrestrial LiDAR system by this project would serve as a more effective and less costly solution to traditional methods used today for infrastructure analysis.

DR 1.1 The system shall have a measurement range of no less than 50 meters.
*Motivation:*In order to meet customer requirements as mentioned in **DR 1.2**, the LiDAR sensor component must be capable of detecting infrastructure at a range of 50m from the system.

Verification: This will be determined by the range of the chosen LiDAR sensor and any software or hardware updates to ensure the sensor will conform to this distance requirement. This will also be tested by comparing the data received to known ground truth measurements.

DR 1.2 The system shall have a horizontal field of view no less than 270 degrees.
Motivation: In order to encompass the entire bridge while passing underneath, the field of view must be large and accurate across all sections of the bridge.

Verification: Product specifications will be verified by testing range with known targets at 270 degrees apart. This will be accomplished by taking stationary data sets as well as data in motion in order to assure the product specifications are met with a high enough accuracy.

FR 2 The LiDAR sensor shall collect and output usable 3D point cloud data (x,y,z coordinates).

Motivation: This requirement is very similar in motivation to **FR 1**. The point cloud data from this system will be useful in determining the structural health of a structure and the most efficient way for this to occur is to have the system output usable 3D point cloud data for immediate post-processing by the customer.

DR 2.1 The point cloud data shall have an average measurement error no more than 15 cm.
Motivation: The customer has expressed a desire to detect objects/faults that are 10 cm in size. However, considering the locomotive nature of this project, accuracy will be affected by range and speed. Thus, 15 cm of error in measurements provides a more reasonable upper limit. Detection of faults will be more dependent upon point cloud resolution (see **DR 2.2**). Accuracy has more to do with the *uncertainty* in the measurement.

Verification: A testing range will be set up with "target" objects of known distances. The LiDAR sensor package will be used to collect point cloud data for the target objects. After post-processing, the spatial coordinates of the target objects will be compared against the known distances of each object (in a common coordinate system). An average error will be computed to verify an acceptable accuracy.

DR 2.2 The point cloud resolution shall be no less than 10 cm.
Motivation: In order to identify faults that are 10 cm in size, the spacing between points in the point cloud must be at least 10 cm. As defined in [3], "resolution governs the level of identifiable details within the scanned point clouds.". Hence, extracting useful information from the point clouds is highly dependent on point cloud density and resolution.

Verification: This requirement will be verified by conducting a stationary test of the product specifications to the actual sensor capabilities. The point cloud data will be post-processed for estimation of point cloud spacing. If the test data's resolution matches or exceeds the project requirement then it will be verified.

DR 2.3 The sensor shall output no less than 150,000 data points per second.
Motivation: In order to obtain accurate and usable data of the infrastructure in question the sensor must be able to scan at a high rate of points per second. During a real test at speed the sensor will only have a few seconds to scan the entire structure which is why a higher data rate must be accomplished in order to obtain usable data.

Verification: This requirement will be verified through stationary tests of the sensors abilities compared to the product specifications. Once the team is confident the sensor can perform to this data rate or faster the requirement will be verified.

FR 3 The system shall be capable of localizing itself even when GNSS services are not readily available.
Motivation: In order to collect data for certain infrastructure such as wide bridges or long tunnels, the system must be able to operate as expected without having connection to GNSS services for short intervals of time. This aspect sets the system apart when compared to traditional non-stationary LiDAR collection systems.

DR 3.1 The system shall incorporate an inertial navigation device with bias instability of less than 2°/hr.
Motivation: In order for the system to recognize where a structure is before it saves the 3D point cloud it must have an inertial reference. This can be provided by an inertial navigation device. In a situation where there are multiple structures in close proximity, the sensor must be able to distinguish between them in order to write the data to a correctly labeled file. This requires the error/bias to be small enough to distinguish the structures.

Verification: This requirement will be verified by comparing the inertial navigation device readings to a reputable navigation map and by determining the difference between these two sets of information the error/bias will be determined and verified.

DR 3.2 The system shall incorporate a Global Positioning System (GPS) module with a positional error of less than 5 cm.
Motivation: This requirement is very similar to **DR 3.1** but pertains to GPS instead of an inertial reference. GPS is a satellite-based radio navigation system that can pinpoint the exact location of the signal anywhere on Earth

if the signals can get through from at least three different satellites. This requirement is also necessary for the exact location of the scanned infrastructure.

Verification: This requirement will also be verified in a similar way to requirement **DR 3.1** as the GPS module will be compared to another reputable source and the difference between the two will determine whether the positional error is within the 5 cm tolerance.

DR 3.3 The system shall utilize a GNSS sensor to assign geographic coordinates to collected data.
Motivation: In order to assure that the data from the sensor is being matched to the correct geographic position a GNSS sensor will be used. This sensor uses geographic coordinates to pin the scan to a specific location as differentiation between multiple scans and pinpointing the scans location.

Verification: In order to verify the accuracy of the GNSS sensor the output file of the 3D scan will contain geographic coordinates where the scan took place and will be checked against ground truth for navigation. If the difference in this comparison is within the tolerance, the requirement will be verified.

DR 3.4 The system shall operate during GNSS service outages of no more than 10 seconds.
Motivation: There are generally known areas where GNSS service is unstable and untrustworthy. These areas include big cities and long tunnels. Since our system may scan in these areas the system must be able to function for a short period of time without the GNSS to reference its current location.

Verification: This requirement will be verified by either driving through one of these areas where the GNSS will be untrustworthy and verifying the sensor will still scan the structure and report to the last closest location point. This requirement can also be tested by simply shutting down the GNSS sensor for a certain amount of time and confirming the sensor performs correctly.

FR 4 The on-board processing unit shall be capable of data storage, handling, and interfacing between components.
Motivation: The incorporation of these components into an onboard computer are common and necessary for the correct functionality of a computer system. There needs to be a large capacity for the data storage in order to handle the sizable files that will be produced from each scan. There will need to be a specialized handling system for converting the data received into usable 3D point cloud data. Finally, the interfacing between components is necessary for completing an accurate scan of a structure.

DR 4.1 The system shall accommodate a cumulative data size of no less than 0.5 TB.
Motivation: A simple LiDAR scan can produce a file well in excess of 1 MB. This system will only be active for short multiple second long periods but the size of the data will still add up over time. The system also needs to be large enough to allow for multiple scans to be taken before having to return to the homing station to offload the information.

Verification: The product specifications will be compared to a stationary test that will accumulate a large file of data for the onboard processor to store and save correctly. If the system can handle a very large test file then it will be successful in storing multiple data files from the structure scans.

DR 4.2 The memory unit shall be compatible with a UDP connection over gigabit ethernet.
Motivation: A user datagram protocol is a communications protocol that is primarily used for establishing low-latency and loss-tolerating connections between applications on the internet [4]. This will be used to help transfer the data stored by the system to a homing device for post processing by the customer.

Verification: This requirement will be verified by confirming the systems memory unit is compatible with a UDP connection over gigabit ethernet.

DR 4.3 The processing unit shall provide an interface between the LiDAR sensor, auxiliary sensors, and a hard drive.

Motivation: Similar to requirement FR 4 the motivation behind this requirement is to make sure there exists a functioning computer as part of this system. A processing unit should successfully communicate with all of the onboard sensors. Without this communication there would be no system to scan any infrastructure.

Verification: This requirement will be verified through a systems test once all the sensors have been tested individually. If the onboard processor can send commands to the individual sensors and receive a confirmation response then the requirement will be verified.

FR 5 The system shall be capable of mounting onto a vehicle and operating while the vehicle is in motion.
Motivation: The system is meant to improve the process of infrastructure fault detection. Traditional methods used today seldom involve non-stationary terrestrial LiDAR systems. Even when these methods are employed, the associated costs are far beyond the budget of this project. The system being mounted to a moving vehicle will drastically reduce the time it takes to collect the data when compared to a stationary system and through the innovation of the team it will be much loss costly then any current off the shelf model.

DR 5.1 The mounting structure shall be capable of supporting a LiDAR sensor up to 5 pounds in mass.
Motivation: Modern and innovative LiDAR systems are incredibly accurate but tend to be extremely expensive and large and bulky. Therefore, the team has set a mass limit for the LiDAR sensor that is feasible for the LiDAR sensors within the team's budget and can successfully satisfy all of the sensing requirements.

Verification: This requirement will be verified by checking if the physical sensor is the same weight as the product specifications says it is as well as to verify that it is below 5 pounds in mass.

DR 5.2 The mounting structure shall withstand drag forces associated with a vehicle speed of no more than 35 mph.
Motivation: As a group of many aerospace engineers the study and effect of drag forces is very well known. Therefore, since the sensor is being mounted on a car and will be driving anywhere from walking speed to 35 mph the structure itself needs to be able to withstand the drag forces and any extra bouncing forces it may encounter while surveying rural areas.

Verification: This requirement will be verified through a bounce test where the vehicle the structure is mounted on will travel through a specific test area where it will experience high velocity air flow as well as various bumps where the system must maintain its fixed position upon the vehicle.

DR 5.4 The mounting structure shall secure all components of the system up to a vehicle vibration frequency of 50 Hz.
Motivation: The mission vehicle may encounter unstable road conditions during infrastructure survey field campaigns. In the event the vehicle begins to vibrate abnormally, the team will ensure that the mounting structure secures the LiDAR sensor and all installed components. Failure to do so could result in a catastrophic loss of mission hardware.

Verification: The mounting structure along with the installed sensor package will be tested on a vibration table (up to 50 Hz) to verify that all components remain secured and that the system's resonant frequencies are not excited.

FR 6 The system shall incorporate a power source that is capable of continuously supplying power to all applicable components.
Motivation: Power supply is an incredibly important part of an electrical and mechanical system. Without a power source on board there would be no sensor measurements. Therefore, the system needs to have a power source onboard to supply enough power to run all applicable components within the system.

DR 6.1 The power system shall supply no less than 30 V.

Motivation: A power supply of 30 V was estimated to be the required amount to successfully power all the components of the system.

Verification: This requirement will be verified by checking the power supply with a voltmeter once all of the components have been added on. This will ensure that the power supply is functioning normally and if all of the components are functioning normally with respect to the supply.

DR 6.2 The power system shall be capable of supplying 20W of continuous steady-state power.
Motivation: A power supply of 20 W has been estimated to ensure the successful operation of all the system components. The customer has also provided this power requirement of 20W in order to operate the system to within functional specifications.

Verification: The power supply will be tested using a power meter under field load conditions with all of the sensor components attached and functioning normally. If this test is successful then the requirement will be verified.

FR 7 The point cloud and localization data shall be consolidated and post-processed into an interactive digital 3D map/model used by the customer to identify structural faults.
Motivation: The purpose of this mission is to provide data to the client in order to search for structural faults. This needs to be done in a time efficient fashion therefore the customer needs to have the data in the correct format to immediately start analyzing for potential faults.

DR 7.1 The point cloud data shall be stitched together to create a 3D map using localization data
Motivation: The engineers that use this data at a later time for post processing need to be able to look at the data in its most useful form which when identifying structural faults using LiDAR will be a 3D point cloud / map.

Verification: This requirement will be verified by testing the system and its sensors in a static environment and confirming that the data collected has been converted into a useful 3D point cloud when it has finished.

FR 8 The on-board communications unit shall be capable of wirelessly transferring point cloud and localization data directly to a designated headquarters.
Motivation: This requirement is based on the need to quickly and efficiently transfer the data received from scanning to the customer who will post-process it for fault detection. The transmission of data wirelessly will allow for a hands free way of transferring the data as none of the hardware needs to be removed once the vehicle has returned to the homing site.

DR 8.1 The system shall be capable of transmitting data at a range of 70 meters.
Motivation: This range allows for multiple vehicles to be in a single garage and start transferring their data to a local/online server. This range allows for the vehicle and the system to be a decent distance away from the homing station in a parking lot and still be able to transmit the data for a quicker turnaround of the results.

Verification: This requirement will be verified by creating a static test where the system will be placed up to 70 meters away from the homing station and will attempt to transmit test data back to the station. If the test data is received then the test will be deemed a success and the requirement will be verified.

DR 8.2 The system shall be capable of transmitting data at a minimum rate of 8 Mbps.
Motivation: The LiDAR sensor will be creating large data files from each structure scan and in order to save time on sending this large amount of data the transmission rate must be reasonably high.

Verification: This requirement will be verified by setting up a static test of the transmission rate by using test data from the system which will be transmitted to the homing station. If this occurs at a rate of 8 Mbps allotted then the requirement will be verified.

FR 9 The system shall be capable of initiating and terminating data collection with minimal driver interaction.

Motivation: The customer required this project to have minimal driver interaction to ensure safe operation of the vehicle and automated functionality.

DR 9.1 The system shall automatically begin data collection 50 m away from the infrastructure of interest, and shall automatically terminate 50 m after infrastructure of interest.
Motivation: The LiDAR sensor takes multiple scans of same obstructions to create a map accurately. If the system is started early enough then, with enough repetitions, the system will be able to map the start and end points of the infrastructure with greater accuracy. The 50m distance was chosen by looking at an average of 30m range on budget-allowing LiDAR sensors.

Verification: The data collected will be overlaid with a GPS map of the locality to get start and end locations of the system. This data will be visually tested to ensure the system is turned ON 50m before target and OFF 50m after target.

DR 9.2 The system shall provide a means of manual data collection initiation and termination.
Motivation: In case the automated, distance-based initiation/termination described in **DR 9.1** fails, there must be a failsafe "start/stop" button that allows the driver to start and end data collection manually. Although this will require driver awareness, a single button press is considered minimal interaction.

Verification: A "start/stop" button will be integrated with the LiDAR sensor package and it will be pressed multiple times to verify that it does indeed initiate and/or terminate data collection.

FR 10 The system shall conform to all relevant safety regulations and guidelines.
Motivation: This project involves a moving vehicle and a laser device, so safety must be addressed.

DR 10.1 The system shall adhere to all applicable Federal Motor Vehicle Safety Standards (FMVSS).
Motivation: LiDAR scanners come with safety hazards of causing eye-injuries and damage to silicon-based sensors on the road. These hazards can be avoided by choosing products that adhere to FMVSS protocol.

Verification: After choice of LiDAR sensor, the safety manager of the team will run through LiDAR guides provided by the National Transportation Library (NTL) in, "Review of Federal Motor Vehicle Safety Standards for Automated Vehicles" (2016), by National Highway Traffic Safety Administration (NHTSA) in, "LIDAR Speed-Measuring Device Performance Specifications" (2013), and FMVSS Article No.150, "Vehicle-to-Vehicle Communication Technology"(2016), and check if the product matches the design specifications given.

DR 10.2 The LiDAR sensor shall adhere to laser safety regulations under IEC 60825-1:2014.
Motivation: All laser emitting products used publicly must adhere to International Electrotechnical Commission's safety regulations. Article IEC 60825-1:2014 specifies the Classification and requirements of laser products.

Verification: After choice of LiDAR Sensor, it will be verified the wavelength of the beam emitted will be in a range of 180 nm to 1 mm. After preliminary comparison of article guidelines and sensor choice, the team will contact the manufacturer for documentation on adherence to these policies. This will be a criteria for further trade studies.

4. Key Design Options Considered

The design options considered for this project fall within five distinct subsystem categories: LiDAR sensor hardware, localization sensor hardware, data processing software, mounting structure, and communications. The success of FLASH is dependent on suitable selection of components in these five critical areas. Since the solution space for this project's application is relatively broad, a reasonable breadth of options were investigated for each subsystem group. The subsections below outline the specific options in more detail, as to provide groundwork for the trade study process described in Section 5.

4.1. LiDAR Sensor Hardware

The centerpiece of this project is LiDAR[1], which stands for Light Detection and Ranging. LiDAR is a remote-sensing technology that, in the most basic sense, uses laser pulses to measure distance/range. When combined with position and orientation data provided by GPS and IMU, integrated LiDAR systems can generate three-dimensional spatial coordinates of the surroundings, which can then be processed to construct digital 3D maps and models. The use of LiDAR is widespread -- its applications include autonomous vehicles, forestry management, and even cloud profiling. In the context of this project, LiDAR will be employed for infrastructure mapping and surveying. There are many LiDAR products commercially available off the shelf, each boasting its own unique features and capabilities. The options explored below are relatively compact, high-resolution LiDAR sensors that can directly output 3D point cloud data.

4.1.1. Velodyne Puck Hi-Res

Velodyne of San Jose, CA specializes in affordable LiDAR sensor solutions, with applications ranging from autonomous vehicle detection avoidance to localized navigation and mapping. The Velodyne Puck Hi-Res (Figure 3) capitalizes on their Velodyne Puck product and narrows its vertical field of view to 20° in order to tighten its channel distribution. Each channel in a LiDAR sensor represents a pair of laser pulse emitters and receivers. The more closely these channels are aligned, the higher the resolution of the resulting output point cloud. The Puck Hi-Res contains 16 channels (industry standards are 16, 32, and 64, with cost increasing with increasing channel number) with a maximum range of 100 m. This means that the LiDAR can detect objects up to 100 m away, which is twice the given requirement of 50 m. This viewing range has a +/- 3 cm accuracy associated with it, which is again within the requirement of +/- 5 cm. The Puck Hi-Res maintains the Puck's 360 ° horizontal field of view with a condensed 20° vertical field of view, as previously mentioned. This 20° ranges from -10° below the horizon to +10° above the horizon. The Hi-Res nature of this LiDAR system minimizes the vertical angular resolution to 1.33°, which is more precise than the industry standard. To collect the 360° horizontal data, the channels rotate (internally) at a rate from 5-20 Hz. This LiDAR optimally requires 8W of power, which is within the 20W requirement. It requires an operating voltage of 9-18 V, which is feasible with the current power bank design options.

Figure 3: *Velodyne Puck Hi-Res*

The Puck Hi-Res weighs 0.830 kg and has dimensions consistent with Figure 4 below. This lightweight, compact design would integrate easily into any vehicle mounting structure. It has an

[1] The use of LiDAR is a customer requirement. Thus, LiDAR alternatives were not considered in the trade study process.

environmental protection rating of IP67, meaning the system could be dropped in 1m deep of water for 30 minutes and still be operational (or at least prevent catastrophic damage). The ideal operating temperature range for the Puck Hi-Res is -10℃ to +60℃ (14℉ to 140℉). These environmental factors allow this LiDAR to be utilized in almost any weather conditions at any time in the year. Because of the lower limit on the operating temperature, cold, winter days would have to be avoided. When operated in dual-return mode, the Puck Hi-Res can capture approx. 600,000 point cloud data points per second. This will be equivalent to 19.4 MB of data per second. This 16 channel model is currently selling for approx. $8,000 from multiple online vendors.

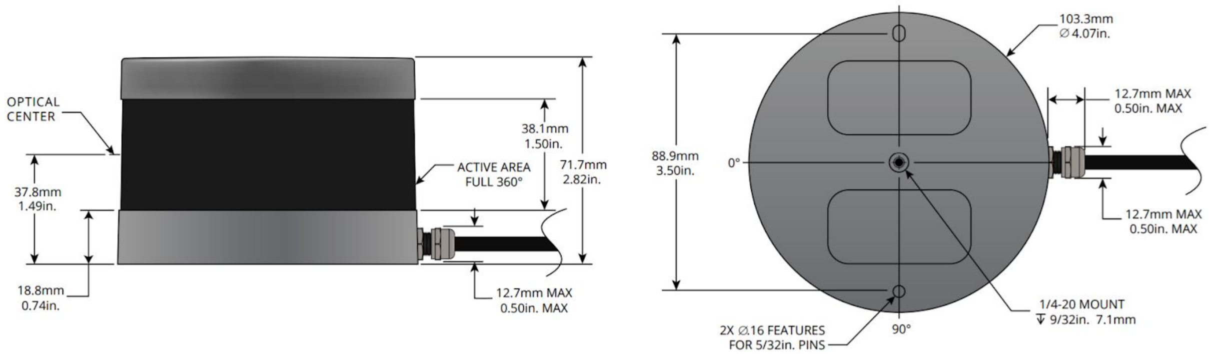

Figure 4: *Dimensions of Velodyne Puck Hi-Res [5]*

Advantages	Disadvantages
Popularity; widespread industry use and recognition	High cost
Low power consumption	Limited vertical field of view
High point cloud resolution at long distances	Not field serviceable

Table 2: *Advantages and Disadvantages of Velodyne Puck Hi-Res*

4.1.2. Velodyne Puck

The Velodyne Puck is the basis for the Velodyne Puck Hi-Res (see Section 4.1.1), and contains many similar features with three primary differences. The first of these differences is the vertical angular resolution, which is 2.0° for the Puck vs. the 1.33° of the Puck Hi-Res. The vertical field of view of the Puck, 30° (-15° to +15°), is greater than that of the Puck Hi-Res, 20° (-10° to +10°). As discussed, this increase in FOV comes at the cost of reduced vertical angular resolution. The Velodyne Puck is selling online for $4,000 versus the Puck Hi-Res $8,000 selling point.

Other than these three specification and cost differences, the Velodyne Puck and Velodyne Puck Hi-Res have notionally identical specifications. See Figures 3 and 4 for the Puck casing and dimensions. (equivalent to those of the Puck Hi-Res).

Advantages	Disadvantages
Popularity; widespread industry use and recognition	Limited vertical field of view
Low power consumption	Not field serviceable

High range and precision	

Table 3: *Advantages and Disadvantages of Velodyne Puck Hi-Res*

4.1.3. Ouster OS0-32

Ouster is a company that creates numerous types of high resolution LiDAR sensors for long, mid and short range applications. They have specialized in transforming LiDAR from an analog device with thousands of components to an elegant digital device powered by one chip-scale laser array and one CMOS sensor [6]. This particular sensor was from the second generation of their ultra-wide view LiDAR sensors.

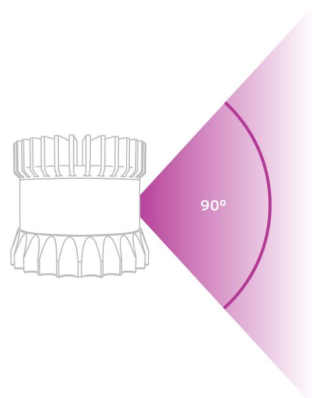

Figure 5: *Ouster OSO-32 scanning field of view [7]*

The Ouster OSO-32 has the following sensor specifications. The vertical resolution is represented by 32 channels with a range of 120 m. The vertical field of view is 90 degrees plus or minus 45 degrees. The precision of this sensor is claimed to be plus or minus 1.5 - 5 cm. This sensor uses 14 - 20 W which falls within the project's requirements. An important factor is that this sensor is only 455 g which will allow for some additional mass in other areas in order to stay under the maximum weight determined by the project requirements. One quality that stretches the project requirements is the price of this sensor which off the shelf is priced at $6,000 but there are discounts for university purchases. This is still over our requirement but it is within a reasonable budget for the group's company sponsor to purchase and donate to the group.

Advantages	**Disadvantages**
Ultra-wide field of view	Lower range than similar options
Built-in IMU for SLAM algorithm support	Relatively high cost
Low weight/mass	

Table 4: *Advantages and Disadvantages of Ouster OS0-32*

4.1.4. Ouster OS1-16 (Gen 1)

This model from Ouster comes from the second generation of sensors from this company. The main differences between this generation and the first one described above is the number of channels for vertical resolution which provide an angular resolution of 0.35 degrees to power perception. They have also improved the precision and accuracy of the sensors by approximately two times. This generation also has a shorter minimum range, wider field of view, and an expanded dynamic range.

Figure 6: *OS1 Sensor Proving Its Weather-Proof Capabilities*

The specifications for this sensor include a range resolution of 0.3 cm with a range in terms of 0.8 m through 120 m (for 80% reflective lambertian target). The power requirements for this sensor ranges from 14 to 20 W which fall within the requirements. This sensor is a lightweight system at only 0.425 kg. This sensor only has 16 channels which means in comparison to the 32, 64 and 120 channels options it will not perform as well but this also means it is the cheapest option from this generation.

Advantages	**Disadvantages**
Low weight/mass	Older, first-generation model
Open source drivers; detailed software documentation	Complex output data packet structure
Lower cost than similar options	Lower range than similar options

Table 5: *Advantages and Disadvantages of Ouster OS1-16 (Gen 1)*

4.1.5. SICK MRS1000/OUTDOOR

This system claims to be used in major industrial scenarios where visibility and clearance are an issue. This sensor collects more data in multiple dimensions which leads to higher measurement accuracy. This sensor claims to be accurate at 6 cm from a range of 64 m. This LiDAR is also a lightweight option at only 1.2 kg which satisfies the project requirements. The sensor also only needs 13 W of power to operate which also falls within the project requirements. The price of this LiDAR is pushing the limits of the groups budget but this could be avoided if the teams company, ASTRA would purchase and donate the sensor to us for the use on this project.

As shown in Figure 8 this LiDAR system is designed to aid large mobile machinery in tight spaces. It allows the driver to have an early and accurate warning system of how close a machine like a forklift is to colliding with another large object. This would be incredibly useful in this field because it could prevent major accidents when this large machinery is maneuvering around large warehouses full of expensive products and other hardware.

Figure 7: *SICK MRS1000/OUTDOOR's industrial capabilities [8]*

The MRS1000/OUTDOOR LiDAR system has its benefits but in the grand scheme of LiDAR systems this range is not very good. Since the system is used mostly in industries where all obstacles would be large and easy to identify the sensor does not need to be overly accurate to complete its purpose.

Advantages	**Disadvantages**
Rotatable connections to enable flexible mounting	Limited field of view
Multi-layer scanner	Higher weight/mass than similar options
High weather resistance	Low scan/point rate

Table 6: *Advantages and Disadvantages of SICK MRS1000/OUTDOOR*

4.1.6. Livox Mid-100

This LiDAR system is a relatively cheap off the shelf option from the Livox Tech Company. This LiDAR boasts a 2 cm range precision at a range of 260 m. It is described as a high-performance LiDAR sensor developed for a wide variety of applications. This model includes an advanced non-repetitive scanning pattern that should deliver highly-accurate details in real time. The specifications on this model also show that it is a lightweight, and compact system that only weighs 2.2 kg which is well below the group's requirement. The power consumption on this system is 30 W which unfortunately is 10 W above the group's requirement but this could be adjusted if this sensor was chosen for the project.

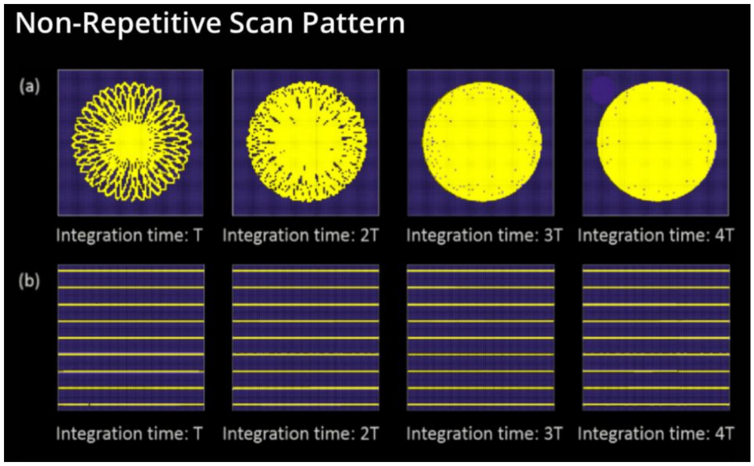

Figure 8: *An example of a Non-Repetivie Scan Pattern covering more surface area [9]*

The most important part of this LiDAR system was its non-repetitive scan pattern that can result in a very high accuracy at large distances. This process functions by showing single frames and the related superimposed frames in a non-repeating scanning regime which is shown in part (a) of Figure 8. Part (b) of this same figure shows how despite the increased number of points used the picture is actually distorted. This is done by showing the single frames and the related superimposed frames in instead, a repeating scanning regime. This company is convinced using this mechanism can boost the accuracy at greater distances. Despite how innovative this technique is it does not quite align with how the group needs the LiDAR to function.

Advantages	**Disadvantages**
High range and precision	Limited field of view
Low cost	High power consumption
Non-repetitive scan pattern	Higher weight/mass than similar options

Table 7: *Advantages and Disadvantages of Livox Mid-100*

4.2. Inertial Navigation System (INS)

In order to correlate LiDAR measurements taken in motion, an internal navigation system (INS) composed of several additional sensors will be required for localization of the LiDAR scanner through time. The data outputted by this system will contain all of the temporal and spatial information necessary to compile the raw LiDAR measurements into a common coordinate frame to create a registered point cloud. For terrestrial mobile LiDAR applications the most common form of INS will primarily be informed by a combination of external positioning data, such as triangulation with a global navigation satellite system (GNSS), with internally measured motion data, such as the linear and angular accelerations measured by a accelerometers and gyros, known as an inertial measurement unit (IMU) [10].

Due to differing bandwidth and capacity requirements between the sensors in the INS and the LiDAR systems, the data outputted by the INS will be stored to a separate memory unit from the LiDAR data storage module. It should also be noted that some of the LiDAR options considered above have built-in hardware and software to perform the localization step automatically.

4.2.1. Inertial Measurement Unit (IMU):

In order to estimate the system's movements through time we will use inertial motion data collected from gyroscopes and accelerometers which can be numerically integrated to calculate position. This subsystem of sensors is called an inertial measurement unit (IMU). Because acceleration is often far easier to directly measure than distance or velocity, IMU's are an extremely popular choice to serve as the foundation for any INS. However, this strategy comes with a downside: since position is being calculated by integrating the measurements over time, a small error in an early position calculation will likely cascade into a much larger error later on as it gets repeatedly integrated, the error growing exponentially. This limitation is a mathematical one, so even very sophisticated IMU's will always have errors which grow linearly with speed and exponentially with distance, unless they are frequently compared against and corrected by another one of the INS's subsystems, such as a GPS receiver.

Advantages	**Disadvantages**
Extremely accurate localization	Increased complexity if built-up from individual accelerometers and gyros
Very common form of sensor data for INS	Cascading errors over long measurements
Can handle vehicle-speed applications	High precision units can be very expensive

Table 8: *Advantages and Disadvantages of IMU*

4.2.2. GNSS

Inertial data from an IMU on its own will not provide sufficient localization accuracy as it is subject to compounding integration errors. Positioning data from a Global Navigation Satellite System (GNSS) is by far the most common choice for making these corrections in modern-day INSs and can provide accuracy in both position and temporal measurements, broadcast over microwave in, typically a combination of the L1 C/A, L2C, L5 and L1C signals are available for civilian use with the US's Global Positioning Satellite (GPS) network.

The protocols and signals for communicating with GNSS networks are still evolving globally, but luckily modern receiver modules are often built by a multi-constellation compatible paradigm and can natively communicate with all of the major GNSS constellations, including but not limited to the US's GPS network, Russia's GLONASS, the EU's Galileo, India's NavIC, Japan's QZSS, and China's BeiDou.

Constellations deployed around or after 2010 saw an iteration in the GNSS standard since its inception with GPS in 1980, referred to as GNSS-2. GNSS-2 networks support higher standards for accuracy and reliability, allowing the network to be considered safe for use in civil aviation and navigation. Of the previously mentioned networks only two will qualify as meeting the GNSS-2 standard: Galileo (launched in 2011) and QZSS (undergoing deployment, TBC 2023) [11].

The exact implementation details of how positioning is performed using a GNSS network varies greatly between networks and orbital configurations, but the basic principle is to triangulate your location by successfully aligning the timings of random bit strings generated from the transmitter. Once the timings are aligned, the satellite can then communicate accurate position and timing data back to the target. This alone will not be enough to perform localization however, as it only gives a one-dimensional distance which is relatively defined between the target and the single satellite. So if we do this for at least four satellites at a time we can triangulate our exact location through correlating the relative distances returned by each one. The satellites also have a highly accurate sense of where they are in relation to the rest of the constellation at any given moment and vice-versa, so simply receiving this position and time data from four satellites is theoretically sufficient to triangulate yourself on Earth's surface.

In reality however, all GNSS signals suffer from aspects of interference, reflection, and degradation during the long transmission. The initial step of establishing the relative timing when passing the random bit string can be problematic in itself due to essentially being a stochastic algorithm, and as a result it typically takes much longer to establish a connection than actually perform communications thereafter, and outages may take disproportionately long to recover from. This is why time to first fix (TTFF) is a critical point of GNSS's performance downsides. GNSS networks are therefore built with many redundant systems and connections in mind to combat these potential issues, including establishing many redundant connections with additional satellites, robust error correction techniques, and in rare cases the ability to cache and retry sending entire packets [12].

Advantages	**Disadvantages**
GNSS coverage very extensive	Poor performance in cities, storms, and dead zones
Most common form of sensor data for INS	Slow initial connection establishment
Low cost	Must plan around outages

Table 9: *Advantages and Disadvantages of GNSS*

4.2.3. Dead Reckoning

A third source of data commonly used in INSs is the output of a dead reckoning measurement. Dead reckoning performs essentially the opposite of an IMU: where IMUs measure accelerations and convert to a position, dead reckoning uses knowledge of the physical dimensions of the system in order to make position calculations directly. They typically combine the output of a distance-measurement encoded directly from the system's movement, such as an odometer attached to wheels in a car, with a pre-defined knowledge of key measurements that could be used to convert the encoder reading back to calculate the distance travelled. On their own, dead reckoning techniques are even more prone to cascading drift error than IMUs because there is effectively no way to remove errors once they have been introduced in previous steps. Because of this, navigation systems based on dead reckoning are almost always paired with an additional data source, such as GNSS or IMU readouts, or must have some sort of landmark from which the system can reorient itself with by setting itself back to a known location.

Since the motion in our system is being generated in a car, the ability to integrate a dead-reckoning system with any of its moving components would involve focusing on precise knowledge of the orientation, circumference, and rotation magnitude of the wheels. Admittedly, much of this data is likely being logged by the car somewhere as it is and perhaps could even be accessed without too much hassle in some makes/models, having found no reasonable options for commercially available ways to retrofit a dead reckoning system *to* a car, we unfortunately have to reject the possibility of a dead reckoning playing a role in this project, despite having potential at face value.

Advantages	**Disadvantages**
Less reliance on GNSS and IMU data	Custom mounted unit expensive for cars
Well supported for registration techniques	Overall accuracy very low over large measurements

Table 10: *Advantages and Disadvantages of Dead Reckoning*

4.2.4. Integrated Units

Several commercially available units exist for the purposes of offering an INS package within a single interface. A variety of solutions exist for combinations of IMUs, GNSS units, altimeters (barometers), and compasses (magnetometer), dead reckoning units, and more.

4.4.2.1. Advanced Navigation SPATIAL

The SPATIAL by Advanced Navigation is a lightweight and compact GPS/INS system that delivers accurate position, velocity, acceleration and orientation for a wide range of applications. It has a horizontal and vertical accuracy of 1 meter without post-processing, and up to 0.02 meters with post-processing, as well as a velocity accuracy of 0.05 m/s. The system has an internal filter that runs at 1000HZ. Data can be outputted via RS232 interface. It is priced at $3126 USD and comes included with the necessary operating software. At this price it would be near impossible to stay within the project budget while still obtaining other necessary components if we are not to obtain a LiDAR system through ASTRA, but could be justified otherwise as we have very demanding localization requirements.

Advantages	**Disadvantages**
High performance outside of GNSS	Expensive
Dual-band GNSS	
Included software	

Table 11: *Advantages and Disadvantages of Advanced Navigation SPATIAL*

4.4.2.2. Vectornav 200/300

The VN-300 by Vectornav is capable of acquiring highly accurate inertial navigation data under both static and dynamic conditions. The device is a Dual GNSS Antenna Inertial Navigation System that is extremely lightweight and small. The VN-200 model offers the same featureset with only single-band GNSS for a lower-cost solution. They offer vertical and horizontal accuracy position measurements of 1.5 m and 1 m respectively before post-processing as well as velocity accuracy of within <0.05 m/s, even after 10 seconds of GNSS outage. It offers a wide range of operation temperatures from -40C to 85C for robust performance in outdoor environments. It comes with a MATLAB toolbox for interfacing with the data as well as post-processing techniques. The VN-200 is extremely lightweight weighing in at just 5g. The unit cost of the VN-200 and VN-300 were not publicly available without requesting a quote from the company directly, however based on units with similar specifications it would be estimated that they cost in excess of $2,000 and $3,000 respectively.

Advantages	**Disadvantages**
High performance outside of GNSS	Expensive
Dual-band GNSS	
MATLAB integration	

Table 12: *Advantages and Disadvantages of Vectonav 200/300*

4.4.2.3. Trimble BD992-INS

The Trimble BD992-INS offers an inexpensive solution for GNSS/INS capabilities. It comes with a fully integrated GPS and MEMS-based tri-axial inertial system while being under $500 USD. It delivers 1 m and 1.5 meter horizontal and vertical positioning accuracy under normal GNSS conditions while live, and up to 0.02 m accuracy with post-processing or RTK techniques. It offers several I/O solutions, including a USB port, LAN ethernet port, and 3 RS232 ports. This is all integrated into a low-profile PCB with pre-drilled mounting holes, and could act as a PCD shield or be integrated separately. The accuracy and capabilities outside of GNSS signal drop significantly.

Advantages	Disadvantages
Inexpensive	Poor performance outside of GNSS
Lightweight	Single-band GNSS
RTK compatible	

Table 13: *Advantages and Disadvantages of Trimble BD992-INS*

4.4.2.4. Gladiator Technologies Landmark 60 GPS/INS

The Gladiator Technologies Landmark 60 GPS/INS is a small and durable device that can be used for navigation, stabilization, and more. It has a 72-channel multi-constellation GNSS receiver. It is a unit focused on durability for externally mounted applications, boasting operating conditions from -50C - 85C and military-grade shock and vibration ratings. It has a horizontal and vertical positioning accuracy of 1 m in the vertical and horizontal directions. The system includes an Extended Kalman Filter which is responsible for error correction and continuous output during GPS outages which runs at up to 600Hz. The unit cost of this unit was unable to be determined without requesting a quote from Gladiator Technologies, however comparing it to units with similar specifications it is safe to assume this unit would cost in excess of $4,000.

Advantages	Disadvantages
High performance outside of GNSS	Gotta be expensive
RTK compatible	Heavier than other INSs
High durability	

Table 14: *Advantages and Disadvantages of Gladiator Technologies Landmark60 GPS/INS*

4.3. Data Processing Software

As specified by **FR 7**, post-processing will be required to transform raw point cloud data into an interactive 3D map/model structural analysts can use to identify faults and damage. The first step in processing raw LiDAR data is point cloud registration (PCR). PCR is the process of determining a transformation that aligns two or more point clouds into a common coordinate system [4]. PCR plays an important role in 3D model reconstruction because it enables the unification of disorganized spatial (*x,y,z*) data outputted by LiDAR sensors. In the context of FLASH, the LiDAR sensor will likely scan a certain portion of infrastructure multiple times as the vehicle passes by, so PCR will be required to synthesize the point clouds into a single frame of reference for later 3D model conversion. Additionally, localization/odometry data will be simultaneously collected by an inertial navigation device or GPS to help "stitch" together point clouds. After registration and "stitching" is complete, points clouds must be segmented into clusters so that they can be fit to geometric shapes [13]. As described here, point cloud processing may not seem like an easy or straightforward undertaking; however, there exist a number of commercially-available software packages capable of directly processing and transforming raw point cloud data into a more useful form such as a BIM (Building Information Modeling) file [14]. The software options explored below are all viable candidates for processing the data which will be produced by FLASH's sensor package.

4.3.1. PointFuse

PointFuse is a high-end, licensed software package that transforms raw point cloud data from laser scanners into sophisticated 3D mesh models for purposes of visualization. These mesh models are automatically segmented into discrete, selectable surfaces to allow for object classification and identification. Additionally, the software's visual user interface has tools for measurement of features in the mesh models. PointFuse supports a wide variety of point cloud file formats for import (XYZ, PTS, E57, etc.) and it can export mesh models into industry-standard CAD formats. The software does not require a third-party plug in and the conversion process can significantly reduce the size of working data. However, for optimal performance, it requires a high-end machine with a dedicated graphics card and sufficient RAM. Also, the software is relatively expensive – the one-month license costs $950 and the 12-month license costs $5000.

Advantages	**Disadvantages**
Produces high-quality 3D mesh models	Expensive, time-restricted license options
Mesh files up to 100x smaller than original point cloud	Requires high-end machine for optimal performance
Feature selection and classification functions	

Table 15: *Advantages and Disadvantages of PointFuse*

4.3.2. ArcGIS

ArcGIS is a software maintained by the Environmental Systems Research Institute. It allows geographic information to be manipulated into an interactive format in order to apply location based analysis to areas of interest. This program has the ability to combine point cloud data (such as data from a .LAS file), GPS information, and existing base maps so customers can easily see how the output of the FLASH system is related to the real world. This kind of visualization would be useful for infrastructure analysis because it would allow analysts to quickly understand the local context of determined faults. The University of Colorado Boulder provides free licensing of this program to students, but students are not on the approved caller list. In order to receive tech support at any point from ESRI, the team would need to be granted access to the university's approved caller list for their customer ID. ArcGIS has the ability to publish to a public map or to give free viewing access to a customer. However, while this program is helpful for stitching different types of data files together and contextualizing geographic data, it only accepts .LAS, .ZLAS, and .LAZ files. While these file types are considered the industry standard for LiDAR data, it is not guaranteed this will be the resulting file format from the FLASH system. Additionally, processing data in ArcGIS is an involved process that allows the user to manipulate their data in many ways. It would be very useful for producing a polished final product the customer could interact with or as a visual verification tool, but it is not the fastest way to get data to the customer. Raw point cloud data and GNSS files could be transferred much faster.

Advantages	**Disadvantages**
Catalog and visualize scan jobs on city-wide scale	Requires students to be on approved call list in order to access tech support
Can consolidate multiple post-processing subsystems into one interface	User-intensive processing that might be more detail than needed
Automatic import and comparison of ground truth	General purpose mapping software, not designed specifically for processing LiDAR data

Table 16: *Advantages and Disadvantages of ArcGIS*

4.3.3. CloudCompare

CloudCompare is a free open-source software package for 3D point cloud and mesh processing. Although it was originally developed for point cloud comparison, it has since evolved into a more general and advanced processing program. CloudCompare's user interface offers a variety of tools and algorithms for point cloud editing, registration, and visualization. The software supports a breadth of file formats (LAS, E57, PCD…) as well as plugins for added functionality. The CloudCompare website includes extensive user documentation/tutorials and the software still receives regular updates, with the most recent version releasing just last month (August 30, 2020). The project customers (ASTRA) mentioned they have used CloudCompare for LiDAR-related work, so their familiarity with the software makes it an even more fitting candidate for FLASH. However, like most open source software, CloudCompare experiences occasional issues and bugs that require troubleshooting.

Advantages	**Disadvantages**
Free, open-source software package	Only one view window
Offers various advanced processing tools	Not easy to classify points
Customer familiarity	Plugins prone to bugs

Table 17: *Advantages and Disadvantages of CloudCompare*

4.3.4. AutoDesk

AutoDesk's suite of general-purpose computer aided design (CAD) software has been an industry leader in civil engineering applications for several years. Their natively supported solutions for generating 3D models from point cloud data include their products AutoDesk ReCap, AutoCAD Civil 3D, and 3DS Max products for registration, visualization, and model rendering respectively. However, since many of AutoDesk's products overlap in functionality and are designed for general-purpose settings, other AutoDesk software packages such as InfraWorks, Revit, or NavisWorks could serve as appropriate substitutes for various steps in the processing chain.

Additionally, Autodesk has had a strong history of supporting the evolving standards defined by Building Information Modelling (BIM), an international effort to standardize methodologies in modern civil engineering. By focusing on creating an extensive chain of compatibility with other mainstream pieces of software, AutoDesk's CAD environment offers an easily configurable solution for every step in the LiDAR post-processing pipeline and supports all major public standards for LiDAR-related file types (.LAS, .LAX, .XYZ, and more) and 3D model file types (.IFC, .COBie, STEP, and more), as well as proprietary formats outputted by AutoDesk, the DoD, and other major CAD brands. Depending on the configuration of the AutoDesk toolchain practically any input or output format specification could be met, including options for interpreting custom ASCII-based file formats.

Advantages	**Disadvantages**
Excellent customization and compatibility options	Requires licensing, price and duration depends on config
Can consolidate multiple post-processing subsystems into one interface	Overly feature-heavy, high overlap between options
Trusted developers, customer support available	General purpose software, not designed specifically for LiDAR

Table 18: *Advantages and Disadvantages of AutoDesk*

4.3.5. TerraSolid

Similarly to AutoDesk, TerraSolid offers a wide range of products to configure a LiDAR post-processing toolchain in a variety of ways. The core of the software sweet lies in TerraScan, which offers tools for registration, generation, and visualization of point clouds and their corresponding 3D models. The compatibility options for integrating third-party or custom software subsystems are not as extensive as AutoDesk's, but still offers a reasonable range of import and export options for the LiDAR and 3D model data. For interfacing with the point cloud data, TerraScan offers compatibility with other TerraSolid binary files, as well as .LAS and custom ASCII-based specifications. TerraScan and TerraPhoto are offered as the default software packages included with many commercially available mobile lidar systems, including IGI's StreetMapper and Phoenix LiDAR System's lineup of mapping products.

Advantages	**Disadvantages**
Designed exclusively for LiDAR systems	Requires licensing for both Lite and Pro versions
Support for batch processing and distributed computing with TerraSlave	Limited filetype compatibility outside of other TerraSolid products (.LAS or custom ASCII only)
Lite version may be robust enough for our needs	

Table 19: *Advantages and Disadvantages of TerraSolid*

4.3.6. MATLAB

MATLAB is a multi-faceted programming platform designed specifically for engineering applications. The latest release of MATLAB (R2020b) includes a LiDAR toolbox with a number of algorithms and functions for the design and analysis of LiDAR processing systems. MATLAB also offers dynamic functions specifically meant for point cloud processing, registration, and visualization. Before point clouds can be processed in MATLAB, they must be inputted as organized 3D coordinate point arrays or as PLY/PCD files. There is no guarantee the LiDAR sensor package to be used in this project will output point cloud data in PLY or PCD format. Furthermore, processed point clouds cannot be directly exported from MATLAB as 3D maps or model files -- hence, all visualization and evaluation must happen within the confines of the MATLAB user interface.

Advantages	**Disadvantages**
Team proficiency with MATLAB	LiDAR and point cloud processing tools are new and unproven
Extensive toolbox documentation	Requires licensing and toolbox installation
Programming-based processing offers flexibility	Requires heavy user engagement for scripting

Table 20: *Advantages and Disadvantages of MATLAB*

4.4. Mounting Structures

An important mission objective is for the LiDAR system to be able to collect data while attached to a moving vehicle (see Functional Requirement 5). This requires the design of a mounting apparatus to safely secure the entire system (LiDAR and attached components) to the top of a vehicle. The mount shall be designed to attach and detach easily to commercial cars, vans, or trucks. The design requirements leave the mounting approach rather open-ended, allowing room for multiple options to be considered. Three of the main selections for mounting possibilities are discussed below along with their advantages and disadvantages. These options consist of using solid attachments with bolts/screws (traded as a permanently attached roof rack), magnetic attachment points, and a clamped roof rack mounting mechanism.

4.4.1. Permanent Attachment

For purposes of trade studying, the group has modeled a permanent attachment mechanism (i.e. one in which the structural housing system components are placed on an apparatus which is permanently attached to the vehicle with screws or bolts) as a permanent off-the-shelf roof rack. One such roof rack is the Base Roof Rack from Rack Attack [15]. Such a structure would provide a base upon which the FLASH housing structure could be removed and attached from. This would be accomplished by a screw system from the housing to the mounting, which itself requires a screw system to be mounted onto the vehicle. What is pertinent about such an attachment mechanism is that it is minimally susceptible to flying off of the vehicle during sharp turns, collisions, and other such events. A typical cargo van (2018 Ford Transit) is used to determine the custom roof rack fitting (to determine a maximum cost case). Such a fitting would require several components: fixpoint feet, fit kits, wingbars, and lock cores.

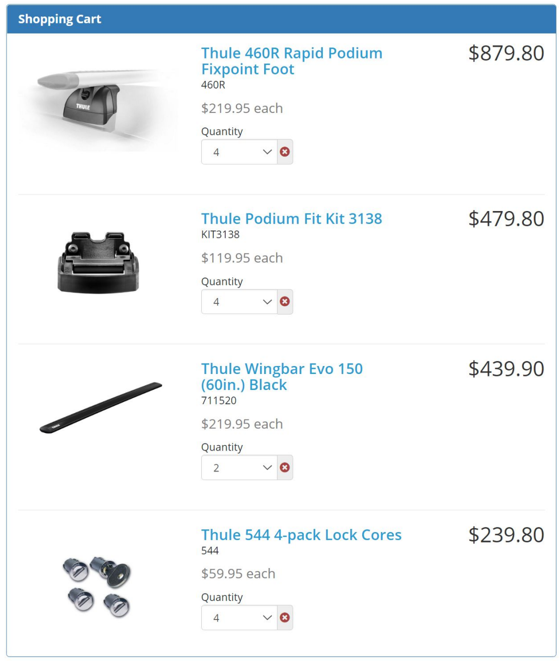

Figure 9: *Commercial permanent attachment components*

These components are costly, however the stability of using such a system is the highest. Furthermore, the fixed attachment can hold large amounts of weight. This method would be most applicable to one specific vehicle for all missions to be performed from, rather than having several FLASH systems able to be mounted onto different vehicles.

Advantages	**Disadvantages**
High stability	High cost
Can hold a large amount of weight	Complicated attachment mechanism
	Permanently alters vehicle

Table 21: *Advantages and Disadvantages of permanents attachments*

4.4.2. Magnetic Attachment

A key criteria of mission success is for the FLASH system to be entirely removable and attachable to any vehicle. One way this can be accomplished is through a magnetic mounting system. CMS MAGNETICS has neodymium magnets (50 LB Holding Power 2.4" Cup Magnets) that can hold up to fifty pounds when working in conjunction [16].

Figure 10: *Magnetic Attachments*

These magnets would be attached to the structural component of FLASH. This allows for easy attachment and detachment to any vehicle with a metal roof. There are some concerns, however. The magnetic mounting cannot hold as much weight as the permanent mounting. Furthermore, there are concerns that this mounting is far less stable than a screw attachment..

Advantages	**Disadvantages**
Fully attachable and detachable	Possible instability
No vehicle alterations	Does not work on plastic car roofs
Minimal attachment complexity	Cannot hold above 50 lbs
Low cost	

Table 22: *Advantages and Disadvantages of magnetic attachments*

4.4.3. Clamped Roof Rack Attachment

The final mounting mechanism traded is the clamped roof rack attachment. The Home Depot manufactures Adjustable Rooftop Rack Crossbars which can hold up to 150 pounds [17]. These crossbars are attachable through clamping to the vehicle's roof, and can adjust horizontally.

Figure 11: *Clamped Roof Rack Attachment crossbars*

The key benefits of this attachment method are that it can be removed easily, is stable, and can hold a large weight. The main drawbacks are that a clamping mechanism would need to be purchased for each FLASH system, as they currently need to be screwed directly onto the crossbars.

Advantages	**Disadvantages**
High stability	Moderate cost
No speed cap	Need to purchase multiple units
Can hold large weight	Complicated installation

Table 23: *Advantages and Disadvantages of clamped roof rack attachments*

4.5. Communications System

The final step in the scanning process is to transmit the data output from the LiDAR and odometry system so that 3rd parties may access the data for analysis without physical connection to the vehicle. In order to design a communication system, different communication protocols and methods will be traded. This trade study will be done primarily on three major factors: The range each protocol is used for, the data transmission rate typically provided and finally the hardware constraints posed by a general off the shelf transceivers, antennas and routers compatible with the communication protocol. The application of a wireless network in our device is to validate multiple prototypes being able to send data to a single receiver, an Internet of Things (IoTs) protocol compatible with star topology is preferred over the Point-to-Point Protocols (PPP). The team is aware that in PPP, there is more opportunity for encryption and furthering security against malicious users as well as higher data transmission rates. In order to integrate PPP, there would be a demand for excessively expensive hardware as well as complicated integration of software which is outside the scope of the communication capabilities as network security is not a functional requirement of the team. Hence a trade study will be done solely on IoT compatible protocols. An introduction to these communication protocols will be done in this section.

4.5.1. Wi-Fi (IEEE 802.11 Family of standards)

The most popular and commonly used protocols in household appliances, computers and smartphones is the WiFi IEEE 802.11 family of networks. This method used to connect other devices to either an access point, which includes a router, which then connects to other appliances on the LAN,WAN or the internet. WiFi can also be used for high speed data transmission from Point-to-Point but is not commonly used for it. This method is dependent on an internet provider sending internet through a modem and then a wireless Wi-Fi connection via a router. In this case, the connection would then be leveraged with a wifi adapter onboard the system which would give it access to the internet. The data stored onboard would then be uploaded to a server which could be accessed for post processing. The primary advantage of using this method is that once the data is uploaded, the post processing can take place at any location. This could expand the systems operating range to virtually any location so long as the vehicle can return to a homebase to upload the data.

The data rate is highly dependent on the internet provider, router, location and Wi-Fi adapter, however it is common to achieve an upload speed from 5 to 15 Mbps. One of the main concerns with this method is the dependence on a homebase location and the Wi-Fi connections range which can be around 90 m. Additionally, this method will require intricate power management design to be able to transmit data when other components are switched off while communication as Wi-Fi capability consumes anywhere between 2 to 20W. A major advantage to using WiFi is that it eliminates the need of a hub separate from the router, and has direct access to the internet. This however has a major tradeoff, the high data speeds and medium range results in a high power consumption by the router and transceiver.

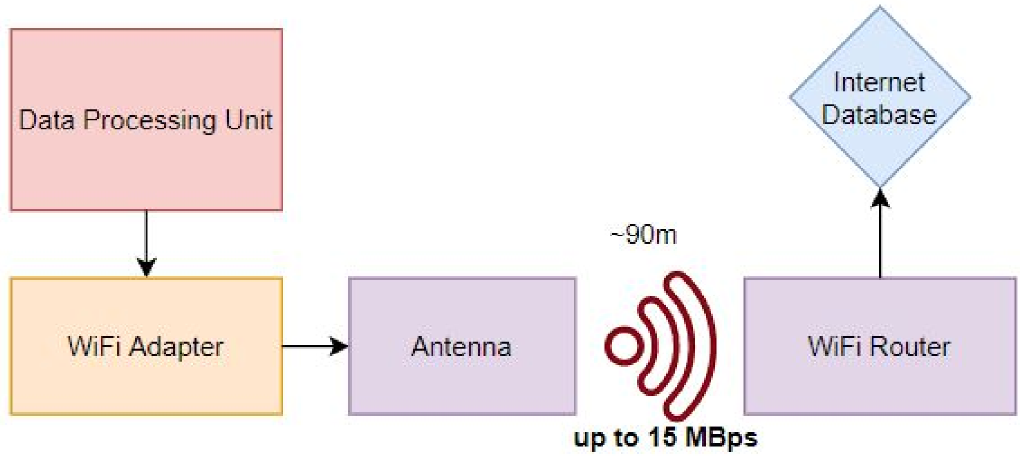

Figure 12: *Data Transfer Graph for Wifi Communication Protocol*

Advantages	**Disadvantages**
Average data upload rate ~ 5 to 15 Mbps	Low range < 300 ft. Can only transmit data at a homebase location
Wifi adapters are cheap	Connection speed depends on location and internet provider
Data is readily available to anyone with access to internet	High power requirements

Table 24: *Advantages and Disadvantages of WiFi Communication Protocol*

4.5.2. 4G LTE Cat

Long-Term Evolution (LTE) is a standard for wireless communication used for GSM/UMTS standards. The LTE technology has been around since 2004 and has a variety of usage examples that the team could study as motivation for this project. The LTE architecture requires the device (User Equipment) to be connected to nodes (Radio Access Network) which will then transfer data onto Evolved Packet Core (EPC) and further to selected servers, or directly to the internet. Today, LTE modems are used to directly connect to the internet which would leave the RAN, EPC and the more complex hierarchy to the Internet Service Providers. This would enable ease of access and low-interaction with the device as it will enable it to transmit data to a cloud on its own. Access to the internet would be possible anywhere where there is coverage provided by a cellular service. This however comes with a crucial drawback of high cost from ISP for cellular data usage. First the LTE modem on the device has a high cost, but moreover, data usage cost can go up to 18-20$ per GB. Since this mission involves high data storage and upload-download requirements this is a strong disadvantage.

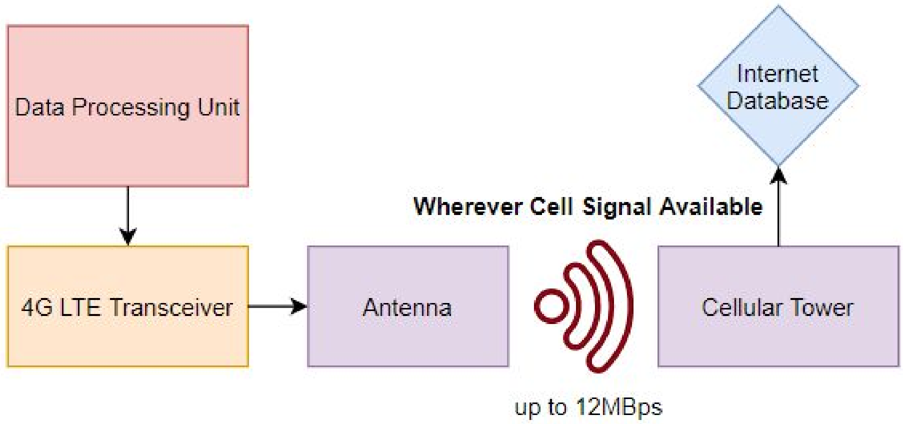

Figure 13: *Data Transfer Graph for 4G LTE Communication Protocol*

Advantages	**Disadvantages**
Upload anywhere within coverage	Data upload rate ~ 2-5 Mbps. Highly variable and dependent on location
Upload data immediately after acquisition lowering onboard storage requirements	Typically less coverage in rural areas
No homebase required.	High Cost

Table 25: *Advantages and Disadvantages of 4G LTE Protocol*

4.5.3. Bluetooth LE

Bluetooth devices communicate directly with each other, rather than sending traffic through an in-between device such as a wireless router. This makes life very convenient and keeps power use extremely low, improving battery life.Bluetooth devices communicate using low-power radio waves on a frequency band between 2.400 GHz and 2.483.5 GHz. This is one of a handful of bands that is set aside by international agreement for the use of industrial, scientific and medical devices (ISM). For the purposes of this mission, the latest version of bluetooth technology, the LE (Low Energy) option is considered. This is due to the openness of many-to-many architecture that can be developed using this technology, as compared to the one-to-one restricting bluetooth classic [18].

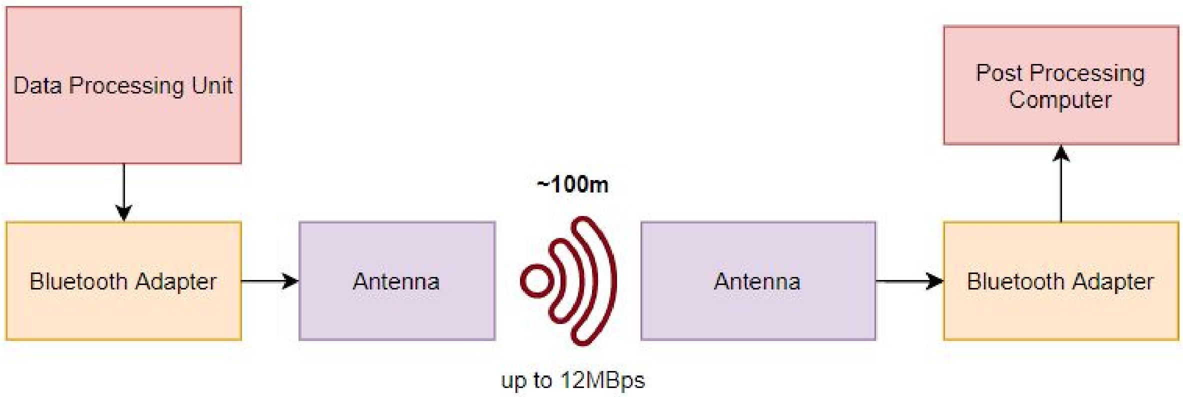

Figure 14: *Data Transfer graph of Bluetooth LE Communication Protocol*

Advantages	Disadvantages
Low Power Usage	Low range ~100m
Avg of 10 MBps transfer rate	Transfers data to hard-drive, no Internet access without data hop
Widely adaptable and ease of use	

Table 26: *Advantages and Disadvantages of Bluetooth LE*

5. Trade Study Process and Results

5.1. LiDAR Trade Study

As a critical project element, the LiDAR system will function as an integral part of the FLASH mission. The decision to trade LiDAR systems originated in ASTRA's open-ended functional requirements for the LiDAR system. They did not recommend a specific LiDAR package and instead preferred the team perform a trade on various COTS LiDAR systems. The purpose of this trade was to determine how well each system met the given functional requirements, and to minimize cost. The LiDAR system will likely be the most expensive component within the team's scope, so ensuring the resulting LiDAR system is cost effective is critical. ASTRA has tentatively agreed to purchase the chosen LiDAR system, so much of the weighting originally on cost has been dispersed to other evaluation criteria. All these criteria are explained in greater detail below.

5.1.1. Evaluation Criteria & Weight Assignment Methodology

5.1.1.1. Accuracy

Accuracy pertains to the precision of each LiDAR point measurement (offset from a real-world, known position data point). A requirement the LiDAR must meet calls for +/- 5 cm accuracy.

A weight of 7.5% was given to this criterion. Both accuracy and range are viewed as critical performance metrics of the system, and are both linked to functional requirements given by ASTRA. This criterion is not weighted higher because accuracy and range have been noted as less important than SLAM implementation/mapping capability. This observation was made in a client meeting regarding the team's shift in focus to localization and mapping.

5.1.1.2. Range

Range pertains to the farthest distance the LiDAR can sense without breaching its accuracy specification. The requirement for range detailed that the chosen LiDAR shall have a range of no less than 50 m.

A weight of 7.5% was given to range, same as accuracy. In ASTRA's opinion, range and accuracy have similar levels of importance to the system. Most of the LiDAR options considered had consistent, proportional accuracy and range specifications, meaning if a system had high range, it also had high accuracy. Same applies to sensors with low range, corresponding to lower accuracies.

5.1.1.3. Field of View (Horizontal and Vertical)

Horizontal field of view (FOV) corresponds to the rotation angle about the LiDAR's vertical axis in which it can detect objects. Vertical FOV corresponds to the angular range above/below the LiDAR's horizontal plane which it can detect objects. Angular FOV ranges are independent of LiDAR orientation. The angular locations which the LiDAR can see relative to the inertial horizontal plane are dependent on the LiDAR's orientation relative to inertial space. Modifying the sensor's orientation will allow the team to determine what objects the LiDAR can detect.

A weight of 30% was given to FOV specifications. This criterion received the highest weighting of all evaluation criteria considered. Most of the LiDAR systems under consideration maintain a 360 degree horizontal FOV, which is desired, but most maintain a limited vertical FOV. This would be satisfactory for mapping a street or horizontal landscape, but since the infrastructure the team is considering will be in both the vertical and horizontal directions (above and around the car), it is desired that FOV is maximized. A limited vertical FOV could compromise the primary mission objective, so the team decided it was imperative that FOV was weighted heavily in the trade.

5.1.1.4. Cost

Given a project budget of $5,000, cost was a prominent evaluation criterion, especially given the high cost of most LiDAR systems. ASTRA has tentatively agreed to purchase the team's LiDAR system (under the assumption that ASTRA maintains ownership of the LiDAR after completion of the project). This generosity has allowed the team to consider design options that the $5,000 budget would not allow. Since the cost of each LiDAR design choice is significant, the team decided to use cost as an evaluator.

Cost was weighted at 20%. This relatively high rating stemmed from the purchasing uncertainty at the time of the trade. While ASTRA has verbally committed to paying for the LiDAR system, there was the chance that the team would have to purchase it with the limited $5,000 budget. If this was the case, cost would be a significant determinant of system selection. Even if ASTRA does purchase the LiDAR system, the team is attempting to minimize cost for their economic benefit.

5.1.1.5. Data Output

Data output refers to the point cloud points per second (pps) generated by each LiDAR system. The more pps, the more complete the finished 3D model will be. Since this data will need to be post-processed, design options were considered for SLAM compatibility. Some COTS LiDAR systems release the entirety of the raw captured data, whereas others release already post-processed data for ease of SLAM algorithm use. While post-processing the raw data would be interesting for the team, it is more cost effective to have a LiDAR system which completes this autonomously.

Data output was weighted at 20%. To ensure a quantitative basis for this evaluation, LiDAR systems were ranked primarily on their pps output. A higher data output corresponds to more points utilized in the point cloud generation. This is more suitable for the application of SLAM. Therefore, SLAM integration is also being indirectly evaluated by this criterion. SLAM integration was not included as its own evaluation criterion because the team found no effective way to quantify each LiDAR's integration ability. Because of this, SLAM integration is included here.

5.1.1.6. Platform Integration

Platform integration consists of three separate embedded evaluation criteria, one quantitative and two qualitative. Each LiDAR system was analyzed given its physical dimensions. The generic shape of each LiDAR was the same, a puck with height similar to its circular diameter. The qualitative criteria were availability of COTS mechanical mounting hardware (for each LiDAR system specifically), and ease of mechanical installation (with the existing mechanical structure). Mounting hardware was either included (with varying degrees of effectiveness) or not, and ease of mechanical installation was evaluated based on customer testimonials.

A weight of 5% was given to platform integration. This relatively low rating is the result of many similarities in LiDAR design options. While each system does have its own dimensions, they are similar enough to the point where any one could be reasonably integrated with the mechanical mounting structure. Only some design options included mounting hardware, but those that did not include mounting hardware have the capability to interface with the mount, although it would require more design work. All design options were considered relatively simple to install. Rather than have a large influence on the trade, this criterion was downsized in importance, due to the similarity of the design options in this regard. The team decided platform integration was still relatively important for mission success, so it was included as a trade criterion.

5.1.1.7. Mass

The mass requirement given by ASTRA constrains the LiDAR system to a maximum mass of 5 lbs (2.27 kg). Mass, in this context, refers to the mass of the LiDAR sensor with no cables or power banks. The mass of these items will be considered with Structures, along with any other mounting/interfacing materials.

A weight of 5% was given to mass. This weight is relatively low due to the fact most LiDAR systems have similar masses (at least the key design options considered) and none that could pose a substantial threat to mechanical integration. Since mass is detailed in a functional requirement, it was decided that it should be treated as an evaluation criterion anyway, just with limited weighted influence.

5.1.1.8. Power Requirement

The power requirement given by ASTRA constrains the LiDAR system to a maximum power of 20 W. The different LiDAR design options were traded solely on their power requirement, without consideration to how the LiDAR will receive that power. The power subsystem is tentatively powered via the vehicle's power system (most vehicle phone charging ports output a maximum of 24 W).

A weight of 5% was given to the power requirement. This criterion also received a relatively low weight for reasons similar to the mass criterion. Namely, all LiDAR design options required similar power levels, and none of which could require too much power for the system to handle. ASTRA did outline power as a functional requirement, so scores were based on compliance to that design point (<20W).

5.1.2. Design Option Scoring

Table [27] below outlines how each design option was scored for each evaluation criterion. When a design option was placed in the 1-2 or 4-5 range, it was up to the team's discretion whether the design option received a higher or lower score. The judgement was based on the relative specifications of each design option, so if two options were in the 4-5 range, the more desirable one received a score of 5 while the other received a score of 4. This decision making process applies to all proceeding trades.

Evaluation Criteria	1-2	3	4-5
Accuracy	Accuracy > +/- 4 cm	+/- 4 cm ≥ Accuracy > +/- 3 cm	+/- 3 cm ≥ Accuracy
Range	Range ≤ 60 m	60 m < Range < 100 m	Range ≥ 100 m
Field of View	Horizontal: < 360°	Horizontal: 360° Vertical: 20° < FOV ≤ 30°	Horizontal: 360° Vertical: > 30°
Cost	Cost ≥ $6,000	$6,000 > Cost ≥ $4,000	Cost < $4,000
Data Output	Output < 200,000 pps	Output ≥ 200,000 pps **and** no mention of SLAM integration	Output ≥ 200,000 pps **and** mention of SLAM integration
Platform Integration	Volume ≥ 2500 cm^3	Volume < 2500 cm^3 **and** no existing mechanical mounting infrastructure	Volume < 2500 cm^3 **and** existing mechanical mounting infrastructure
Mass	Mass > 1 kg	1 kg ≥ Mass > 0.5 kg	Mass ≤ 0.5 kg
Power Requirement	Power > 17 W	17 W ≥ Power > 13 W	Power ≤ 13 W

Table 27: *Design option scoring criteria for LiDAR Sensors*

5.1.3. Trade Study Results & Analysis

		Velodyne Puck Hi-Res	Ouster OS0-32	Ouster OS1-16 (Gen 1)	SICK MRS1000	Livox Mid-100	Velodyne Puck
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**	**Score**	**Score**
Accuracy	7.5%	4	3	2	1	5	4
Range	7.5%	4	1	2	3	5	4
Field of View	30%	3	5	4	2	1	3
Cost	20%	1	2	4	3	5	3
Data Output	20%	3	5	4	2	3	3
Platform Integration	5%	4	3	3	5	3	4
Mass	5%	3	4	5	2	1	3
Power	5%	5	3	3	4	1	5
Total	100%	2.9	**3.7**	3.65	2.45	2.9	3.3

Table 28: *Trade Study of LiDAR Sensors*

5.2 Inertial Navigation System

If our LiDAR system is not to have in-built localization capabilities, then a capable INS unit will be a critical addition to FLASH. This system is composed of several sub-components from which we could also consider building up a system from, but for the sake of this trade study we have selected systems specifically focused on integrating IMU and GPS capabilities. These units also come with a number of additional features which were not as critical of considerations as the IMU or GPS, including altimeters, compasses, and more.

5.2.1. Evaluation Criteria & Weight Assignment Methodology

5.2.1.1. IMU Performance

IMU performance pertains to the precision of the accelerometers and gyroscopes within the IMU subsystem. A requirement the localization system calls for +/- 5 cm positional accuracy and less than 2°/hr heading bias instability. It should be noted that often these specifications are given in separate measurements for real-time and post-processing capabilities that holistically take into account the other sensor data, or use advanced ranging techniques such as RTK with GNSS.

A weight of 25% was given to this criterion. Both accuracy and range are viewed as critical performance metrics of the system, and are both linked to functional requirements given by ASTRA.

5.2.1.2. GNSS Performance and Compatibility

GNSS performance pertains to the precision, TTFF, and any additional RTK or similar features. The GPS system as given by the design requirements is to have an accuracy of within 0.05 centimeters after post-processing techniques are applied. This criterion is a holistic consideration which will take into account several factors about the GNSS system, including supported constellations, single vs. dual-band, and compatibility with A-GPS, RTK, and other advanced processing techniques.

A weight of 25% was given to this criterion. ASTRA emphasized how they would prefer to not have to be totally reliant on GNSS coverage, however in order to perform adequate localization at our desired speeds (as well as any geo-tagging of scan sites performed) this will be of critical importance, even when designing around our requirement of outages as long as 30 seconds.

5.2.1.3. Additional Sensors

This criterion pertains to any localization sensors that are not IMU or GNSS-based. The exact lineup varies depending on system, but can include altimeters, compasses, thermometers, color cameras, or any other system used for direct integration or as redundancy for when other subsystems are unavailable, in particular GNSS.

A weight of 10% was given to the presence of systems outside of the IMU and GNSS. This is in consideration of our relatively short-duration scanning periods, estimated to take place over just 1-2 seconds when passing under a bridge, making the need for redundancy during a single measurement to be quite low, but is of non-negligible importance if they can significantly improve the quality of data outside of redundancy considerations.

5.2.1.4. Cost

Similarly to the discussion of LiDAR units, our mission's budget of just $5,000 means cost was a prominent evaluation criterion, especially given the high cost of most INS systems. Some systems looked at, but not considered for the purposes of the trade study, ran in excess of $30,000, while still having potential downsides when considering longer-duration data collection periods. For the purposes of this trade study, we attempted to only consider units which were under $2,500, though at times this information was difficult to obtain without requesting a quote. The scoring will assume a 1-2 score for systems which cost in excess of $4,000 USD. This is relatively high given our overall budget, however the INS is undoubtedly the second most critical and expensive system in FLASH only to the LiDAR scanner; and considering ASTRA's potential to purchase that on our behalf we will want to commit a significant portion of the remaining budget towards the INS.

Cost was weighted at 20%. For the systems which we are not aware of a cost figure without first asking for a quote, this will be assumed to be ‘1’, as they are all generally high-end systems and will likely be near or over $4,000.

5.2.1.6. Platform Integration

Platform integration consists of three separate embedded evaluation criteria, one quantitative and two qualitative. Each INS was analyzed given its physical dimensions. The generic shape of each INS was similar, small rectangular unit, often with four mounting holes included. Since the output data from the INS will be used to correlate LiDAR data over time, it is critical to have those two subsystems enclosed within the same structure at the very least, preferably with as little physical separation as possible.

A weight of 10% was given to platform integration. While each system does have its own dimensions, they are similar enough to the point where any one could be reasonably integrated with the mechanical mounting structure. The only potential downside are units which require non-standard mounting solutions, but for the purpose of this trade study we chose models with reasonable integration solutions as a baseline requirement.

5.2.1.7. Mass

The mass requirement given by ASTRA constrains the entire system to a maximum mass of 5 lbs (2.27 kg). Mass, in this context, refers to the mass of the INS sensor package with no cables or power banks. The mass of these items will be considered with Structures, along with any other mounting/interfacing materials.

A weight of 5% was given to mass. This weight is relatively low due to the fact that, similarly to the LiDAR sensors, most INS systems have relatively similar and low masses. Since mass is detailed in a functional requirement, it was decided that it should be treated as an evaluation criterion anyway, just with limited weighted influence.

5.2.1.8. Power Requirement

The power requirement given by ASTRA constrains the LiDAR system to a maximum power of 20 W. Similarly to the LiDAR systems, the different INS design options were traded solely on their power requirement, without consideration to how the INS will receive that power. The power subsystem is tentatively powered via the vehicle’s power system (most vehicle phone charging ports output a maximum of 24 W).

A weight of 5% was given to the power requirement. This criterion also received a relatively low weight for reasons similar to the mass criterion. Namely, all INS design options required similarly low power levels, well within our 20W limit.

5.2.2. Design Option Scoring

Table [27] below outlines how each design option was scored for each evaluation criterion.

Evaluation Criteria	1-2	3	4-5
IMU Performance (*with* post-processing)	Accuracy > +/- 4 cm	+/- 4 cm ≥ Accuracy > +/- 3 cm	+/- 3 cm ≥ Accuracy
GNSS Performance	Private constellation, single-band, no additional features (RTK, SBAS, etc)	GPS compatible, single-band, some additional features	Multi-constellation, dual-band, many additional features
Additional Sensors	None	Some additional sensors, for redundancy only	Many additional sensors, for accuracy and redundancy
Cost	Cost ≥ $4,000 or no online quote available	$4,000 > Cost ≥ $2,000	Cost < $2,000
Platform Integration	Custom integration necessary		Existing mechanical mounting infrastructure
Mass	Mass > 0.5 kg	0.5 kg ≥ Mass > 0.25 kg	Mass ≤ 0.25 kg
Power Requirement	Power > 5 W	5 W ≥ Power > 1 W	Power ≤ 1 W

Table 29: *Design option scoring criteria for LiDAR Sensors*

5.2.3. Trade Study Results & Analysis

		Advanced Navigation SPATIAL	Vectornav 200	Vectornav 300	Trimble BD992-INS	Gladiator Tech Landmark 60
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**	**Score**
IMU Performance	25%	5	4	4	4	5
GNSS Performance	25%	4	3	5	3	4
Additional Sensors	10%	5	4	4	4	4
Cost	20%	3	1	1	5	1
Platform Integration	10%	4	4	4	4	5
Mass	5%	5	5	5	5	4
Power	5%	4	4	4	5	3
Total	100%	**4.2**	3.2	3.7	4.05	3.7

Table 30: *Trade Study of LiDAR Sensors*

5.3 Data Processing Software Trade Study

Data processing software is another key project element that will play an integral role in the success of FLASH. The rationale for trading data processing systems is twofold. First, the primary deliverable specified by the project customer, ASTRA, is a 3D map of infrastructure, so thoughtfully executed data processing will be required to produce this deliverable. Second, processing of point cloud and localization data is a project requirement (as denoted by **FR 7**), so careful consideration of the key software design options is necessary before a decision can be made. There are a number of options available for point cloud processing, each with their own functions and capabilities as outlined in Section 4. The purpose of this trade is to determine how much value each software option brings to the table, especially considering the scope and time constraints of this project.

5.3.1 Evaluation Criteria & Weight Assignment Methodology:

5.3.1.1 Cost

This criterion evaluates the financial burden of acquiring and utilizing each software package. Since this project has a limited budget of $5000, cost is an important consideration and it must be factored in when comparing software systems. A scoring weight of 35% was assigned to cost to account for budgetary constraints. In order to satisfy all functional requirements, the budget will need to be dispersed across multiple subsystems, so minimizing the price of software is crucial.

5.3.1.2 Breadth of Tools/Capabilities

This criterion evaluates the extent of tools and capabilities provided by each software package in terms of point cloud processing and visualization. This criterion also takes into account useful features and unique functionality offered by each software, specifically in regards to the needs of this project. A scoring weight of 25% was assigned here because satisfaction of **FR 7** depends upon how robust the selected software package is. A less versatile and less robust software suite will hinder the quality of the final deliverable.

5.3.1.3 Compatibility

This criterion assesses how compatible each software package is with different import/export file types. There are quite a few file formats for point cloud storage, including but not limited to OBJ, PLY, XYZ, E57, and LAS. There is no “standard” point cloud file format, so the ability to work with multiple file types is an important characteristic of any given software. Compatibility was assigned a scoring weight of 20% to reflect this need for flexible interfacing -- there is no guarantee that the selected LiDAR sensor package will output point cloud data in a form accepted by a certain software program, so care must be taken to ensure seamless integration.

5.3.1.4 User Engagement/Ease of Use

This criterion evaluates how much user involvement/engagement is required for operation of each software package. Difficulty of use is also assessed here, since less intuitive software suites will call for more time and effort dedicated to learning. Considering the FLASH CONOPS, the time between LiDAR field data collection and 3D map/model delivery should ideally be minimal. As such, this criterion was assigned a scoring weight of 20% -- the more user-friendly and the more automated a software package is, the less time required for post-processing.

5.3.2 Design Option Scoring

Table [31] below outlines how each software option was scored with respect to the evaluation criteria. Cost was judged in terms of annual subscription price, with a low score indicating expensive (>$500) and a high score indicating free. Breadth of tools/capabilities was a primarily qualitative criterion, with a low score indicating limited functionality and a high score indicating substantial/comprehensive functionality. The scoring for compatibility was split up based on the amount of file formats accepted for input (point clouds) and output (3D map/model). Finally, the scoring for user engagement was categorized based on the expected learning curve and “hands-on” work required for effective utilization of each software suite.

Evaluation Criteria	1-2	3	4-5
Cost	Annual subscription price > $500	Annual subscription price < $500	Free and/or available through CU Boulder
Breadth of Tools/Capabilities	Has very limited point cloud processing functionality	Has some desired point cloud processing functionality	Has most/all desired point cloud processing functionality
Compatibility	Supports only a few limited point cloud or LiDAR data formats	Supports some point cloud or LiDAR data formats	Supports most/all point cloud or LiDAR data formats
User Engagement/Ease of Use	Requires heavy user engagement and/or steep learning curve	Requires some user engagement and/or moderate learning curve	Requires minimal user engagement and/or minimal learning curve

Table 31: *Design option scoring criteria for Data Processing Softwares*

5.3.3 Trade Study Results & Analysis

Table [32] below presents the results of the data processing software trade study conducted in terms of weighted scoring and the evaluation criteria described previously. Relative scores were determined through research and comparison of systems. Based on these results, the selection of a baseline software design is explained in Section 6.

		PointFuse	ArcGIS	CloudCompare	AutoDesk	TerraSolid	MATLAB
CRITERIA	**WEIGHT**	**Score**	**Score**	**Score**	**Score**	**Score**	**Score**
Cost	35%	1	4	5	3	2	4
Tools/Capabilities	25%	3	2	4	5	4	3
Compatibility	20%	4	2	5	3	1	2
User Engagement, Ease of Use	20%	5	2	3	4	3	1
Total	100%	2.9	2.7	**4.35**	3.7	2.5	2.75

Table 32: *Trade study of Data Processing Softwares*

5.4. Mounting Structure Trade Study

The three mounting structure design options were traded to determine the optimal attachment method to the mission vehicle. The evaluation criteria were decided upon in regards to the functional and design requirements as well as mission operation concepts such as driving speed (and associated drag on the structure), structural stability, and ease of attachment/detachment for the vehicle driver. These criteria were weighted as discussed below.

5.4.1. Evaluation Criteria & Weight Assignment Methodology:

5.4.1.1. Ease of Attach/Detach

This criteria measures the success of the system attaching and detaching from any vehicle. It is adverse to have a mounting mechanism requiring a permanent attachment since this will increase the cost of implementing the system. Furthermore, the qualitative gauge of how simple the mechanism is to attach is included in this measure. A weight of 30% is given to this criteria, since it is a key design goal of the structures team.

5.4.1.2. Stability Risk

This is a qualitative criteria assessed by the structures team pertaining to how stable the proposed mounting mechanism shall be when in certain driving scenarios (i.e. sharp turns, collisions, going down hills, etc). Stability pertains to the FLASH system staying securely attached to the vehicle during the entire mission operation. A weight of 25% is given to the stability risk criteria. It is pertinent the system stays on the vehicle for the entire time, otherwise a mission failure will occur.

5.4.1.3. Mass

This refers to the mass of any platform/mounting components and hardware used to secure the system to the vehicle. Ideally this will be as low as possible so that heavier LiDAR systems can be considered while still meeting the design requirement (DR 5.1) for the LiDAR system mass of 5 pounds or less. The mass criteria is given a weight of 20%, since it is not entirely pertinent the system weight be conserved.

5.4.1.4. Cost

This describes the funds taken from the budget in order to construct the mounting system. Acquiring a LiDAR sensor within our budget that will achieve our requirements will not be easy. Therefore, the cost of the less sophisticated components such as the mounting system will be weighted in order to save room in the budget for higher level components.The cost of the proposed mounting mechanism is weighted at 10%, since most options considered were relatively low-cost. The cost compounds when multiple mounts need to be purchased.

5.4.1.5 Manufacturability

Manufacturability refers to how complicated the construction of each mounting mechanism would be. It is a qualitative measure, gauged by the instruction manual and required number of parts of each mounting method. This criteria is given a weight of 10% as well, since time constraints for manufacturing are not as important as mission success or failure.

5.4.1.6. Size

Finally, the size criteria designates how large the actual mounting system shall be. Ideally, a mounting mechanism should take up as little volume as possible to conserve space. This criteria has the lowest weight at 5%. The reason being is that this is not a requirement designated by the team or ASTRA.

5.4.2. Design Option Scoring

Evaluation Criteria	1-2	3	4-5
Ease of Attach\Detach	Cannot be detached	> 10 min to attach	< 10 min to attach
Stability Risk	Unstable	Risk of instability	Maximum stability
Mass	> 10 lb.	< 10 lb.	< 5 lb.
Cost	> $500	< $500	< $200
Mechanical Complexity	Complicated construction	Able to construct	Minimal construction required
Size	> 10,000 ccm.	> 1,000 ccm.	< 1,000 ccm.

Table 33: *Design option scoring criteria of Mounting Structure*

5.4.3 Trade Study Results and Analysis

		Fixed Attachment	Magnetic Attachment	Clamping Attachment
Criteria	**Weight**	**Score**	**Score**	**Score**
Ease of Attach/Detach	30%	2	5	4
Stability Risk	25%	5	3	4
Mass	20%	1	5	3
Cost	10%	1	5	4
Manufacturability	10%	2	5	4
Size	5%	2	5	2
Total	100%	2.45	**4.5**	3.7

Table 34: *Trade study of Mounting Structure*

5.5. Communication Protocol Trade Study

Three communication protocols were traded with criteria based on **FR 8, DR 8.1 and DR 8.2**. These requirements placed constraints on data rate, range and hardware weight. A few other criteria were added based on the added functionality and budgetary constraints (both power and cost). ***Figure 15*** shows how communication protocols are compared primarily based on data rate and range. It was also vital to the group to choose protocols which are widely adopted as it enables various highly optimized COTS products to be used for transmission.

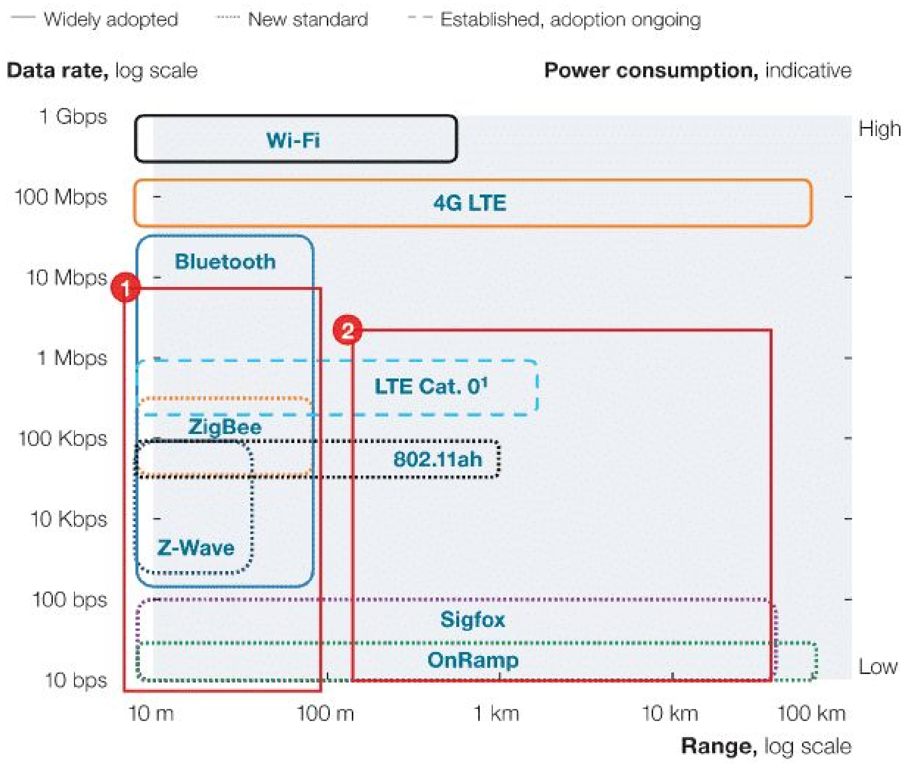

Figure 15: *Data rate vs. Range graph of different established communication protocols [18]*

5.5.1. Evaluation Criteria & Weight Assignment Methodology

5.5.1.1. Data Rate

Data rate pertains to the minimum amount of data in Mbps the communication system can reliably transmit. The LiDAR sensor will be creating large data files from each structure scan and in order to save time on sending this large amount of data, the data upload rate must be a minimum of 8 Mbps. A weight of 30% is assigned to this criteria. A functional requirement is that the point cloud and localization data shall be consolidated and post-processed into an interactive digital 3D map/model that can be used by the customer to identify structural faults. In order for this to occur the point cloud data captured by the LiDAR system must be transferred from the onboard storage to an off-board receiver (could be to the internet, or another computer). Without a sufficient data rate the data may never be transferred or take an unreasonable amount of time resulting in mission failure. The sensor suite is predicted to create about 1 Gb per minute of data collection. Assuming a 2 minute scan, a file size of 2GB will be created. Using a 8 Mbps data rate, this will take about 4 hours to transfer a which the team thinks is a reasonable upload time. Hence for every protocol discussed, the team will take the average transfer rate to calculate the values of this criteria in the trade study.

5.5.1.2. Range

Range pertains to the maximum distance the vehicle can be from its wireless connection without compromising its data transmission rate. The requirement for range detailed that the chosen communication protocol shall have a range no less than 70m. A weight of 10% was given to range as it is a negotiable requirement. The primary purpose of this criteria is that upon the success of this design, multiple cars are able to be in a single garage and start transferring their data to a local/online server. This requires an approximate range of 70m. Range extension techniques can also be used, (for example a wifi extender for larger availability radius) but this compromises data transfer rate. Hence the team will compare the average ranges of typical commercial off the shelf (COTS), antenna-transceiver systems to put values in the trade study.

5.5.1.3. Hardware Constraints

Wireless communication required a transceiver chip, an impedance matching circuit and an antenna. The latter two have to be tuned specifically to the transceiver chip. Often these chips require high loads of power to modulate and demodulate data. Given a system weight of 5Lbs, appropriate hardware is to be chosen to meet functional requirements. Since hardware constraints is a critical portion of the system's design, a weight of 35% is assigned to this criteria. The hardware available should be small and light in size to allow for more of the weight percentage to go towards the sensors and data processing unit. The team will compare average total weight produced by the typical COTS sensors to fill in the values to the trade study.

5.5.1.4. Power

The power requirement given by ASTRA constrains the entire system to a maximum power of 20 W. By the time the data is ready to be transferred for the purposes of post processing the LiDAR won't be in operation. That leaves 20 W that can be allocated for the purposes of data transmission only. The systems involved in this would be the onboard processing unit that will read data from a hard drive, convert it to a transmittable data format, and send it to the transceiver. This transceiver will modulate the data onto RF signals and send the data to the antenna. If the antenna is perfectly matched, all the power sent will be transmitted. The power used will be proportional to the range and transfer rate. A weight of 5% is assigned to this criteria given that the communication protocol options can be up to 20 W which would be sufficient. That is to say that the data transmission is the only system operating at the time. Scores for criteria were assigned based on compliance with ASTRA's requirement of < 20 W. To find the power requirement, the team calculates the power taken by just the transceiver to match the data rate and range found in the previous criteria of the trade. This is used to find an appropriate value for the trade study.

5.5.1.5. Cost

The cost requirement pertains to the cost of implementation in the realm of hardware and service provider cost. The service provider cost is typically charged monthly, whereas the physical adapter is a one time purchase. Moreover the cost increases as the data requirement of the mission increases. The LiDAR sensor alone on average produces 2GB of data per 2 minutes of scanning and this will demand high data usage and will take a significant portion of our budget to upload data. A weight of 10% is given to this criteria. To find quantitative values, the team adds up the hardware implementation cost (transceivers, antennas and routers) along with monthly expenditure on ISPs (~ 60-80$ p/m for wifi, 80$ p/m for 4G LTE 22Gb plans, etc.) to get a total testing and implementation cost from December 2020 - May 2021 (6 months).

5.5.1.6 Internet Accessibility

Though not a functional requirement for the data to be uploaded onto an online database, the team finds that this feature will significantly increase data availability of the system. The team will be able to test the data redundantly on different systems using different algorithms and cleaning filters simultaneously without the need of continually copying into a personal hard drive. This feature would enable the customer to look at the raw data for any method of verification and initial removal of unneeded data before the team processes it. Because of this added functionality, a weight of 10% is added to internet accessible protocols.

5.5.2. Design Option Scoring

Evaluation Criteria	1-2	3	4-5
Range	under 50m	under 70m	above 70m
Data Rate	< 5Mbps	< 10 MBps	> 10MBps
Hardware Constraints	avg. weight > 1lb	0.5lb < avg. weight < 1lb	avg. weight < 0.5Lb
Power	<10W transmit power	<5W transmit power	< 1W transmit power
Internet Accessibility	No internet access	-	Internet accessible
Cost	total cost above $1000	total cost below $1000	total cost below $700

Table 35: *Design option scoring criteria for Communication Protocols*

5.5.3 Trade Study Results and Analysis

		Wi-Fi	4G LTE	Bluetooth LE
Criteria	**Weight**	**Score**	**Score**	**Score**
Range	10 %	5	5	5
Data Rate	30 %	5	5	4
Hardware constraints	35 %	3	3	3
Power	5 %	3	3	5
Cost	10 %	3	1	5
Internet Accessibility	10 %	5	5	1
Total	100%	**4**	3.8	3.6

Table 36: *Trade Study of Communication Protocols*

6. Selection of Baseline Design

After numerous hours of research the team has traded many different ideas and concepts to address the task that this project has presented. The results of these trade studies are shown in the tables above but a synthesis of these trade studies and a description of what each means moving forward with the project continues below.

6.1 LiDAR System

Table [28] gives the individual scoring for each design option as well as their combined weighted scores. As seen in the bottom row, the **Ouster OS0-32** has been deemed the most viable LiDAR system given the evaluation criteria. This system was followed closely by its relative **Ouster OS1-16 (Gen 1)**. Beyond the two Ouster products, the two Velodyne products scored relatively high, and the Livox Mid-100 and SICK MRS1000 rounded out the least desirable products. These results are consistent with ASTRA's understanding (and each company's engineering reputation) of the two most sought after companies, Ouster and Velodyne.

The primary determinants between the two Ouster products were FOV, data output, and cost. While both systems maintain 360 deg of horizontal FOV, the OS0-32 has an extra-wide vertical FOV of 90 deg, whereas the OS1-16 only has 33 deg in the vertical. The OS0-32, with its 32 channels, can output 655,360 pps of data, whereas the OS1-16, limited to 16 channels, can only output 327,680 pps of data. Both Ouster products mentioned that their LiDAR systems have built-in functionality and data formatting for easier SLAM implementation (as noted on their website and product descriptions). The only criterion which the OS1-16 performed better was cost, coming in at $3,500, versus the OS0-32s $6,000.

The cost of these systems would have previously eliminated them as viable options given the team's $5,000 budget (the team did not want to spend 70% of their budget on one component in regards to the OS1-16). However, given ASTRA's generosity in purchasing this system for us, cost has become a much less significant factor. After discussing procurement options with ASTRA, they have decided to loan a LiDAR system to the team, with the condition that the system costs somewhere between $2,000 and $5,000. This price range effectively eliminates the team's top choice of the OS0-32 system. Given this non-negotiable constraint, the team can only consider LiDAR systems that cost less than $5,000. The OS1-16 has the benefit of not only being in this price range, but it is directly available from the manufacturer, Ouster, at $3,500. This eliminates the risk of finding the OS1-16 from an online retailer, with potential variations in price.

The results of the trade remain the same, however, given ASTRA's purchasing constraint, the OSO-32 is no longer a viable option. Rather than redo the trade to reflect this, the team has made the decision of going with the best, most feasible LiDAR system. Given this analysis, the **Ouster OS1-16 (Gen 1)** has been selected as the FLASH mission baseline design LiDAR component. This component meets all functional and design requirements. Its specifications are given in ***Table [37]*** below:

Criteria	Specifications
Accuracy/Performance	5 cm
Range	60 m
Field of View (FOV)	360° H, 33° V
Cost	$3,500
Data Output	327,680 pps
Physical Dimensions	85x85x73.5 mm
Weight	0.425 kg
Power Consumption	17 W

Table 37: *Specifications of OS1-16*

6.2. INS

Table [30] gives the individual scoring for each design option as well as their combined weighted scores for the traded INS systems. As seen in the bottom row, the **Advanced Navigation SPATIAL** was selected as the standalone INS unit of choice for FLASH, provided we do not get a LiDAR system with built-in localization functionality. The critical point that won this system over other high-performance MEMS INS systems was the very high performance while still having a reasonable cost and very small form factor. It should be noted that the cost of some of the units could not be obtained, and were thus assumed to be near or over $4,000 for the purposes of the trade study (thus granting them a '1' score), though in the absence of a price quote this assumption was reasonable compared to units with similar specifications. This unit still comes with a considerable cost of $3,126 USD, however this can hopefully be justified if our LiDAR cost is offset by ASTRA (and does *not* contain its own localization system), as localization is undoubtedly the second-most critical and costly component if FLASH is to meet the given design requirements.

Each system considered was well-equipped with additional sensors beyond just IMUs and GNSS receivers, all including compasses (controlled by electronic magnetometers) for increased heading accuracy. Some units included other sensors such as barometric altimeters for the Gladiator Technologies Landmark 60 GPS/INS and the Vectornav 200 and 300, and a variety of other components primarily for the purposes of redundancy rather than improving localization, or for use cases where such extraneous information may be desired. Considering this, these were less important compared to the IMU and GNSS criteria. The SPATIAL included a battery backup in the case of unreliable power supply to ensure up to 60 seconds of continuous operation in the case of brownout, which is useful for our purposes when acquiring our power from the vehicle itself, which is powering many other components and could be a potentially unreliable source.

A viable alternative to the SPATIAL that is significantly lower cost is the Trimble BD992-INS, and was only narrowly beaten out in the trade study. This unit has a notable downgrade in performance and integrated features, but still offers capable specifications when paired with certain post-processing techniques, of which we are planning on employing regardless.

The specifications of the selected system, the **Advanced Navigation SPATIAL**, can be found below in ***Table [38]***:

Criteria	Specifications
IMU Performance	0.02 m (with post-processing)
GNSS Performance	72-channel GPS. RTK, SBAS, A-GPS ready
Additional Sensors	Magnetometers
Cost	$3,126
Platform Integration	Standardized screw-mount included
Mass	37 g
Power	0.5 W (includes battery backup)

Table 38: *Specifications of Advanced Navigation SPATIAL*

6.3 Data Processing

Table [32] gives the individual scoring for each data processing software package considered, as well as their weighted scores. Based on those results, **CloudCompare** was selected as the 3D point cloud data processing software baseline for the FLASH system. CloudCompare received the highest score in two categories (cost and compatibility) and the second-highest score in one category (breadth of tools/capabilities). The AutoDesk family of tools was determined to be the second-most desirable option, while TerraSolid was determined to be the least desirable option. CloudCompare "won" the trade by a decent margin, especially because it received a score of 5 in the cost criterion (weighted 35%). Although PointFuse was determined to be less user-intensive and less difficult to use, CloudCompare outperformed in more important criteria. PointFuse was found to be far too expensive considering the budget of this project. Additionally, even though the AutoDesk software package was determined to have a slight edge in terms of capabilities, CloudCompare offered more than enough functionality as well.

What distinguishes CloudCompare from the software alternatives is its free, open-source nature and its specialized focus. Unlike ArcGIS and MATLAB, CloudCompare was strictly designed for 3D point cloud processing. Hence, it is geared more towards the objectives of this project, where accurate processing of the LiDAR data will be critical (see **FR 7**). It is important to note, however, that MATLAB and ArcGIS will still most likely be used during the design process for supplementary analysis (through CU Boulder licenses). The project customers (ASTRA) indicated that they have used CloudCompare in the past, so their existing experience with the software is simply an added benefit (this factor was not taken into account in the trade study scoring). Other advantages of CloudCompare that make it the best candidate include its extensive documentation, its active user base with helpful online forums, its regular updates, and its comprehensive GitHub repository. ***Table [39]*** below summarizes CloudCompare's key specifications.

Criteria	Specifications
Cost	$0 (open source)
Primary Tools/Capabilities	● Point cloud registration ● Distance computation ● Segmentation ● Geometric feature estimation ● Point cloud meshing and visualization
File Compatibility	BIN, ASCII, PLY, OBJ, STL, E57, LAS/LAZ, VTK, PCD, FBX, SHP, OFF, PTX, DXF, FARO, and more
User Interface	Clean graphical interface based on Qt and OpenGL

Table 39: *Specifications of CloudCompare*

6.4 Mounting Structure

Table [34] gives the individual scoring for each mounting structure traded, as well as their weighted scores. The **50 LB Holding Power 2.4" Cup Magnets** attachment mechanism from CMS MAGNETICS is the selected mounting structure for the FLASH system. It had perfect scores in every area besides the stability risk, which was a qualitative gauged criteria. The product description indicates it also works with car top signs, which was indicative of this mechanism's integrity for a very similar process to the current mission. The permanent roof rack attachment was too costly, too difficult to manufacture, too large, and would not have reached the highest level of success of being attachable and detachable. The clamped roof rack was also too costly, and too large. Cost was a key consideration in the mounting structure determination since the most expensive components require most of the budget in this project.

The **Cup Magnets** attachment mechanism costs $14.15 total (for five magnets [16]), and can hold a maximum of 22.7 kg (50 lb.), which is well under the system required weight. The magnets themselves weigh 0.52 kg (1.15 lb.) total, and occupy 720 cubic centimeters. Though there was a determined risk of instability, anecdotal product reviews show no signs that the magnetic attachment was unstable while driving. The group is confident in moving forward with this selection as the mounting structure. A summary of this mechanism's specifications are given in ***Table [40]*** below:

Criteria	Specifications
Ease of Attach/Detach	< 10 min to attach (est.)
Stability Risk	Slight risk of instability
Mass	0.52 kg
Cost	$14.15 (per 5 magnets)
Mechanical Complexity	Minimal construction required
Size	720 ccm.
Carrying Capacity	22.7 kg

Table 40: *Specifications of Cup Magnets*

6.5 Communication

Table [36] gives the individual scoring for each communication protocol traded as well as their weighted scores. The **Wi-Fi IEEE 802.11 family of networks** is the method that will be implemented as the data transmission method for the FLASH system. This communication protocol had perfect scores in range, data rate and internet capabilities. Given the high data upload rate and reliability of Wi-Fi, a large amount of data can be easily uploaded to a server via the internet directly and accessed anywhere for post processing. In the event of a multiple vehicle fleet, only one internet service provider subscription is needed for multiple vehicles to upload which keeps costs down. The vehicle in question will need somewhere to be stored while not in use which provides an opportunity for a homebase where a Wi-Fi connection can be established and the data can be uploaded. Wi-Fi connection also had a sufficient range given the functional requirement of 70 m. Wi-Fi systems can also implement range extenders and routers can be placed at distances far away from the modem. Power nor weight infringed on the FLASH system given the requirements of 20 W and 5 lbs. It is important that the data collected by the FLASH system be transferred to another location for post processing and implementing the Wi-Fi protocol will achieve this wirelessly, efficiently and reliably. A summary of the WiFi protocol is given in ***Table [41]*** below:

Criteria	Specifications
Range	above 70m
Data Rate	> 10MBps
Hardware constraints	avg.wight b/w 0.5lb and 1lb
Power	<5W transmit power
Cost	total cost below $700
Internet Accessibility	Internet accessible

Table 41: *Specifications of WiFi Communication Protocol*

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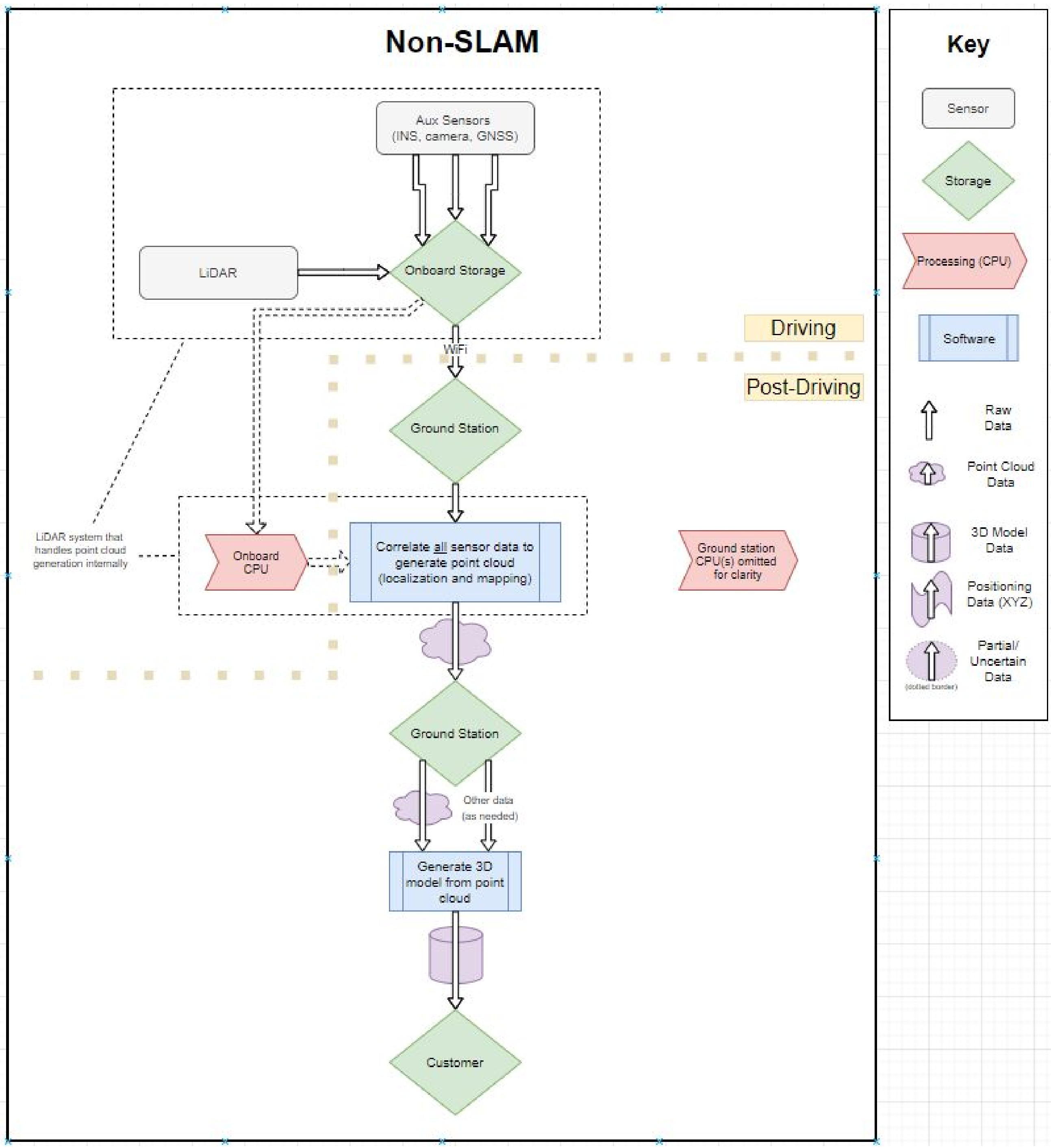
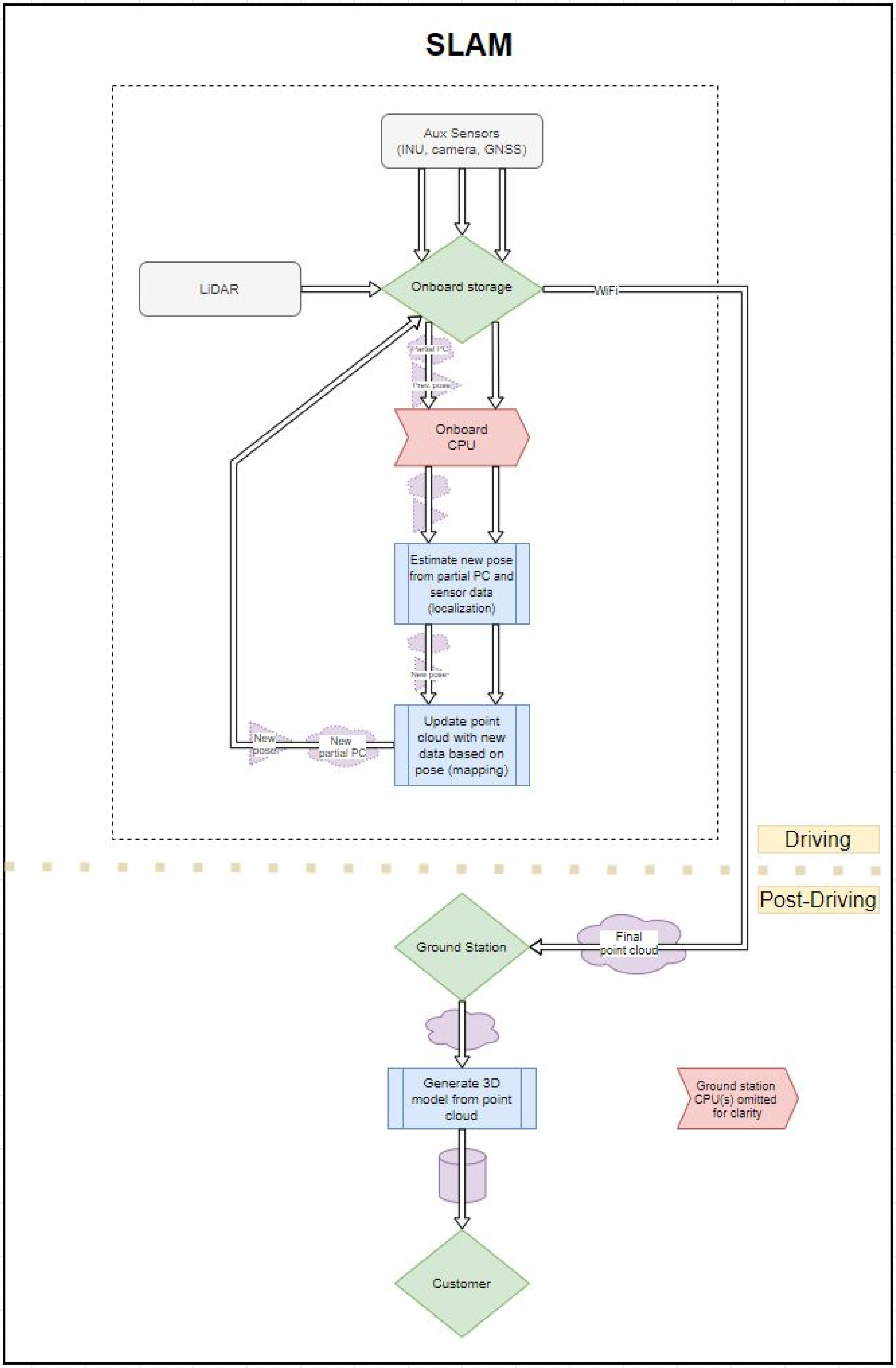
Appendix

SLAM Additional Information

Simultaneous localization and mapping (SLAM) is the computational problem of continuously constructing and updating a map while inferring the location of the sensor/vehicle within that map. SLAM is an inherently dynamic and challenging problem and there exist a multitude of solution approaches. These general algorithms can be tailored to serve various applications; however, they differ in their consistency, accuracy, computational complexity, and so on. Although full implementation of SLAM is outside the scope of this project’s requirements, the customer has expressed interest in the application of SLAM. If it was within the scope of this project, SLAM would be implemented on 3D spatial data collected by the vehicle-mounted LiDAR sensor, in conjunction with positional data collected by an inertial navigation device. This data would be simultaneously processed in real-time to generate a map, hence serving as an input into a navigation system.

A comparison of non-SLAM processing vs. SLAM processing:


Non-SLAM
Aux Sensors (INS, camera, GNSS)
LiDAR
Onboard Storage
WiFi
Driving
Post-Driving
Ground Station
LiDAR system that handles point cloud generation internally
Onboard CPU
Correlate all sensor data to generate point cloud (localization and mapping)
Ground station CPU(s) omitted for clarity
Ground Station
Other data (as needed)
Generate 3D model from point cloud
Customer
Key
Sensor
Storage
Processing (CPU)
Software
Raw Data
Point Cloud Data
3D Model Data
Positioning Data (XYZ)
Partial/ Uncertain Data
(dotted border)


SLAM
Aux Sensors
(INU, camera, GNSS)
LiDAR
Onboard storage
WiFi
Partial PC
Prev. pose
Onboard
CPU
Estimate new pose
from partial PC and
sensor data
(localization)
New pose
Update point
cloud with new
data based on
pose (mapping)
New
pose
New
partial PC
Driving
Post-Driving
Ground Station
Final
point cloud
Generate 3D
model from point
cloud
Ground station
CPU(s) omitted
for clarity
Customer

Point Cloud Registration Additional information

Point Cloud Registration (PCR) is the process of determining a transformation that aligns two or more point clouds into a common coordinate system [19]. PCR plays an important role in 3D model reconstruction because it enables unification of the raw, unorganized spatial (*x,y,z*) data outputted by LiDAR sensors. PCR algorithms fall under two categories: rigid and non-rigid registration. Rigid registration yields a transformation that does not change the distance between any two points in each point cloud -- thus, it primarily consists of translation and rotation. On the other hand, non-rigid registration involves transformations such as anisotropic scaling and shear mapping which displace the relative position of points. Non-rigid registration is more challenging than rigid registration, and rigid registration generally has more applications. In the context of FLASH, the LiDAR sensor will likely scan a certain portion of infrastructure multiple times as the vehicle passes by, so PCR will be required to synthesize the point clouds into a single frame of reference for later 3D model conversion and visualization. The PCR methods explored below are all potentially viable candidates for this project. **NOTE**: Originally, a trade study was to be conducted for these algorithmic approaches. However, it was determined that the software for this project will not necessarily be developed from scratch, so it doesn't make sense to trade these options. Most point cloud processing software packages use ICP registration by default. Hence, the purpose of this section is moreso to educate readers on the underlying algorithms of point cloud processing.

Option 1: Iterative Closest Point

Iterative Closest Point (ICP) registration is a widely-used algorithm that can directly solve rigid body transformation without the need for an initial estimate of location. However, it does rely on an initial transformation estimate to serve as a starting point for iteration. ICP is built upon the quaternions method which defines a 3D transformation with three rotations and one angle. Because of its iterative nature, ICP is computationally expensive and is less efficient when dealing with large-scale, high-density point clouds. Furthermore, ICP is susceptible to convergence upon a local optimal solution rather than an ideal global solution, so it sometimes requires fine-tuning and manual validation. Nevertheless, ICP is stable and robust overall, and when implemented correctly, it yields highly precise results for registration of raw LiDAR point clouds.

Advantages	**Disadvantages**
High precision	Prone to local optimal solution convergence
Widely-used and documented	Less efficient with large-scale point clouds
MATLAB function support	Requires initial transformation estimate

Option 2: Normal-Distributions Transform

Normal Distribution Transform (NDT) is a registration method which employs probability density functions to estimate the transformation required for point cloud alignment. The first key step in the NDT method is the construction of a 3D grid to be occupied by a given point cloud. Then, a probability distribution is computed for each grid cell (cube) based on the physical distribution of points within that cell. Finally, the probability of normal distribution of two point clouds is iteratively optimized until satisfactory registration is achieved. In general, NDT-based algorithms have fast computational speeds and are able to handle large data volumes. However, NDT is a fundamentally 2D approach and there is a lack of applied NDT research in complex 3D environments. Additionally, the determination of an appropriate grid cell structure is a problem in and of itself, so NDT often requires error-prone user engagement.

Advantages	Disadvantages
High precision and efficiency	Results depend on selected grid cell size
Suitable for large-scale point cloud data	Rarely used in 3D LiDAR research
MATLAB function support	Requires large overlapping areas in point clouds

Option 3: Coherent Point Drift

Coherent Point Drift (CPD) is a complex, probabilistic registration method which leverages a Gaussian mixture model to minimize the error between two point clouds. It can yield both rigid and non-rigid transformations, and it is a global method that does not rely on an initial transformation estimate. Although CPD-based processes are very slow and computationally intensive, they have demonstrated accuracy and robustness even in the presence of data outliers.

Advantages	Disadvantages
Accurate and stable in presence of outliers	Computationally expensive and slow
Does not require initial transformation estimate	Limited history with 3D LiDAR
MATLAB function support	Performs poorly on variable-density data

INS Additional Information
IMU and Gyroscope technologies: MEMS vs FOG vs RLG

MEMS stands for microelectromechanical systems and represents a technology that utilizes microscopic devices that have moving parts. These can be used in a wide variety of applications but for this project it will be used to guide the system when GPS is patchy or unavailable. MEMS is described as a low cost, high accuracy inertial sensor but is less accurate than the other options that are considered in the IMU trade study. A MEMS sensor works by applying a tilt to the sensor, then a balanced mass makes a difference within the electric potential. This can be measured like a change within capacitance. Then that signal can be changed to create a stable output signal in digital, 4-20mA or VDC. These sensors are fine solutions to some applications which do not demand the maximum accuracy like industrial automation, position control, roll, and pitch measurement, and platform leveling. [20]

These sensors have been improving through increasing availability, increased bandwidth, getter g-sensitivity, and improved error characteristics. MEMS has increased its popularity over the FOG technology, explained below, mostly due to its antenna array stabilization applications. Machine control applications are also looking to trade to the MEMS technology instead of the traditional technologies. The antenna stabilization is particularly important for this project because the LiDAR sensor needs to either be kept stable by the mounting structure or its disturbances must be documented carefully for use in correcting for errors in the data later. The advance of this technology into the dynamic applications as well as the reasonable cost is what encourages the group to trust this system to stabilize the LiDAR and to function as the inertial navigation system.

FOG stands for fibre-optic gyroscope and is used to sense changes in orientation by performing the function of a mechanical gyroscope. This is done by injecting two laser beams into the same fibre but in opposite directions. Due to the Sagnac effect the beam travelling against the rotation experiences a slightly shorter path delay than the other beam. The resulting differential phase shift is measured through interferometry, thus translating one component of the angular velocity into a shift of the interference pattern which is measured photometrically. [21] This technique has even been tested in areas where GPS was poor such as in a large city. In this area of poor quality GNSS measurements the FOG system does 20 to 30% better than the MEMS system. This is an important factor when considering how this project may be faced with the same issue of poor GNSS signal.

This particular form of determining position has a very high rate of precision but this comes at cost. FOG systems are particularly costly and therefore, would pose budget problems for this project. In comparison to ring laser gyroscopes they are fairly cheap but when compared to the MEMS they are much more expensive. Regardless, the potential of this system is very high and a good option to consider for this particular part of the project.

Ring-laser gyroscope (RLG) systems function in a similar way to FOG systems but are typically treated as a high-precision alternative. Both systems operate based on the principle of the Sagnac effect. One advantage is that RLG does not include any moving parts. This means that there is no friction as seen in traditional spinning gyro systems which results in the RLG not experiencing any inherent drift. These systems are also extremely small, light, and durable. A single RNG is capable of measuring any rotation about its sensitive axis which allows for its orientation in inertial space to always be known. It does this by splitting an input laser beam into two circular paths, one traveling clockwise and the other counter-clockwise. The laser beams meet each other and are sent into the detector. If the system does not rotate, the output will be the constructive interference of the signals that are outputted by each beam. If the system has rotated, there will be a difference in the lengths of the paths of the two laser beams which results in a phase difference and a destructive interference output signal. The amplitude of the signal is measured through the output voltage which decreases with increasing phase difference between the recombined signals. The amplitude of the recombined signals is a direct measurement for the phase shift and therefore the rotation rate.

FOG directly measures the phase difference between the two beams whereas RLG measures the difference in frequency caused by rotation. The actual optical fiber used in FOG is rather in-expensive but also vulnerable to uniform thermal expansion and contraction from changes in temperature. RLG are much more precise when compared to FOG systems due to the beams in RLG being propagated within a resonant cavity rather than within the fiber. This results in RLG systems experiencing low amounts of interference from the outside. The resonant cavity component typically makes RLG systems more expensive than FOG systems. For this reason alone it would be challenging to obtain this high-level of a component given the budget restrictions.There are less expensive inertial navigation solutions that can fulfill the requirements for this project.

Tronics GYPRO2300 MEMS Gyroscope

The GYPRO2300 MEMS Gyroscope by Tronics serves as a solution for platform stabilization, guidance and navigation control, inertial measurement unit (IMU), attitude and heading reference system (AHRS), flight control instrumentation, autonomous vehicles, three dimensional mapping, and more. It is slightly more accurate than the FOG option but much less accurate than a RLG system.

Advantages	**Disadvantages**
Moderate levels of accuracy	Less stability over temperature and humidity
Low cost	Poor reliability when without GNSS signal

KVH Industries DSP - 3000 Fiber Optic Gyroscope

The DSP - 3000 fiber optic gyroscope by KVH industries is a compact, durable, and versatile single axis FOG. The company states that it has “superior precision and reliable performance at a lower cost” when compared to similar products made by competitors. It is designed with the choice for analog, digital, and RS-232 outputs making it capable of fulfilling requirements for a wide range of applications. It is a considerable solution for the guidance and stabilization aspects of the inertial navigation system for FLASH. Some specifications listed in the datasheet that are different depending on if the system output is analog or digital are input rate, bias instability, bias offset, angle random walk, etc. Some of the accuracy specifications will be detailed later in the IMU trade study portion of this document. Other important information found in the datasheet is component dimensions, weight, power consumption and more. KVH does not list the retail price of this component but it is assumed to be more expensive than the MEMS options and less expensive than the RLG option [22].

Advantages	**Disadvantages**
No moving parts	High cost
Good reliability when GNSS signal is poor	More noise
Supports analog, digital, and RS-232	

Honeywell GG1320 Digital Ring Laser Gyroscope

The GG1320 digital ring laser gyroscope (RLG) by Honeywell is a highly precise rotation measurement device. It is typically used for inertial navigation and platform pointing/stabilization. This inertial sensor comes with the electronics, sense components, and power supply packaged into a compact, user friendly device. Honeywell has reported that the GG1320 RLG is capable of measuring as little as an arc-second of rotation. It is far more accurate when compared to the DSP - 3000 FOG which can be seen from the large differences in error specifications detailed in the IMU trade study. These RLG devices tend to be more expensive due to the resonant cavity component that differentiates it from both the MEMS and the FOG devices.

Advantages	**Disadvantages**
Extremely accurate	High cost
Compact	Limited to digital output
No moving parts	Complex design and manufacturing

GNSS Additional Information

From Design Requirement 3.4 defined in the first section of this document, we must design for expected GNSS outages of up to 30 seconds. Depending on the relative quality of the other INS subsystems and their ability to remain accurate over time without GNSS corrections, this may not be a length of time which warrants an additional redundancy system for improving the GNSS accuracy. However, several strategies do exist for the purposes of improving accuracy and availability in areas with poor GNSS connection availability. Two of the most popular options are reviewed below:

6.1.1.1. RTK GNSS

RTK, or "Real Time Kinematics" is a class of GNSS data transmission technique which involves adding an additional receiver at a stationary terrestrial location that can both receive and transmit GNSS packets, making it a GNSS ground station of sorts. Provided the receivers of both the ground station and target are connected to the same satellites within the constellation, then the knowledge of your ground station's location as a stationary ground truth point can be used in a number of ways to help improve the target's data. These techniques include simple subtractions, such as removing biases detected in the form of false motion of the ground station, or even more directly you can analyze the carrier wave's phase and length to do a direct ranging calculation using your ground station. Depending on the strength of the ground station's receiver, this process can improve pure-GNSS systems' accuracy to just 1 cm or less, and the ground station should provide at least some benefit to any targets within about a 40 mile radius.

In practice, solutions such as this typically involve adding more than just one ground station, either introducing several additional "mobile" relays to extend or strengthen the signal your ground station outputs, or more directly by just planning and constructing several appropriately spaced ground stations for permanent use. The increased budgetary and complexity requirements to implement a single ground station for these sorts of purposes, let alone potentially multiple, clearly rules out any RTK solutions.

Advantages	**Disadvantages**
High versatility in ranging options	Requires dedicated GPS relay ground station
Increased quality when GNSS signal is poor	Increased complexity

6.1.1.2. Ephemeris File Injection (A-GPS)

Another common way to improve the GNSS's understanding of each of the locations of the connected satellites in our constellation is to supplement the collected GNSS information with actual ephemeris information about the satellites. In applications where we can reliably acquire that type of data this technique provides very versatile options for performing measurements in low-coverage areas, and even some potential for quasi-offline observations to be made exist. However, this situation implies having access to such data at all, which if we are using the US's GPS network it is unlikely that ephemeris tables will be readily available for individual satellites in the constellation so we must unfortunately disregard the consideration for this project.

Advantages	**Disadvantages**
Excellent accuracy	Required data likely unavailable
Increased quality when GNSS signal is poor	GPS unit needs additional hardware

Standalone GNSS trade study

For the purposes of the trade study, we will be examining two multi-constellation receivers which come in the form of integrated chips, the Telit SL869-V3 and the Telit SL871, and comparing it against a non-integrated standalone receiver the ATLAS A222. These models and their relevant specifications will be discussed in detail below.

6.1.1.3. Telit SL871

Telit Wireless Solutions, a leading global provider of high-quality machine-to-machine (M2M) modules and services. They offer a number of GNSS receiver and transmitter solutions. It comes equipped with a multi-constellation receiver capable of communicating with the GPS, Glonass, Beidou and Galileo constellations, as well as planned support for upcoming constellations including Compass and QZSS. It hosts an onboard ARM processor and flash storage. Weighing just 1 gram, it is focused on portable and weight-restricted GNSS applications. Advanced features include ephemeris file injection (A-GPS) and Satellite Based Augmentation System (SBAS) for cases when signal acquisition is limited or unreliable. Its family comes with a variety of submodels that can be configured for extra-low power consumption requirements, though this is unlikely to be necessary for our power budget.

6.1.1.4. Telit SL869-V3

The TelitSL869-V3 is based off of an improved chipset compared to the SL871 (see Section 4.2.2.1). The SL869-V3 is designed to deliver the best pure GNSS tracking performance Telit offers in a single integrated chip. It comes equipped with a multi-constellation receiver capable of communicating with the GPS, Glonass, Beidou and Galileo constellations. Advanced features include external MEMs support, A-GNSS onboard generation, and A-GNSS server-generated file injection. The SL869-V3 includes a number of communication ports such as UART, I2C and embedded flash memory for firmware upgrades and customization.

6.1.1.5. Telit SC872-A

Modern GNSS modules with additional signal processing capabilities directly integrated into the units, either through software or hardware, have been dubbed “smart antennas”. Telit offers a number of options for smart antennas, including the SC872-A. This offers additional features to the SL871 lineup that reduces TTFF significantly by performing on-board acquisition algorithms with a knowledge of the orbital parameters of multiple satellites and applying filter-based algorithms, rather than needing to receive the data from the satellite itself after the TTFF (including EGNOS, WAAS, GAGAN, MSAS). This combined with a battery backup, integrated data connectivity ensures maximal uptime and reliability in GNSS performance.

Gyroscope Trade Study

5.2.1.1. Evaluation Criteria & Weight Assignment Methodology:

5.2.1.1.1. Accuracy / Performance

There are a few specifications which define the accuracy of inertial measurement units. Bias instability describes the amount of deviation that the sensor has from its average value of the output rate. Bias offset describes the small difference in average signal output that is seen even when the system is stationary. Angle random walk is a noise specification that applies to angle calculations. It is used to describe the mean error that is seen when the signal is integrated. The accuracy of this component is important due to the high-level accuracy requirements for this project. Any error in localization adds to uncertainty in the precision of the point cloud.

5.2.1.1.2 Mass

The mass of these components are typically not too high and should not pose much of an issue to the design of this project. It makes sense to have mass as a trade aspect for localization components such as the IMU. This is because the entire system has a rather strict weight requirement so keeping individual components as light as possible is optimal. However, it is also understood that localization is a key part of this project, so a lightweight should not drastically outweigh high accuracy.

5.2.1.1.3. Cost

As mentioned above, this project is constrained by a $5000 budget constraint. This is a project that could have thousands of dollars dedicated to a single sensor alone, so the challenge is to obtain the best possible results without breaking the budget. While the budget is important, the IMUs being traded are in a similar price range, so a weight of 10% has been awarded to the cost criteria because it is prefered that accuracy and mass are valued over a small cost differential.

5.2.1.1.4. Capability to Work Without GNSS Signal

Ideally, this system will be able to operate in areas that fluctuate in and out of GNSS services. However, the system is not required to operate without GNSS services for extended durations, so this criteria should be less impactful than accuracy and mass.

5.2.1.2. Design Option Scoring

Evaluation Criteria	1-2	3	4-5
Accuracy / Performance	Low Precision	Medium Precision	High Precision
Mass	> 1 lb.	< 1 lb.	< 0.7 lb.
Cost	> $500	< $500	< $200
Working Without GNSS Signal	Not Functional	Functions Within Tolerance	Functions Above Standards

5.2.1.3. Trade Study Results and Analysis

		Tronics GYPRO2300 MEMS Gyro	Fiber Optic Gyro DSP - 3000	Ring Laser Gyro Honeywell GG1320
Criteria	**Weight**	**Score**	**Score**	**Score**
Accuracy/Performance	30%	4	3	5
Mass	20%	5	4	3
Cost	10%	5	1	1
Working Without GNSS Signal	10%	2		
Total	100%	4.0		

5.2.2 GNSS Trade Study

5.2.2.1. Evaluation Criteria & Weight Assignment Methodology:

5.2.2.1.1. Accuracy / Performance

Due to the complex nature of triangulating a GNSS signal, GPS units typically offer accuracy on the order of meters. This is unfortunately much higher than **DR 3.2** which specifies that our INS performs within an accuracy of 5 cm, but since the GNSS signal will be used for making corrections in the IMU data this will be sufficient for our purposes. High accuracy units can get results within 1 meter reliably. Since we would still like to keep performance as high as possible, this category will be given a weight of 25%.

5.2.2.1.2. Constellations

Our unit will preferably have support for the United States GPS constellation as it is extensive, reliable, and publicly accessible. For global compatibility concerns, a multi-constellation unit that is compatible with all major GNSS networks is generally an option available at little increase in cost. Compatibility with major GNSS networks is of utmost importance, so this has been given a weight of 50%.

5.2.2.1.3. Power Consumption

The power consumption for card-based solutions are typically very low. Some units with standalone capabilities or additional features have slightly higher requirements, but since it is all still in the <1W range this has been given a weight of only 5%.

5.2.2.1.4. Additional Features

Although we do not plan on implementing a ground station within our system, for compatibility and future-proofing concerns it may be desirable if an RTK and/or A-GPS capable was purchased. Since it is not being integrated into our solution directly however, this will be given a weight of just 5%.

5.2.2.1.5. Cost

The cost of receivers being considered is overall fairly low compared to the price of other components in the system, but also non-negligible if higher-end receivers are purchased. As such, it has been given a weight of 15%.

5.2.2.2. Design Option Scoring

Evaluation Criteria	1-2	3	4-5
Accuracy / Performance	> 2 m	< 2 m	< 1 m
Constellations	Private network	GPS	Multi-constellation
Power Consumption	> 250 mW	< 250 mW	< 150 mW
Additional Features	None	RTK, A-GPS	Advanced features
Cost	> $200	< $200	< $100

5.2.2.3. Trade Study Results and Analysis

		Telit SL871	Telit SL869-V3	ATLAS A222
CRITERIA	**WEIGHT**	**Score**	**Score**	**Score**
Accuracy/Performance	25%	3	5	4
Constellations	50%	3	5	5
Power Consumption	5%	5	3	2
Additional Features	5%	2	3	4
Cost	15%	4	3	
Total	100%	3.2	**4.5**	