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Utilization of LiDAR Technology to Assess Vertical Clearances of Civil Infrastructure

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UTILIZATION OF LIDAR TECHNOLOGY TO ASSESS VERTICAL CLEARANCES OF CIVIL INFRASTRUCTURES

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Of the Requirements for the Degree
Master of Science

By
Daniel Levi McIntosh

December 2020

UTILIZATION OF LIDAR TECHNOLOGY TO ASSESS VERTICAL CLEARANCES OF CIVIL INFRASTRUCTURES

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The issue of vertical clearances along highway systems impact the functionality of the road network. Extracting current routing clearances for each structure can be a challenging and hazardous task. Pavement changes and roadway rehabilitation projects can alter roadway geometry, complicating efforts to maintain accurate clearance databases. Vertical clearance measurements may vary from one lane to another beneath overhead structures and are often difficult to obtain due to high traffic volumes. Inherently, traditional methods that are used to obtain the measurements routinely impede the flow of traffic and subject workers to dangerous environments. This study will examine the use of a Mobile LiDAR system and its applicability and accuracy to obtain vertical clearances on bridge structures. Further, the study will investigate the impact of utilizing a Mobile LiDAR system on traffic disruption and worker safety. The measurements extracted from LiDAR point clouds are compared to measurements obtained from traditional techniques using a laser tape meter and total station. Results will be analyzed to assist in quantifying the potential error between field and LiDAR measurements. Furthermore, the impact on work zone safety and traffic disruption is investigated. The results obtained from this study can be used to help identify the most effective method to extract infrastructure clearances and aid in future assessments.

Problem Statement

As of 2017, the state of Kentucky maintains a total of 14,265 bridges, supporting an estimated traffic volume of more than 64.3 million daily crossings (KY Chamber, 2017). Obtaining accurate clearances from overhead structures provides essential information for the safe routing of oversized vehicles, especially along highly traveled routes such as interstates and parkways. According to the Bureau of Transportation Statistics (BTS, 2017) a total of 10,776 million tons of freight was transported using U.S. highways in 2015, with a projected growth to 14,829 million tons by 2045. The Federal Highway Administration (FHWA) has established design guidelines for overhead structures which accommodate for the safe travel of most vehicles. However, extracting current routing clearances for each structure can be challenging. Pavement changes and roadway rehabilitation projects can alter roadway geometry, complicating efforts to maintain accurate clearance databases.

Significance of the Research

Although many technologies have been successful in extracting vertical clearances, a recommended methodology has not been established. Current practices routinely involve disruptive lane closures, exposing workers and public motorists to dangerous environments. A report published by the FHWA (2015), compiled data on the frequency of work zone crashes in the US. The study found that in 2015 work zone accidents occurred once every 5.4 minutes. Utilizing Mobile LiDAR technology greatly diminishes the need for work zones and may prove to be an alternative tool in Civil engineering practices.

Purpose of the Research

The purpose of this study is to evaluate the extraction of vertical clearances along active highway systems using a Mobile LiDAR system (MLS). Data collected from three overpasses using a laser tape, mobile LiDAR, and total station will be used to test the theory of utilizing MLS to determine safe routing clearances. Measurements from each method will be recorded and categorized into three groups: (1) MLS, (2) total station and (3) laser tape. A statistical analysis using a one-way anova model will be used to determine differences between methods. The resulting relationship of data and collection procedures obtained from this study can help aid in future infrastructure assessments.

Research Questions

For the purpose of this study the following research questions will be determined to test the applicability of Mobile LiDAR.

1. Does Mobile LiDAR technology provide an accurate alternative to traditional methods used to extract vertical clearances from civil infrastructures?
2. Can Mobile LiDAR technology be recommended for future infrastructure assessments?
3. How do traditional collection methods compare to MLS procedures?
4. Does the use of Mobile LiDAR alleviate exposure to dangerous environments?
5. Do Mobile LiDAR collection procedures impact routine traffic operations?
6. Does the data collected represent an allowable accuracy in the extraction of overpass clearances?

Assumptions

The following assumptions were made while conducting this study

1. Processing software is able to accurately extract measurements.
2. Traditional methods used adhere to known collection standards.
3. Instruments have been properly calibrated for accuracy.

Limitations

The study had the following limitations:

1. Proper weather conditions.
2. GPS signal quality.
3. LiDAR equipment is calibrated and functional.
4. Limited traffic flow at testing locations.

List of Acronyms

LiDAR - Light Detection and Ranging

MLS- Mobile LiDAR System

FHWA - Federal Highway Administration

GPS - Global Positioning System

IMU - Inertial Measurement Unit

FOV - Field of View

TOF - Time of Flight

NCHRP - National Cooperative Highway Research Program

CMV – Commercial Motor Vehicle

MMS- Mobile Mapping System

MLS- Mobile LiDAR System

DMI – Distance Measurement Indicator

GNSS- Global Navigation Satellite System

DOT – Department of Transportation

EDM – Electronic Distance Measurement

REM – Remote Elevation Method

TLS – Terrestrial Laser Scanning

SBET- Smoothed Best Estimate of Trajectory

CORS – Continuously Operating Reference Station

SA- Selective Availability

Review of Literature

History and Advancements

In 1971, Apollo 15's lunar module *(Falcon)* landed on the surface of the moon. Concurrently, the control center module *(Endeavor)* remained in orbit conducting tests using an array of cameras and sensors. One of the mission's objectives was to measure surface profiles of the moon using a laser measurement device. NASA's experiment emitted light pulses from a laser altimeter, recording the elapsed time of reflectance from the lunar surface. The control center module carrying the device as shown in figure 1, obtained measurements approximately every 20 seconds for the duration of 4.5 orbits. The results provided spatial coordinates consisting of X, Y and Z values that were used to recreate lunar surface profiles. Subsequent missions also carried the laser altimeter aboard Apollo 16 and 17 (Abshire, 2010).

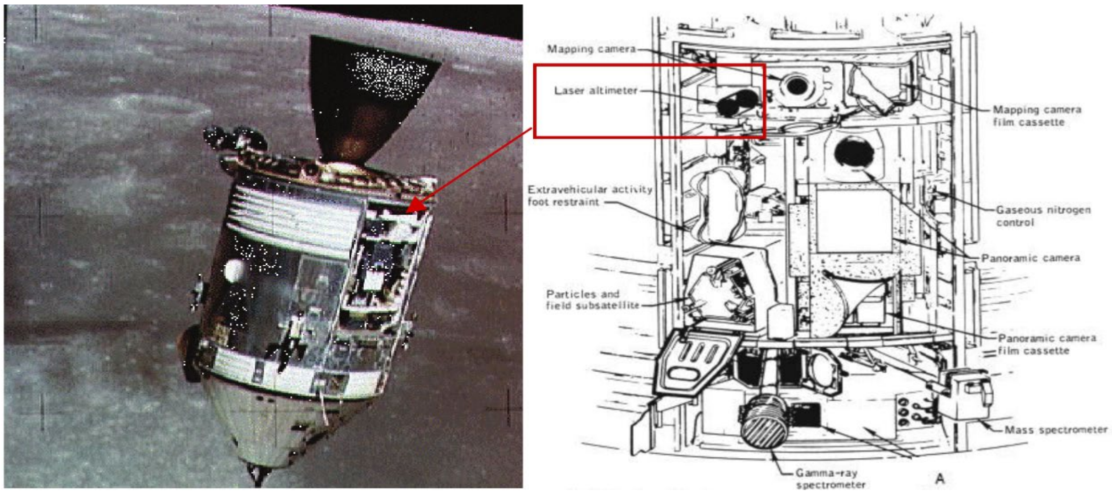


Figure 1. Apollo 15 mission carrying the laser altimeter. Adapted from "NASA's Space Lidar Measurements of the Earth and Planets" by J, Abshire, (2011). Retrieved from http://ewh.ieee.org/r2/wash_nova/photonics/archive/IeeeSpaceLidAbshireFinal4-5-11.pdf

NASA's experiment proved successful in remotely obtaining measurements to recreate surface profiles. However, the lack of Global Positioning Systems (GPS) and Inertial Measurement Unit (IMU) solutions hindered the commercial development of sensor positioning technologies. In 1983, President Reagan announced that the United States GPS would be made available for civilian use. Although, due to national security concerns, the signal was intentionally degraded. Known as selective availability (SA), consumers were unable to acquire location accuracies under 328 feet. In efforts to improve upon the limitations of SA, the private market began developing DGPS or differential GPS in 1995. By using a network of fixed ground-based reference stations, the difference between the GPS satellite signal and the known coordinates of the reference station could be identified and corrected, greatly improving accuracies (Cunha & LoPiccalo 2008).

By the late-1990's laser scanner manufacturers were producing aerial LiDAR sensors capable of 2,000 to 25,000 pulses per second. Outfitted to planes, the sensors could produce high resolution topographic maps that rivaled the established practice of aerial photogrammetry. Although primitive by today's standards, these instruments proved to advance the growing belief that LiDAR technology was the way of the future (Gaurav, 2017).

In 2000, President Clinton announced that the US would eliminate intentional degradation of the GPS signal. The decision was part of an ongoing effort to make GPS more responsive to civil and commercial users worldwide (Clinton, 2000). Figure 2 shows the horizontal and vertical positional errors before and after the transition.

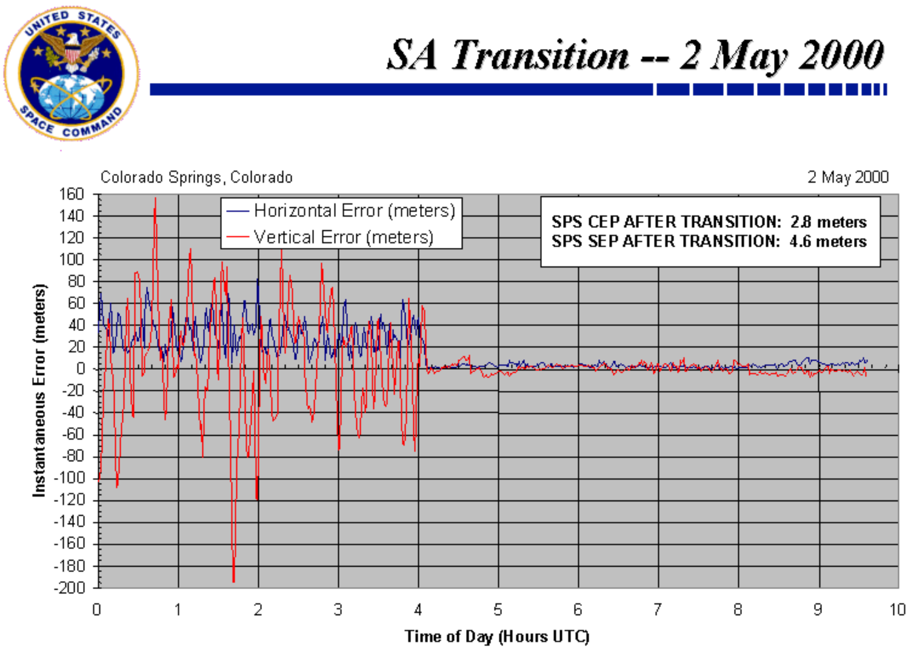


Figure 2. SA Transition. Retrieved from:
https://www.gps.gov/systems/gps/modernization/sa/data/timeline.gif

Glennie (2009), recounts the history of the first Mobile Lidar System (MLS). Constructed in 2003, sensors from a helicopter based aerial system were removed and mounted in the bed of a pickup truck. The newly configured MLS system was used to survey Highway 1 in Afghanistan, a potentially dangerous corridor for helicopter-based scanning. The initial system had many downfalls, primarily its limited field of view that accompanies aerial systems. However, its successful implementation demonstrated the potential value of MLS (Williams, Olsen, Roe, and Glennie, 2013).

Since the introduction of the laser altimeter by NASA, laser measurement systems have evolved to support an extensive array of platforms. This study will focus on Mobile LiDAR, a term widely used for laser scanners that are deployed on a variety of vehicles such as cars, trains, boats and other land-based platforms.

Recent Studies

Previous studies have shown promising results from LiDAR technology. Coiner & Bruno (2002), found that when compared to traditional surveying methods, LiDAR data provides a significantly higher level of true geometric completeness and detail of the site. Using a conventional total station or GPS equipment, the experienced surveyor typically captures the minimal amount of data needed to represent the targeted surface or feature. As with all highway measurement techniques, this process is prone to costly errors and/or omissions in the data and can sometimes be impossible to collect due to traffic or inaccessible regions. The authors state that laser scanning may eliminate many of these errors due to the high resolution of the point cloud. Features or targets missed in the field can be extracted from the data without returning to the site. Recommendations for use of LiDAR for are proposed, highlighting benefits such as lower costs, higher productivity, and increased safety conditions. Furthermore, the authors state that LiDAR provides a detailed, reliable, and accurate solution to many surveying and measurement problems (Coiner & Bruno, 2002).

A study by Chang, Findley, Cunningham and Tsia (2014), evaluated the use of Mobile LiDAR systems for transportation agencies. The authors found that the use of LiDAR is becoming increasingly popular across the United States and agencies are adopting this technology for practical uses in transportation related applications. The primary factors behind this trend are that surveyors, engineers, and technicians are becoming more educated and increasingly open to LiDAR and its applications, providing a cost-effective alternative to traditional surveying technologies. Transportation agencies have discovered many benefits in using LiDAR technology such as higher levels of safety, productivity, applicability, and detail acquisition. A definitive advantage of mobile LiDAR over traditional methods is its ability to collect data from a distance at highway speeds, thus reducing or eliminating the need for lane closures and exposure to potentially hazardous environments. Inherently, MLS technology improves the safety of field personnel as well as the traveling public during data collection efforts (Chang, Findley, Cunningham & Tsia, 2014).

The authors also explore challenges in utilizing LiDAR systems for transportation applications. The study found that as with many new technologies, widespread acceptance of laser scanning to replace traditional methods has not been fully embraced. The main factors conveyed are that laser scanning systems are still expensive, workflows are complicated, and the size of collected data sets tend to be overpowering for most computer systems. The data also requires the knowledge of trained staff and technicians to post-process and extract accurate deliverables. The study concludes that there is little more than anecdotal evidence to determine when a specific LiDAR platform should be applied over traditional methods for various applications (Chang et al, 2014). Additionally, this study is unique in that it incorporates considering factors for transportation agencies such as budget restrictions, current methods/workflows, hardware and software costs, external contracts, employee training, and resource allocation.

Work Zone Safety

One of the key advantages in utilizing mobile LiDAR is its ability to collect data at highway speeds, resulting in minimal traffic impacts and diminishing the need for lane closures. Additionally, LiDAR systems are not limited to daylight conditions and are capable of operating in dark environments when traffic flow is off-peak. The mobility of the system allows for data to be collected without exposing workers to high speed traffic. Static LiDAR systems, total stations, and physical measurements all require personnel on the ground, requiring the support of work zones where areas are often established to provide a safety buffer between traffic and employees. Statistics from an FHWA report state that in 2015 there were an estimated 96,626 crashes in work zones, an increase of 7.8% over 2014. This continues a rise in work zone accidents since a low of 67,887 in 2013. The report also compiled data on the frequency of work zone crashes stating that in 2015, accidents occurred an average of once every 5.4 minutes (FHWA, 2015). Williams et al. (2008) found that drivers may become distracted by survey instruments, diverting their focus from safely passing through the workzone. Additionally, surveyors routinely have no other option but to place themselves in precarious situations to acquire necessary measurements, whereas mobile LiDAR requires little to no need for surveyor and vehicular interaction.

The deployment of Mobile LiDAR systems will likely reduce or eliminate the need for establishing work zones, thus minimizing the threat of potential accidents and exposure to hazardous working environments. Although traffic disruption is minimal, it should be noted that when utilizing Mobile LiDAR technology, heavily congested areas or vehicles traveling in the LiDAR sensor(s) FOV (Field of View) can obstruct the instrument from reaching the targeted surface.

MLS technology

Positioning components. Mobile LiDAR Systems (MLS) can be broken down into two sub-systems, comprised of geo-positioning and LiDAR components. The geopositioning system is composed of Global Navigation Satellite System (GNSS) receiver(s), a Digital Measurement Indicator (DMI), and an Inertial Measurement Unit (IMU). Geo-referencing for MLS is determined by time variable position and orientation parameters. The three components of the geopositioning sub-system work together to synchronize outputs from the sensor(s). The GNSS antenna(s) collect satellite positioning data, the IMU records inertial measurements and orientation such as pitch, roll and yaw, while the DMI collects speed and linear distance information (Sokolova, Morrison & Haakonsen, 2015). Post processing of data gathered by the positioning components yields an accurate representation of the vehicle's orientation parameters along the traveled route.

LiDAR components. The LiDAR system is made up of laser scanner(s), a control unit, a logging computer for data synchronization, and a laptop PC used to control system functions. Laser scanners measure surroundings using light pulses to obtain range and angle measurements. Figure 3 illustrates common components of an MLS system. Using Time-Of-Flight (TOF), the scanner sends a short laser pulse to the target, the time difference between the emitted and received pulses are used to determine the range from the scanner. The range R can be calculated using the following expression:

$$R = \tfrac{1}{2} c\Delta t$$

Where c is the speed of light and Δt is the time of flight of the pulse (Puente et. al 2013).

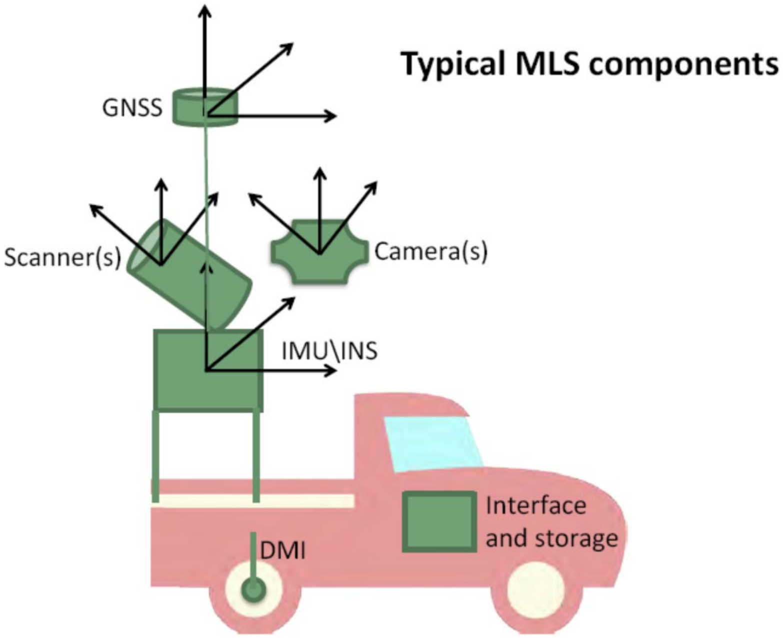


Figure 3. Typical MMS components. Retrieved from Guidelines for the use of Mobile LiDAR in Transportation applications, 2013, p.55

MLS Operations

During operational procedures the MLS system collects synchronized location and orientation data from the GNSS antennas(s), IMU and DMI along with spatial data from the LiDAR sensors. Post processing navigational data produces a trajectory depicting a 3-dimensional representation of the traveled route. The generated trajectory is then used to synchronize LiDAR scanner outputs correlating to the time of incidence. The resulting data is an accurate 3D collection of surface measurements also referred to as a point cloud.

In addition to spatial collection the LiDAR scanners(s) are also capable of extracting surface reflectance properties. Each scanned point can be assigned an intensity value based off of the return strength of the pulse. Varying surface properties affect the amplitude of the return pulses. Intensity values are assigned within a defined numeric range which can be displayed over graduated color tables. Intensity properties allow visualization software to differentiate between low reflectance surfaces such as pavement and structures with highly reflective surfaces such as lane striping and signage. Figure 4 shows the differences in point cloud data with and without intensity values.

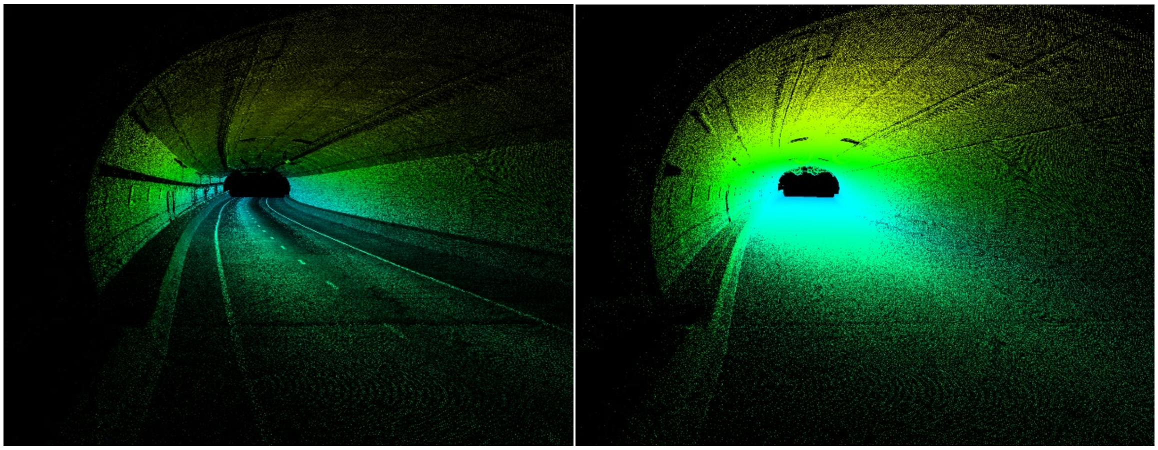


Figure 4. I-264 tunnel w/intensity and w/o intensity values.

Guidelines for MLS Accuracy

The National Cooperative Highway Research Program (NCHRP) report by Olsen et al. (2013), suggests guidelines for the use of Mobile Mapping systems in regards to specific applications. The suggested accuracy and resolution requirements as shown in figure 5 for clearances suggest an accuracy of <0.16 ft. and point densities >9 points per square foot. It should be noted the graphic indicates that accuracies may be relaxed for clearance applications are subject to change based on specific DOT requirements.

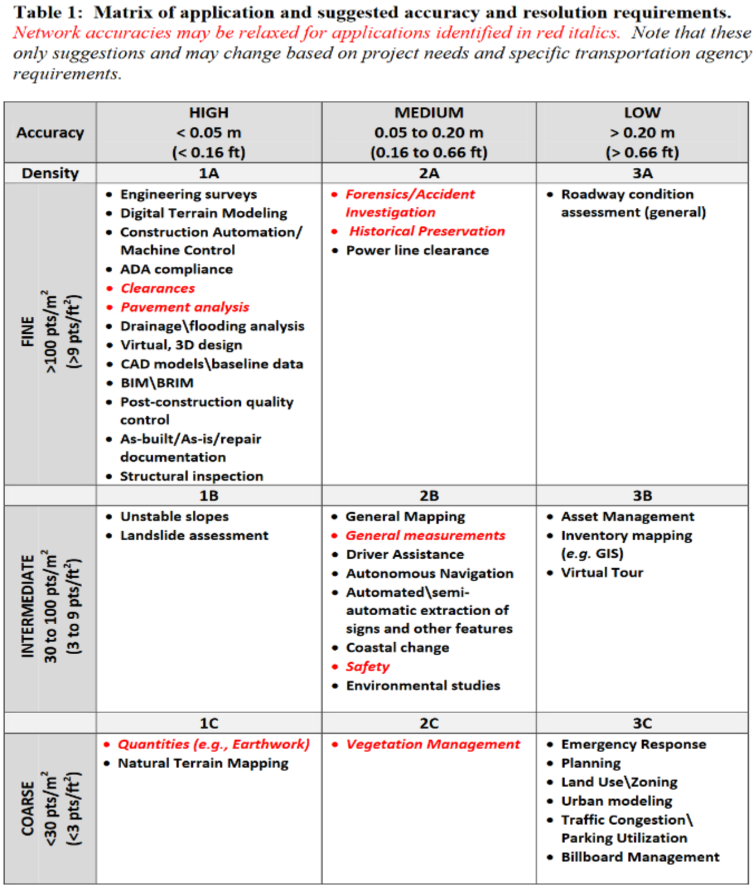


Table 1: Matrix of application and suggested accuracy and resolution requirements. *Network accuracies may be relaxed for applications identified in red italics. Note that these are only suggestions and may change based on project needs and specific transportation agency requirements.*

Accuracy	**HIGH < 0.05 m (< 0.16 ft)**	**MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)**	**LOW > 0.20 m (> 0.66 ft)**
Density	**1A**	**2A**	**3A**
FINE >100 pts/m^2 (>9 pts/ft^2)	• **Engineering surveys** • **Digital Terrain Modeling** • **Construction Automation/ Machine Control** • **ADA compliance** • ***Clearances*** • ***Pavement analysis*** • **Drainage\flooding analysis** • **Virtual, 3D design** • **CAD models\baseline data** • **BIM\BRIM** • **Post-construction quality control** • **As-built/As-is/repair documentation** • **Structural inspection**	• ***Forensics/Accident Investigation*** • ***Historical Preservation*** • **Power line clearance**	• **Roadway condition assessment (general)**
	1B	**2B**	**3B**
INTERMEDIATE 30 to 100 pts/m^2 (3 to 9 pts/ft^2)	• **Unstable slopes** • **Landslide assessment**	• **General Mapping** • ***General measurements*** • **Driver Assistance** • **Autonomous Navigation** • **Automated\semi-automatic extraction of signs and other features** • **Coastal change** • ***Safety*** • **Environmental studies**	• **Asset Management** • **Inventory mapping (*e.g.* GIS)** • **Virtual Tour**
	1C	**2C**	**3C**
COARSE <30 pts/m^2 (<3 pts/ft^2)	• ***Quantities (e.g., Earthwork)*** • **Natural Terrain Mapping**	• ***Vegetation Management***	• **Emergency Response** • **Planning** • **Land Use\Zoning** • **Urban modeling** • **Traffic Congestion\ Parking Utilization** • **Billboard Management**

Figure 5. Suggested accuracy Matrix. NCHRP guidelines, 2013, p.14

It is important to note that the Kentucky Transportation Cabinet (KYTC) has also established certain guidelines for the use of MLS data. Procedures outlined in HD-302.5 of the Highway Design Manual require the data to be referenced to validation points spaced along 500’ intervals with respect to the KY Single Zone Coordinate System (KYTC, 2006). This method requires the use of survey personnel to collect highly accurate coordinates and mark corresponding points on the roadway surface. Painted chevrons are commonly used providing a visual location in the point cloud to reference or “tie” lidar data to known coordinates. Control points are collected from a recognizable point such as the tip of a chevron, as shown in Figure 6.

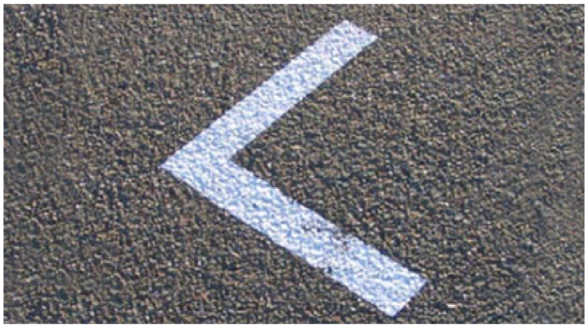


Figure 6. Chevron representing control point location. Retrieved from: http://www.pobonline.com/articles/98850-three-acronyms-you-should-know-in-mobile-mapping

Establishing control points allows the point cloud data to be tested for accuracy against known coordinates. Depending on the application, the guidelines state vertical and horizontal accuracies that should be met when utilizing LiDAR data for state level projects.

Clancy (2009), found that data used to determine under height clearances for bridge overpasses does not benefit from absolute accuracy provided by established control. The determination of minimum clearances only requires the data to have a high relative accuracy between points. The data collected for this project is not subject to the guidelines discussed in HD-302.5. This project will be analyzed from a Cartesian perspective. Establishing control and aligning point cloud data to a defined coordinate system does not alter spatial point distances or aid in the intent of this study.

Highway Design Guidelines

A report published by the American Association of State Highway and Transportation Officials (AASHTO, 2016), established design guidelines for minimum vertical clearances allowed for each roadway type. Regarding freeways, the report states that the vertical clearance to structures passing over freeways should be at least 16 feet over the entire roadway width, including auxiliary lanes and the usable width of shoulders with an allowance for future resurfacing. Additionally, because of their lesser resistance to impacts, vertical clearance to sign trusses and pedestrian overpasses should be 17 feet. The study also establishes guidelines for minimum vertical clearances on arterial roads as 14-16 feet, and local roads as 14 feet in both rural and urban areas (AASHTO, 2016). Table 1 illustrates the minimum vertical clearances allowed for each roadway design. The guidelines specify that vertical clearances should provide additional height for future resurfacing, indicating that the allowable clearance is subject to change due to roadway maintenance or design alterations.

Table 1.

Minimum vertical clearances.

Type of Roadway	**Rural**		**Urban**	
	US (feet)	**Metric (meters)**	**US (feet)**	**Metric (meters)**
Freeway	14-16*	4.3-4.9*	14-16*	4.3-4.9*
Arterial	14-16	4.3-4.9	14-16	4.3-4.9
Collector	14	4.3	14	4.3
Local	14	4.3	14	4.3

* 17 feet (5.1 meters) for sign trusses and pedestrian overpasses.

Oversize Load Impacts

Impacts between vehicles and bridge components can result in damage or failure to the bridge structure, injuries, traffic hazards, and loss of lives. Lee, Mai Tong, & Yen

(2006), compiled data on bridge failures and found that the second leading cause of bridge failure or collapse is due to collision damage from vehicle or vessel impacts. Currently, there is no nationwide database for tracking overheight collisions. However, references to the problem appear frequently in related research. Harik, Shaaban, Gesung, Valli & Wang (1990), studied U.S. bridge failures over a span of 38 years between 1951 and 1988. Of the 79 bridge failures analyzed, 11 (14%) were precipitated by truck collisions. Hilton (1973), investigated bridge related accidents in Virginia and found "inadequate vertical clearance" as a key contributing factor. In 1988 the Michigan Department of Transportation reported an increase of 36% in overheight collisions in a span of one year (MRC, 1988). The Mississippi State Highway Department installed warning systems on some rural bridges after an increase in damage to bridge structures from overheight logging trucks (Hanchey and Exley, 1990).

A study by Fu, Burhouse and Chang (2004), quantifies the problem of over-height impacts using collision statistics for structures in Maryland. The authors compiled data on 1496 bridges and found that 116 over-height collisions occurred between 1995 and 2000, an increase of 81%. Police reports were reviewed to classify the type of vehicles involved. Results indicated that box trucks were involved in 36% of accidents, flatbed trailers carrying oversized loads such as construction equipment accounted for 31%, dump trucks 16% and 17% involved mobile homes, refuse trucks, and other large vehicles.

A study by Agrawal, Xu and Chen (2011), discussed contributing factors to bridge impacts in the state of New York. The authors found that impacts from collisions were the third leading cause of structure collapse, trailing flooding and overweight vehicles. In an effort to perceive the problem on a national scale the authors proposed a survey focused on bridge impacts at the state level. The survey asked state transportation agencies, “Do you consider bridge hits to be a major problem in your state?” Out of the 50 states polled, 44 responses were received and analyzed. The results were mapped along with bridge impact data from 2005-2008 as shown in figure 7.

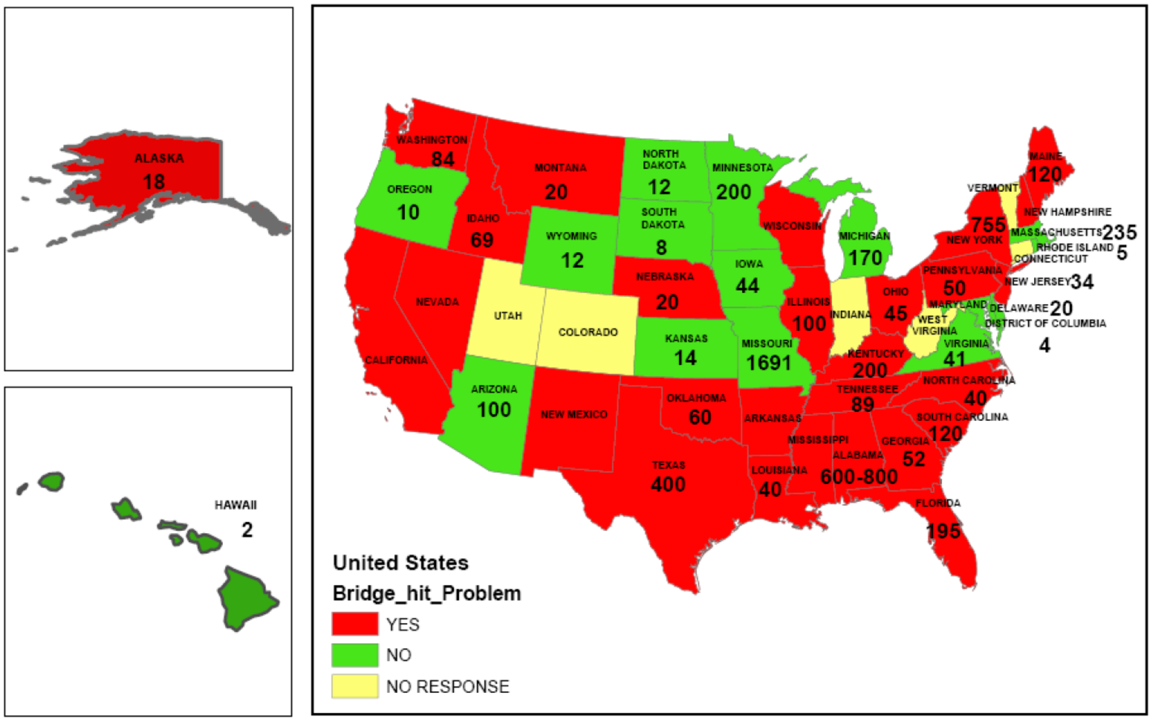


Figure 7. Bridge Impacts by State. Reprinted from “Bridge Vehicle Impact Assessment,” by A. Agrawal, X. Xu and Z. Chen, 2011, p.27

The results of the survey show that over-height load strikes occur frequently with the majority of states considering it a major problem. On average, roughly four overheight load strikes occurred per day in the United States during the 4-year period spanning 2005 –2008. The results of this survey are somewhat skewed as each state records bridge impacts differently. Louisiana for instance only reports impacts resulting in serious damage, however, Missouri records all impacts. Furthermore, it is likely that a high percentage of minor bridge impacts are never reported (Agrawal et al. 2011).

In March of 2015, the National Transportation Safety Board (NTSB) released a safety alert regarding the importance of preplanning and acquiring permits for oversized loads. The report states that "Commercial motor vehicle carriers transporting oversize loads on the nation's highway system are continuing to impact bridge structures. These impacts often lead to catastrophic events that result in fatalities and injuries, as well as enormous costs to repair the bridge structures" (NTSB, 2015 p.1). The report investigated two recent bridge impacts where vehicles transporting an oversized load collided with bridge structures resulting in partial collapses of the span.

Skagit River Bridge. The first instance in Mt. Vernon, Washington occurred on May 23, 2013 when an oversized load collided with the Skagit River Bridge leading to collapse and a replacement cost of $8.5 million. A follow up review by Stark, Benekohal, Fahnestock, LaFave, He and Wittenkeller (2006), investigated factors leading up to the incident. The report states that a truck was hauling an oversized steel container traveling Southbound on Interstate 5 when it struck an overhead beam. The impact caused a 160 ft. bridge span to collapse and fall into the Skagit River along with four other passenger vehicles.

Permitting for oversized vehicle routing is not federally regulated, therefore states establish individual requirements. Some states such as the Washington Department of Transportation (WSDOT) allow private companies to create their own oversize permit without agency oversight. In this case, the truck shown in figures 8 and 9, obtained an oversized load permit for a maximum vertical clearance of 15'9" and a width of 11'6".

Figure 8. Oversized Load.

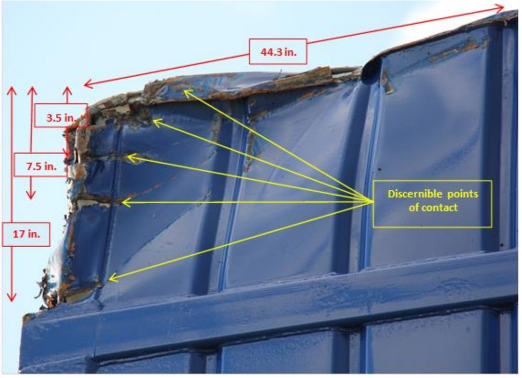


Figure 9. Damage to trailer

Figure 10. Collapsed Bridge Span. Reprinted from “Collapse of the Interstate 5 Skagit River Bridge,” NTSB, 2013, p.12

The southbound portal dimensions, as shown in figure 11, show a published height of 17’9” above the left lane line and 14’5” above the right edge of the shoulder, a difference of 3’4”. Vertical clearance variability, which changes based on roadway and overhead structure geometry was a major attributing factor in this incident. The height of the oversized vehicle was greater than the minimum southbound vertical clearance of 14’8” as listed in the WSDOT Bridge List (WSDOT 2015c, d). Consequently, the potential for inadequate vertical clearance was not recognized. The authors state that along a permitted route, different lanes may have different clearances. The oversized load measuring 15’9” vertical height exceeds the vertical clearance of the bridge over a portion of the right lane and all of the right shoulder, while it does not exceed the vertical clearance of the bridge over the left lane. If the truck was travelling in the left lane, the bridge impact may not have occurred (Stark, et al. 2016).

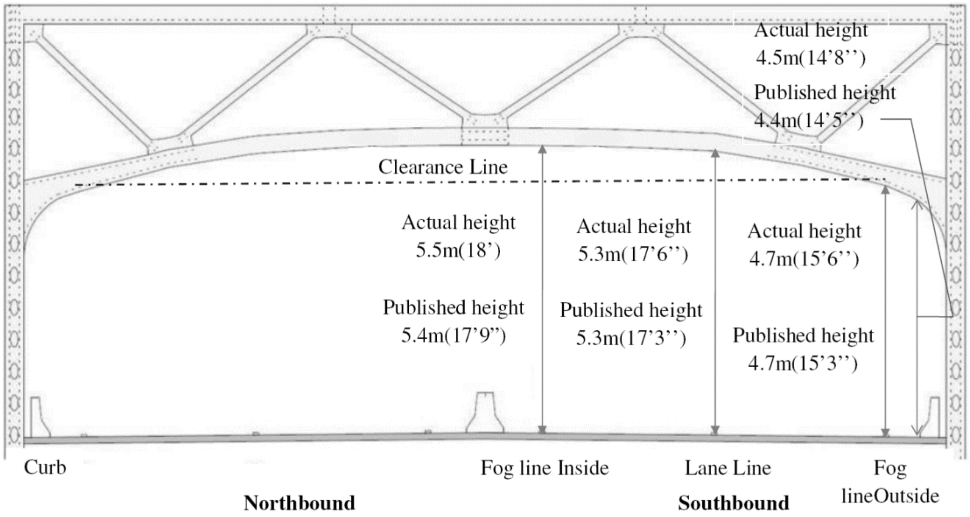


Figure 11. Southbound Portal Dimensions. Reprinted from “I-5 Skagit River Bridge Collapse Review,” T. Stark, R, Benekohal, L. Fahnestock, J. LaFave, J. He, and C. Wittenkeller, 2016, *Journal of Performance of Constructed Facilities, 30*, p.3.

Pilot vehicles provide an additional level of redundancy for identifying inadequate vertical clearances. Using a height rod, pilot vehicles travel ahead of the oversized load and relay information about possible overhead obstructions. The pilot vehicle in the Skagit River Bridge incident carried a height rod set at 16’2”, 5” higher than the oversized load (Stark, et al. 2016). However, the rod was installed at an angle reducing the overall vertical height as shown in figure 12. Given the variable bridge geometry, the height pole was not positioned to detect the inadequate clearance. The NTSB report found that due to changing bridge geometry, the pilot vehicle was not positioned below the lowest point of the structure along the right edge line and therefore was not alerted to the insufficient clearance (NTSB, 2015).

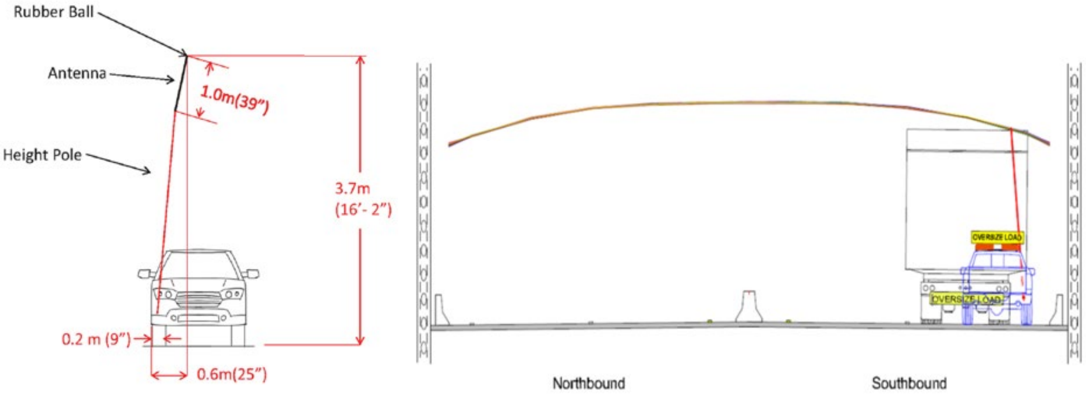


Figure 12. Appoximate depiction of Pilot Vehicle. Reprinted from "Collapse of the Interstate 5 Skagit River Bridge," NTSB, 2013, p.42

The accident resulted in a replacement cost in excess of 8 million and induced a major economic impact for the state, however, no fatalities were reported. The probable cause of the incident as stated in the NTSB report found multiple deficiencies: (1) insufficient route planning by the trucking company and the oversize combination vehicle driver; (2) failure of the certified pilot/escort vehicle to perform required duties and communicate potential hazards; and (3) inadequate evaluation of oversize load permit requests and no provision of low-clearance warning signs in advance of the bridge by WSDOT (NTSB, 2015).

The second incident occurred on March 26, 2015 in Salado, Texas. The NTSB report states that a commercial vehicle transporting a boom lift was traveling northbound on Interstate 35 when it collided with bridge structures supporting the Farm-to-Market Road overpass. The impact caused two concrete beams to collapse and fall into the travel lanes resulting in one fatality, three injuries, and about $150,000 of structural damage.

The report states that the vehicle was operating without a permit and was considered an over-height load, measuring approximately 14’-7” at its highest point. Under Texas law, no vehicles over 14’ may be operated on state highways without a permit. Additionally, the truck was stated to have passed several low clearance signs indicating an approaching clearance of 13’6”. Probable cause of the incident was attributed to the failure of the commercial motor vehicle carrier to obtain a permit for transporting the oversized load, stating that a permit would have included a route map illustrating detours around all bridges that had insufficient vertical clearances (NTSB, 2015).

Figure 13. Salado, Texas overpass impact. Retrieved from: http://www.statesman.com/news/local/bridge-collapse-near-salado/JxaB1MxnFqOYjcDGxng6MK/

According to the FHWA, there is no Federal vehicle height requirement for Commercial Motor Vehicles (CMV). Thus, states may set their own height restrictions. Most height limits range from 13’6” to 14’ with exceptions granted for lower clearances on designated roads. (FHWA, 2014).

Information regarding legal dimensions of overweight/oversized loads for the state of Kentucky show that the allowable height is regulated at a maximum of 13’6” for all vehicles except car haulers which are allowed 14’ (Over-dimensional Legal Dimensions, 2020).

Most tractor trailers using the national highway system are similar in height. The typical trailer height is 13’6” as shown in figure 14, allowing for the majority of freight to freely access road networks without obtaining a permit.

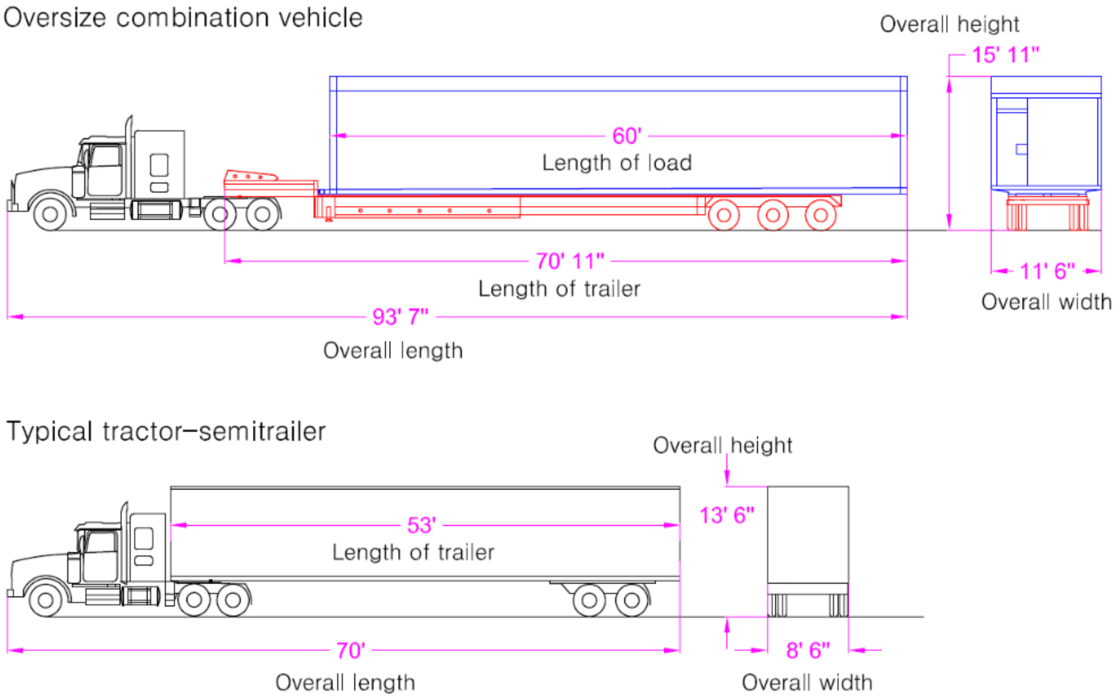


Figure 14. Typical and Over dimensional load examples. Reprinted from “Collapse of the Interstate 5 Skagit River Bridge,” NTSB, 2013, p.12

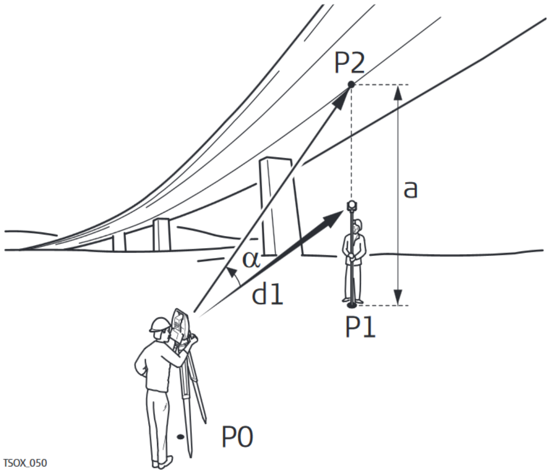
Review of current and previous methods

Design guidelines for minimum vertical clearances have been established but extraction methods have not been specified. The decision has been left to state Department of Transportation (DOT) agencies to utilize the best method to obtain the necessary measurements. Although a variety of tools and techniques exist for acquiring minimum vertical clearances, a defined approach has not been determined. As new technologies are introduced, these methods continuously change. A review of previous and current techniques are outlined below.

Grade Rods. Most likely due to the simplistic approach, research for this method is sparse but mentioned as a previous extraction method and a current quality control technique. Normally used for surveying applications, grade rods are an extendable measurement device with graduated units used to determine differences in elevation. A study by Lauzon (2000), notes that vertical clearance extraction performed by ConnDOT utilized a fiberglass measurement rod to determine the minimum vertical clearances of overpasses. Measurements were taken from each lane line and recorded to overhead clearance diagrams. The study also notes that this method requires traffic protection, which can be substantial on interstates and in urban areas.

Total station. Total stations combine electronic EDM (Electronic Distance Measurement) technology and theodolites into a single unit, they are capable of digitally calculating horizontal, vertical and slope distances and angles. Using an internal or external microprocessor, these digital data observations can be adjusted and transformed to local X, Y, Z coordinates (US Army Corps of Engineers 2007).

A few key measurements are required when utilizing a total station to determine the height of overhead objects. The graphic in figure 15 illustrates the typical parameters needed to calculate object heights, also referred to as remote elevation (REM).



P0	Instrument station
P1	Base point
P2	Remote point
d1	Slope distance
a	Height difference from P1 to P2
α	Vertical angle between base point and remote point

Figure 15. Remote Elevation Method. Leica user Manual, 2014, Adapted from http://surveyequipment.com/PDFs/Leica_FlexLine_UserManual.pdf

The principle of the REM method is explained through figure 15, where a base point P1 is positioned vertically below point P2. From the instrument P0, a measurement is taken at the prism above base point P1, providing the slope distance d1. A subsequent measurement at P2 is used to calculate the angular difference α, from P1. Given the height of the prism, the height (a) can then be calculated internally by the total station.

Traditional surveying techniques and equipment such as the total station are widely used and accepted by the Civil Engineering, surveying and mapping community. However, these operations often expose workers to dangerous conditions especially in highway applications. The Kentucky Highway Design Manual states that "surveyors work in hazardous environments, such as rugged terrain or in the vicinity of construction equipment and high-speed traffic. Working in these conditions requires a constant awareness of the need for safety" (KTC, 2006, p.812). Additionally, safety measures taken to protect surveyors and field personnel can directly affect traffic flow.

Laser Tape Measure. Techniques commonly used to aid in structural measurement include tape measurements combined with hand recording and optical methods (Banister, Raymond & Baker, 1998). Since the publication of this study in 1998, advancements in distance measuring devices such as the laser tape measure have been introduced. Utilizing laser tape meters has proven to be a more efficient and simplified method to extract vertical clearances over analog methods. The device can be operated by a single individual providing quick and accurate measurements displayed in a digital format. Although an improvement over previous methods, extracting overpass clearances via laser tape is not without its challenges. Accurate readings are obtainable, though many aspects of height extraction are subject to the individual operator. Human error and judgement can adversely affect the quality of the data. Visually assessing and determining the location of the lowest point overhead can be difficult, especially with changing roadway and structure geometry. Additionally, failure to hold a perpendicular angle to the roadway can result in inaccurate measurements.

Terrestrial Laser Scanner. In recent years, the use of terrestrial laser scanners (TLS) in engineering surveys has gained an increasing interest due to the advantages of high accuracy and rapid data collection. Millions of 3-D points can be delivered by this technology in a short period of time providing efficient data collection for large scale engineering applications such as roads, bridges and tunnels (Wang, Zhao, Huang, Vimarlund & Wang, 2014).

Stationary terrestrial laser scanning technology refers to laser scanning applications that are performed from a static point on the surface of the earth (CDOT, 2011). Utilizing many of the same principles found in MLS systems, terrestrial scanners differ in their platform. Often mounted atop a tripod, TLS scanners remain stationary during operation. Due to its static location, TLS systems are capable of highly accurate and rapid data collection. A study by Zhang, Arditi and Chen (2013), used a terrestrial laser scanner to measure the vertical clearances of thirty-seven bridges along the Circle Interchange in Chicago, IL. The study reports the data collection procedures undertaken to complete the project. Over the course of a month, 150 scans were completed using a Leica C10 terrestrial scanner. Scanning at midnight to avoid traffic disruption and data noise, each bridge consisted of four static scans per structure as depicted graphically in in figure 16.

Figure 16. Representation of scan locations. Reprinted from "Applications of Terrestrial laser scanning," by C. Zhang, D. Arditi, and Z. Chen, 2013, *Journal of traffic and Transportation Engineering, 1(5)*, p. 328.

Collected data was aligned and post processed to determine the minimum vertical clearances. The extracted measurements were then compared to AASHTO design guidelines and published into clearance reports for the state DOT. The authors state that data collection through the use of a total station would provide adequate results, although laser scanning is more accurate, generating millions of points as opposed to a limited number of specified points (Zhang et al, 2013). The study also notes that due to security concerns, some of the data was not available to the public. The scope of this study does not provide accuracy statistics, as structures were only tested to meet minimum clearance guidelines. Additionally, while TLS scanners were proven effective in measuring vertical clearances, traffic disruption and employee safety were not discussed.

Additional Technologies. Additional technologies have been developed; however, most are proprietary or developed privately. Little research is available and therefore were not included in this review.

Methodology

To compare differences between Mobile LiDAR and traditional methods, the research will identify procedures and workflows currently used to extract vertical clearances from civil infrastructures. Three different locations will be chosen for this study. Mobile LiDAR data will be collected using an Optech Lynx Mobile Mapping System, utilizing two V100 laser scanners. Traditional extraction methods will utilize a Spectre laser meter and a Nikon NPL-332 total station. Measurements extracted from the LiDAR data will be processed using CAD software. Vertical clearances will be extracted from each outside beam using roadway edge lines as a perpendicular reference. This study will collect measurements obtained using each technique from the same location. Graphical representations of the data will be analyzed along with a review of collection procedures and its perceived impact on traffic and safety.

Software Tools. Four software tools were used in this study: Microstation Connect Version 5, Topodot Version 3.7, Optech LMS Pro Version 3.2, and Applanix PosPac MMS Version 7.2. Microstation is a computer aided drafting program created by Bentley. PosPac MMS (Mobile Mapping Suite) is a software tool used in post processing GNSS data collected by the POS system (Positional Orientation System). Optech LMS Pro is a post processing platform which aligns laser scan data with trajectories exported from PosPac. Topodot is an add-on application running within Microstation used for extracting features, measurements, topographies, and 3D models from LiDAR point clouds.

Hardware. LiDAR Mobile Mapping System. This study utilizes an Optech LYNX V100 mapping system, as shown in figure 17. The system uses dual 360° scanners, capable of a combined collection rate of 200,000 points per second with an absolute accuracy of ± 5cm (1 σ). An Applanix POS LV sub-system composed of an LN-420 IMU, DMI, and dual Trimble Zephyr 2 GNSS antennas will also be used to log correlational position and orientation data.

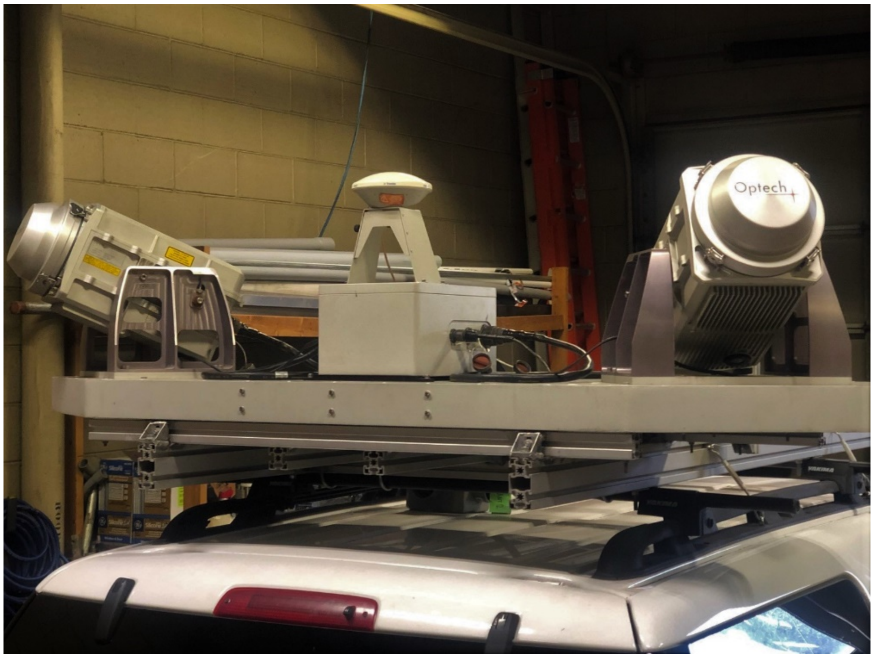


Figure 17. Optech LYNX Mobile Mapping System

Laser Meter. A Spectra Precision QM55 Laser distance meter will be used to measure vertical clearances as shown in figure 18. This device will be mounted to surveying prism pole as shown in figure 19 to provide perpendicular vertical measurements. Manufacturer's specifications list a maximum range of 165' with an accuracy of ± 1/16".

Figure 18. Spectre QM55 Laser Meter

Figure 19. Prism Pole attachment

Total station. A Nikon NPL-332 total station will be used obtain vertical clearance measurements as shown in figure 20. Manufacturers specifications list an accuracy of ± (2+2 ppm × D)mm for measuring distances, and a 5s resolution for measuring angles. To limit human error, a bipod and prism pole will be incorporated to aid in extraction of bridge clearances.

Figure 20. Nikon NPL-332 Total Station

Location Selection. Three locations were chosen for this project as shown in figures 21-23. The areas were selected based on site conditions where safety concerns for the traveling public and researchers could be adequately managed.

Figure 21. Cincinnati Rd at I-75 - Sadieville, KY.

Figure 22. Rogers Gap Rd at I-75 - Stamping Ground, KY.

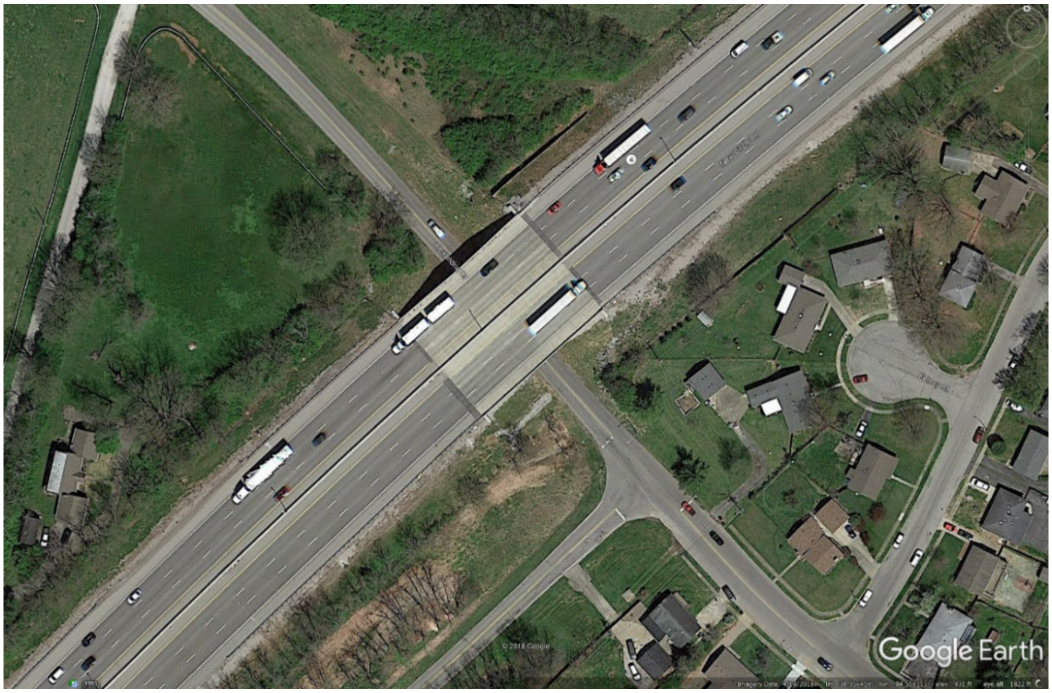


Figure 23. Alexandria Rd at New Circle - Lexington, KY.

Procedures

The experimental procedures conducted are the same for each test area and are described as follows:

Laser Tape. The laser tape device was affixed to a survey rod and bipod to ensure level, perpendicular measurements from the roadway surface. Through the use of the integrated laser, the center of each beam was located and measured from roadway edge lines. In areas where no lane lines were present, a distance from 6” from the pavement edge was used. A PK nail was driven into the asphalt to ensure location accuracy between methods. The average of three measurements were taken from each location and recorded. The height of the instrument was measured from the ground and added to each measurement to calculate total height.

Total Station. Using the PK nail as a reference, the pole, bipod, and prism were placed under the targeted beam as shown in figure 24. The total station was set up and leveled as shown in figure 25. Using the REM method, measurements were collected and recorded for each location.

Figure 24. Survey Pole, prism, bipod set up.

Figure 25. Total station setup.

Mobile LiDAR. An Optech Lynx Mobile Mapping System as shown in fig x was used to scan the project areas after the field measurements were completed. A boresight procedure as discussed below was performed in order to calibrate the system for the upcoming scan. Travelling at a constant speed of 40MPH, data was collected from each structure.

Figure 26. Optech Lynx Mobile Mapping System.

Post Processing. Trajectory and GPS information collected from the POS (Position Orientation System) during scanning operations was post processed through Applanix POSPAC MMS software. Using data from continuously operating reference stations (CORS) to compute a set of corrections for the roving receiver, the software is capable of exporting an accurate overall position and orientation solution. The exported smoothed best estimate of trajectory (SBET) file is GPS timestamped and used to align with correlational LiDAR outputs. Data used in this study was processed with six CORS stations, KYBO, KYTF, GRTN, KYTI, KYBU and KYTG as shown in figure 27. The solution was then exported using the Kentucky Single Zone coordinate system. Additional metrics for the trajectory solution can be found in Appendix A.

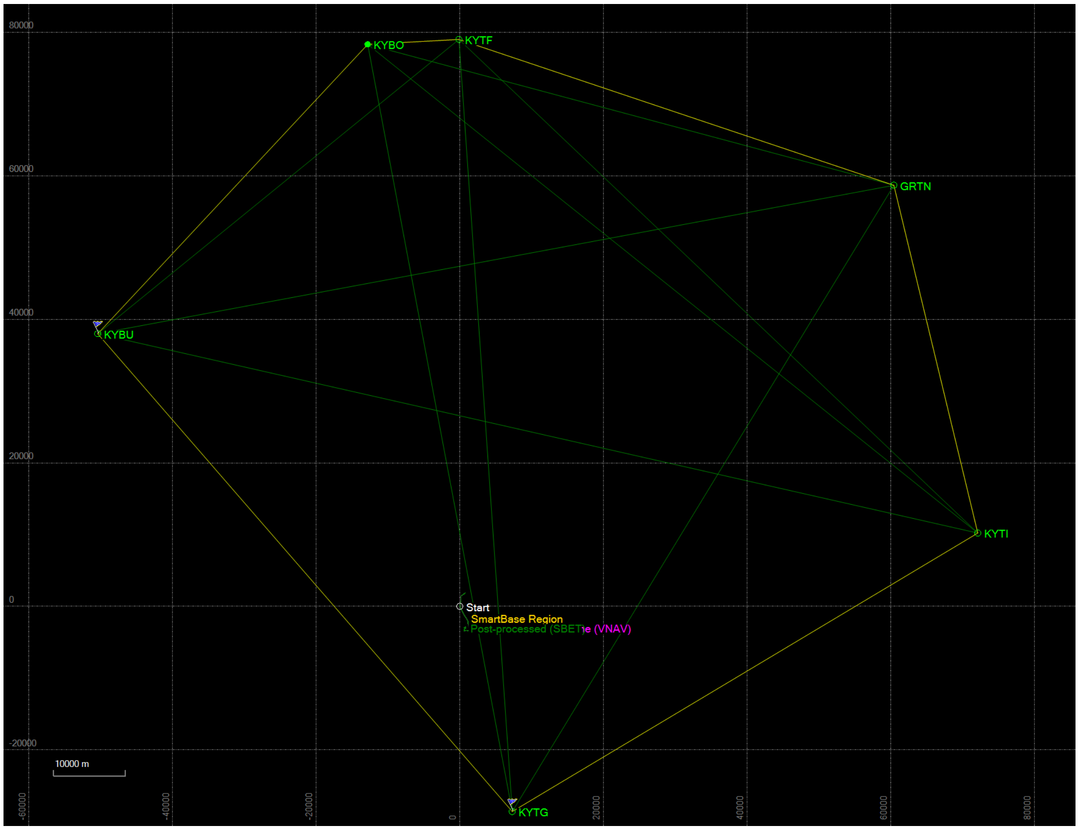


Figure 27. POSPAC Basestation control network

System calibration/boresight. System calibration parameters were obtained using a boresight scan. Data was collected in order to calculate differences in like planar surfaces detected from each sensor. Multiple passes produce a set of point clouds covering redundant surface observations. Recommended conditions for the boresight area should include objects with multiple planar surfaces in various orientations. Areas with tall buildings or tree canopies should be avoided in order to retain consistent GPS data. During post-processing LMS software detects differences in planar surface orientations. Using the method of leastsquares, the software determines a set of unknown parameters from a set of redundant observations. Misalignments between the measurement axes of the IMU and laser scanners are calculated. The software applies a correctional value to offset errors in laser range, scan angle, sensor position and orientation. The values are then applied to the instrument in order to produce corrected data for the scan project (Optech LMS Manual, 2013).

An urban intersection was chosen as the boresight location for this project. This area provided multiple buildings with limited overhead obstructions. Four passes were made in order to obtain planar surfaces from different orientations. Figure 28 shows the point cloud of the scanned area. Figure 29 shows planar surfaces extracted for boresighting calculations. Using the corrected parameters from the boresight, LMS software was used to export the point cloud for each overpass. Figure 30 shows an image of the exported point cloud for the Cincinnati Rd. location.

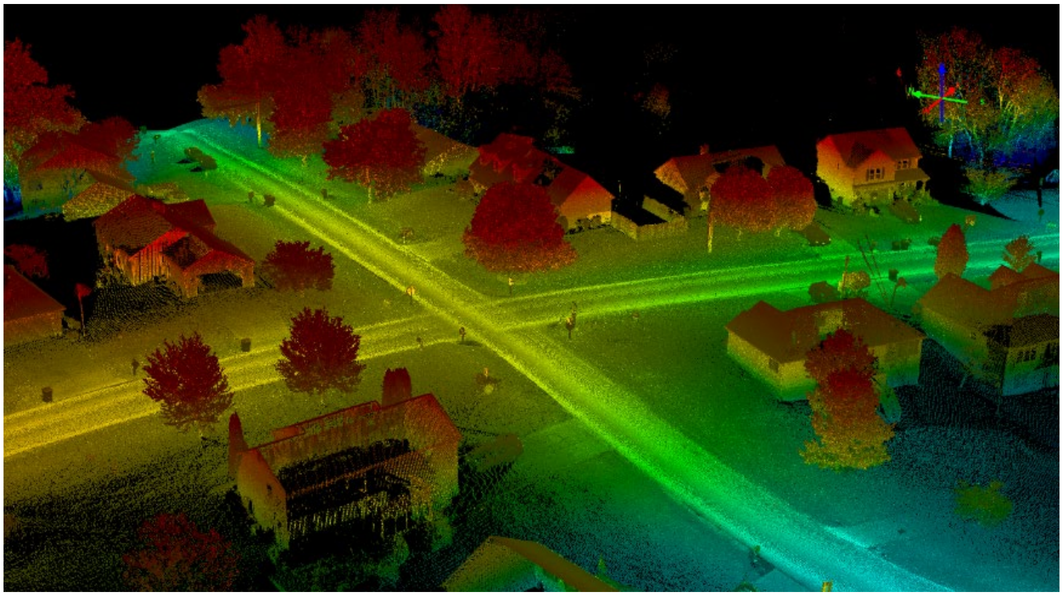


Figure 28. Point cloud of boresight area

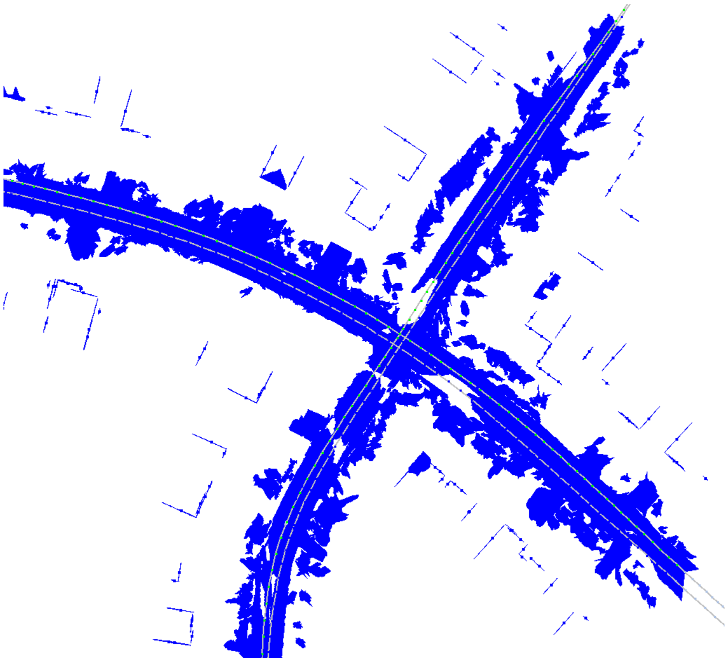


Figure29. Detected planar surfaces extracted from boresight.

Figure 30. Cincinnati Rd. point cloud.

Clearance Extraction. A combination of Bentley Openroads Designer and TopoDOT software was used to extract minimum clearances from the point clouds. Visualizing the data by intensity values, exterior lane lines were used as a reference path for the extraction tools. Given the referenced line, the software calculates the clearance values between the roadway and the above structure. Cross section examples for each project location depicting minimum clearances are shown in figures 31-33. Table 2 shows the clearance values for all measurement methods.

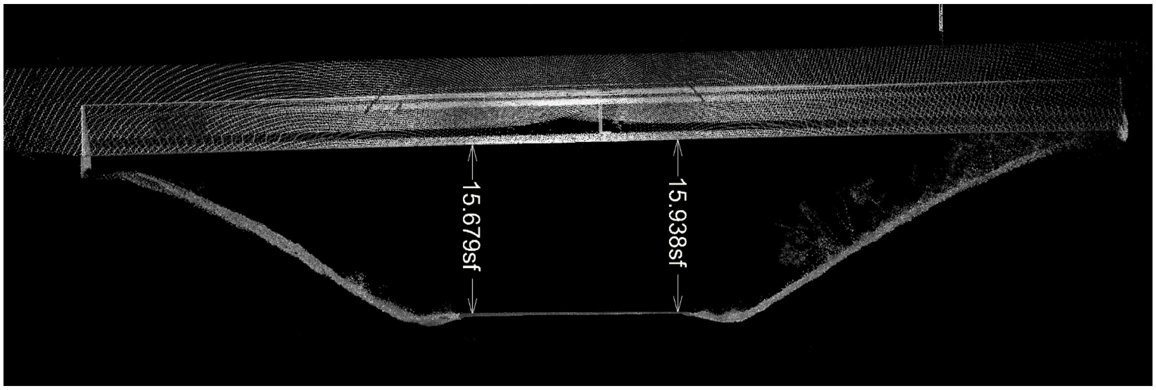


Figure 31. Rogers Gap cross section.

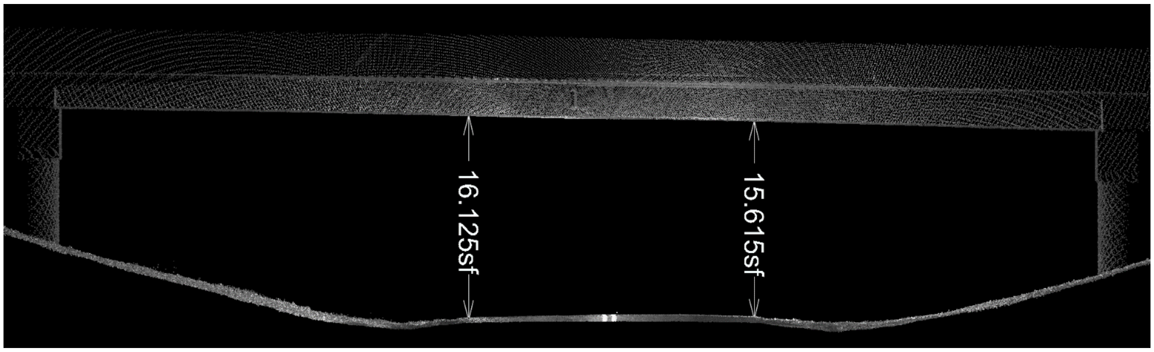


Figure 32. Alexandria Dr. cross section.

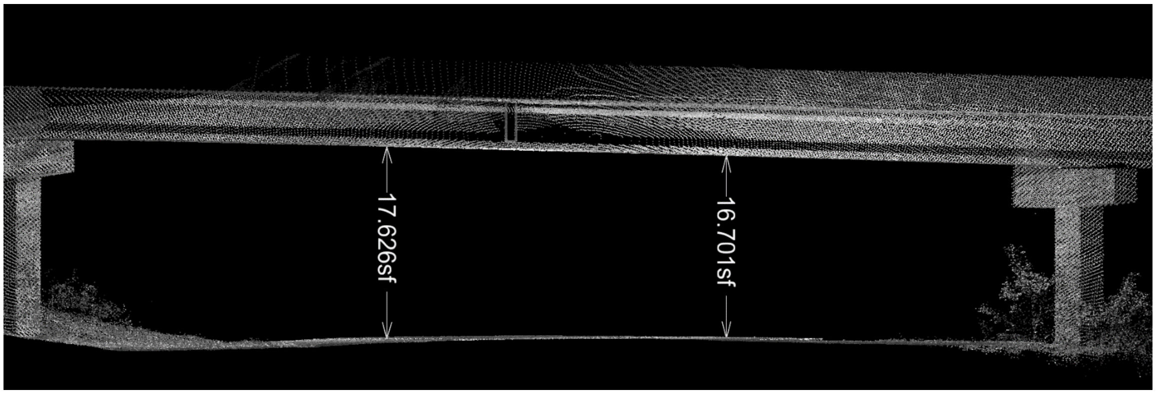


Figure 33. Cincinnati Rd. cross section

Table 2.

Measurement Results in feet

Alexandria Dr. at New Circle Rd.			
Location	**LMS**	**Laser Tape**	**REM**
Southern Beam NB	15.615	15.655	15.609
Northern Beam NB	20.963	20.977	20.910
Southern Beam SB	16.125	16.182	16.125
Northern Beam SB	21.393	21.412	21.317

Cincinnati Rd at I-75			
Location	**LMS**	**Laser Tape**	**REM**
Southern Beam NB	17.626	17.646	17.588
Northern Beam NB	21.877	21.888	21.810
Southern Beam SB	16.701	16.723	16.664
Northern Beam SB	20.824	20.837	20.789

Rogers Gap Rd at I-75			
Location	**LMS**	**Laser Tape**	**REM**
Southern Beam NB	16.856	16.844	16.861
Northern Beam NB	15.938	15.957	15.906
Southern Beam SB	16.405	16.439	16.431
Northern Beam SB	15.679	15.693	15.691

Method of Data Analysis

The results of this study can be divided into two parts. First a One-Way Anova test was run to statistically show how each method of clearance extraction performed relative to the others under the same conditions. The researcher tested the hypothesis that the Laser tape, REM, and LiDAR methods did not show statistical differences between each collected dataset using an $\alpha=0.05$. Table 3 provides a summary of the defined alternative hypotheses (H_1) as well as the null hypotheses (H_0). The null hypothesis (H_0) will be rejected if the one-way ANOVA test falls into the rejection region ($p<.5$). Otherwise, the null hypothesis would be retained. The laser tape group is represented by $\mu_{1,}$ REM method by $\mu_{2,}$ and LiDAR by $\mu_{3.}$ Sample size for each group is represented by n. Second, the researcher compared each method on operational procedures, impact on work zone safety and traffic disruption.

Table 3

Hypothesis Summary.

H_0: $\mu_1 = \mu_2 = \mu_3$
H_1: Means are not all equal

Threats to Validity

Several factors could threaten the validity of this study. First, Mobile LiDAR technology can be affected by rain, fog, snow, or dust present in the scanning atmosphere. Data collection performed during these conditions can adversely affect data quality. Additionally, the GPS component is dependent on satellite coverage and signal strength. The precision of the GPS can vary day-to-day depending on atmospheric conditions. Traffic can also affect the collection of LiDAR data; any surrounding vehicles can prevent the laser from reaching its target surface. Laser tape and total station methods require precise setup and operational decisions that could impact the quality of data acquired.

Results and discussion

Statistical analysis. A one-way ANOVA was conducted to determine if collected measurements were statistically different for groups using different collection methods. Methods were classified into three groups: Laser tape ($n = 12$), Mobile LiDAR ($n = 12$), and REM ($n = 12$). There were no outliers, as assessed by boxplot (Appendix B). The mean of measurement increased from the REM ($n = 12$, $M = 17.958$, $SD = 2.433$), to Mobile LiDAR ($n = 12$, $M = 18.00$, $SD = 2.481$), to Laser Tape ($n = 12$, $M = 18.021$, $SD = 2.477$) measurement method groups, in that order, but the differences between these groups were not statistically significant, $F(2, 33) = 0.002$, $p = .998$. The group means were not statistically different ($p > .05$). Therefore, we cannot reject the null hypothesis and we cannot accept the alternative hypothesis. The second analysis looks to discuss operational procedures as well as each methods impact on traffic and safety. Due to safety concerns, site selection for this project was based on locations with low traffic flow. However, the procedures undertaken can be theoretically applied to high traffic areas.

Remote Elevation Method. Data collected using the REM method proved to be the most challenging. The magnified sights of the total station limited the field of view, dark conditions and similar materials made it difficult to distinguish features and locate individual beam centers. Small changes in vertical inclination of the instrument can significantly change the result of the intended measurement, this effect was apparent when performing operations at close range. Setup and data acquisition time was moderate, multiple setups for each structure were required in order to retain a line of sight to the intended target. Multiple setups introduce a greater possibility for error. Improper leveling and varying instrument heights can skew results. This method requires workers to occupy areas of interest below the structure, potentially exposing them to hazardous situations. Depending on site layout and bridge design this method may require the use of traffic control measures to provide a safe working environment.

Laser Tape. The laser tape proved to be the fastest method of acquiring vertical clearance data when a limited number of data points are needed. Results are obtained in real time and the operation can be carried out by a single individual. This method directly subjects workers to vehicular traffic hazards for the longest duration. Individuals must level the instrument under the overhead target while acquiring measurements, potentially distracting them from surrounding hazards. The Laser tape, when added to a bipod and prism pole can mitigate human error when used properly. However, if the pole is out of level the correct value may not be obtained. Depending on site conditions, this method may require additional traffic control measures.

MLS. This method did not require any workers to be present under the structures and had little to no impact on traffic. Traffic control measures are usually not required unless needed under special circumstances. Unlike the REM and laser tape method, LiDAR technology does not provide real time data. Additional time is needed to post process the trajectory and point cloud data before extracting results. Boresighting procedures are also recommended before data collection. Unforeseen complications in GPS signal quality or hardware components can negatively impact accuracies. LiDAR systems require additional resources such as hardware, software, and trained personnel and therefore may not be always be a feasible option.

Data collected for this study concentrated on extracting clearance heights from exterior lane lines. However, changing roadway geometry and bridge designs can result in overhead clearance variability, reducing minimum clearances in other locations below the structure. In these scenarios, additional traffic control measures may be needed to properly access and measure these areas when using the REM or laser tape methods.

Conclusion

No significant statistical differences were observed between the laser tape, REM, and MLS methods. Therefore, the study found that all three methods of vertical clearance extraction are capable of providing accurate measurements under the right conditions. The selection of which technology to utilize involves multiple factors such as site conditions, time, environmental conditions, resource availability, and safety provisions. The laser tape and REM methods provide a proven option to extract clearances on small scale projects in low traffic areas where safety concerns can be adequately managed. Mobile LiDAR is best suited for projects involving multiple structures, variable overhead clearances, hazardous conditions or areas prone to traffic congestion such as interstates or parkways.

Future Research

While the current research provides a solid basis for the use of MLS systems to determine minimum clearances for bridge structures, the technology is not a one size fits all approach. This study identifies several key points; however, it does not discuss cost variability between methods. A cost benefit analysis encompassing all aspects of various projects and methods would further aid in future decision-making processes.

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APPENDIX A

Trajectory and GPS Tracking information and metrics.

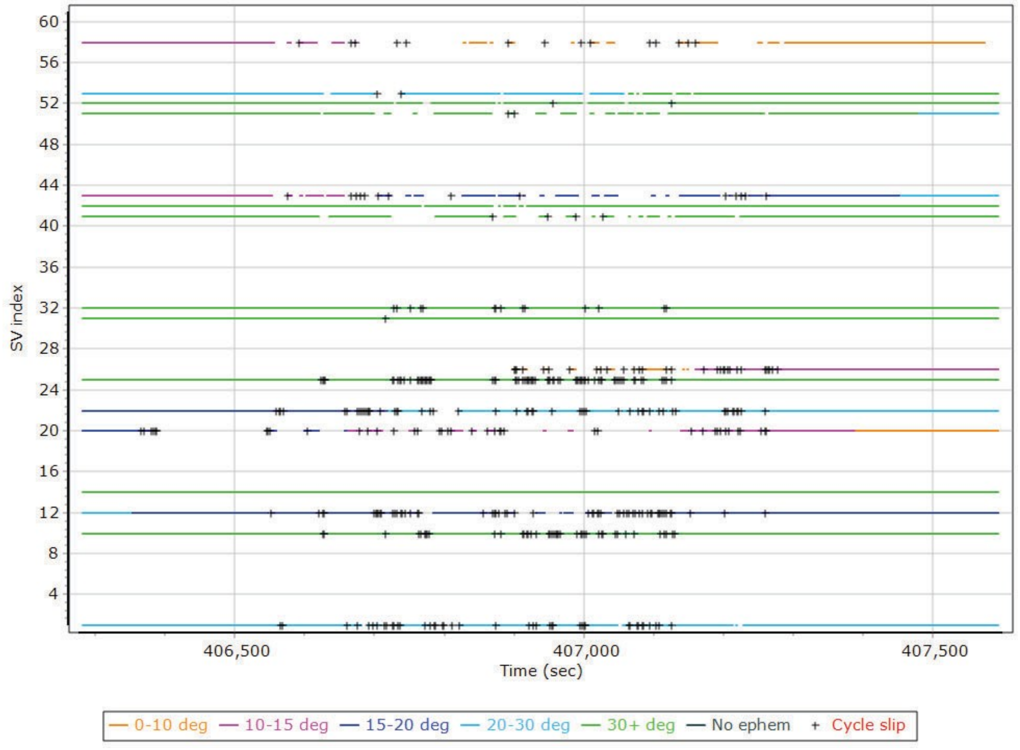
Rover Data QC

Raw IMU Import QC Summary

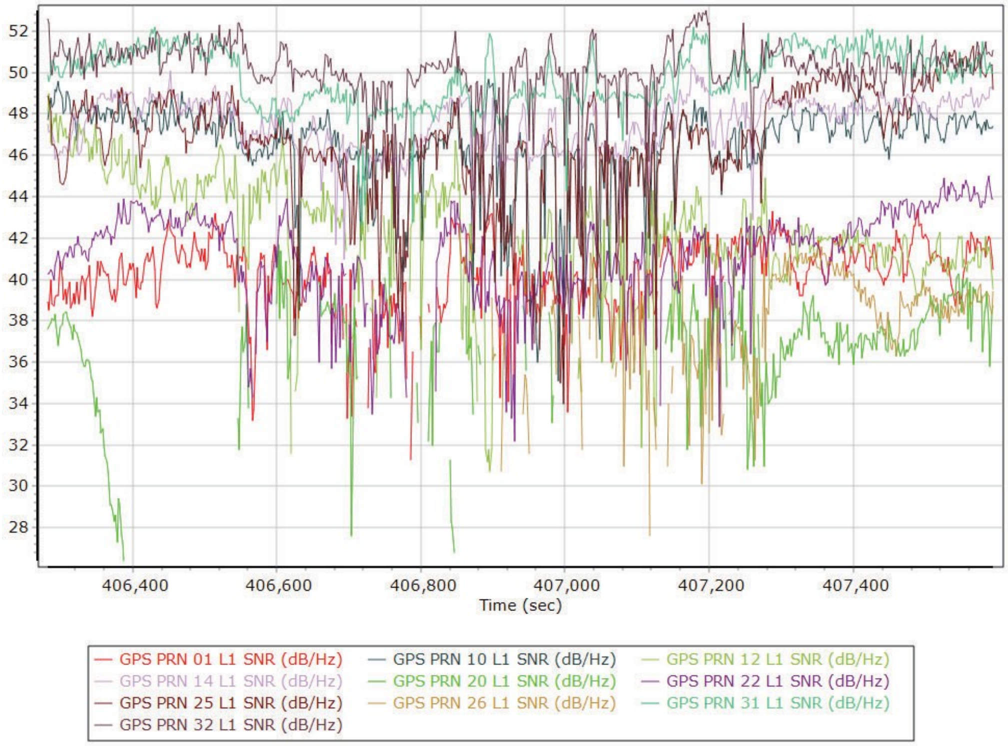
IMU data input file	imu_Mission 1.dat
IMU data check log file	imudt_Mission 1.log
IMU Records Processed	275371
Termination Status	Normal
IMU Anomalies	0

Primary Observables & Satellite Data

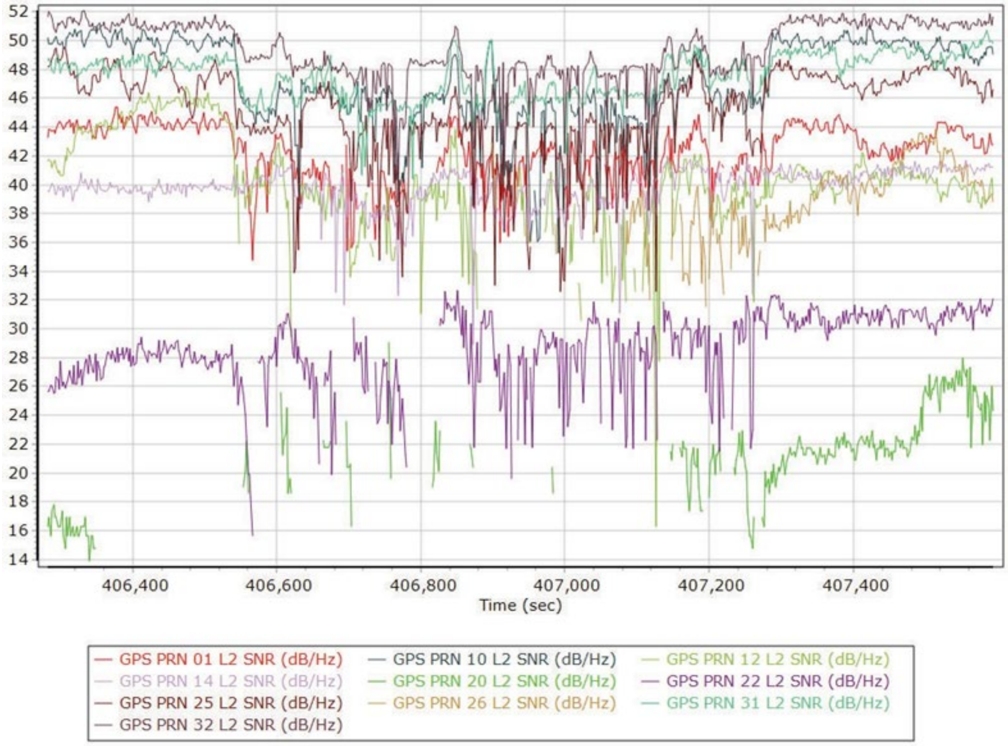
L1 Satellite Lock/Elevation



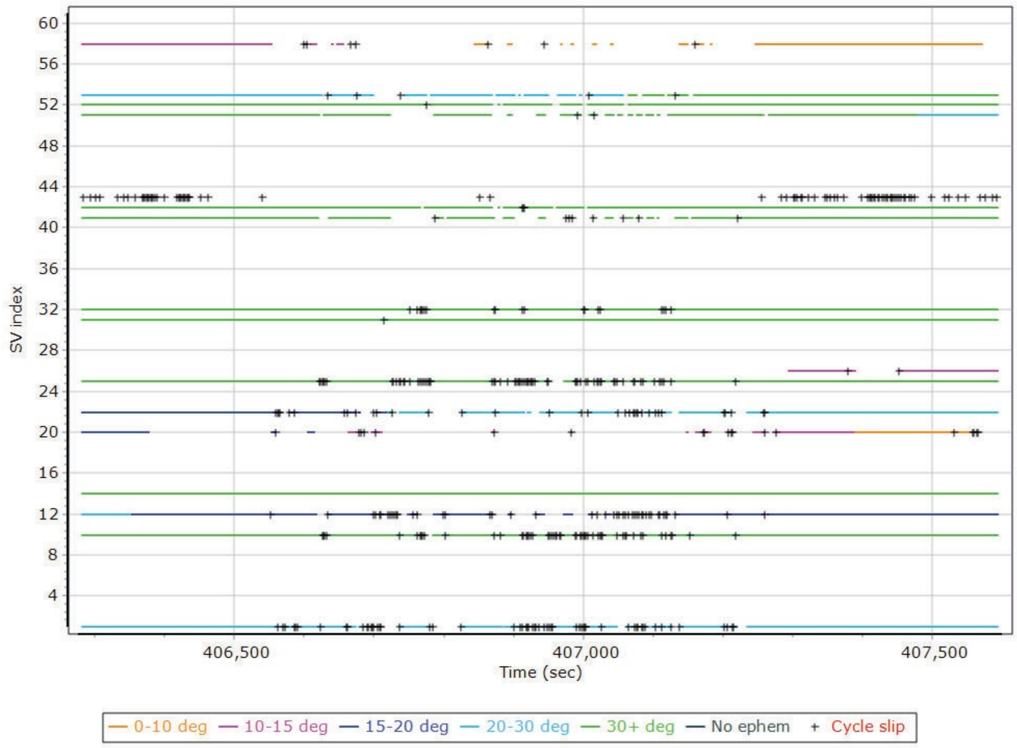
GPS L1 SNR



GPS L2 SNR

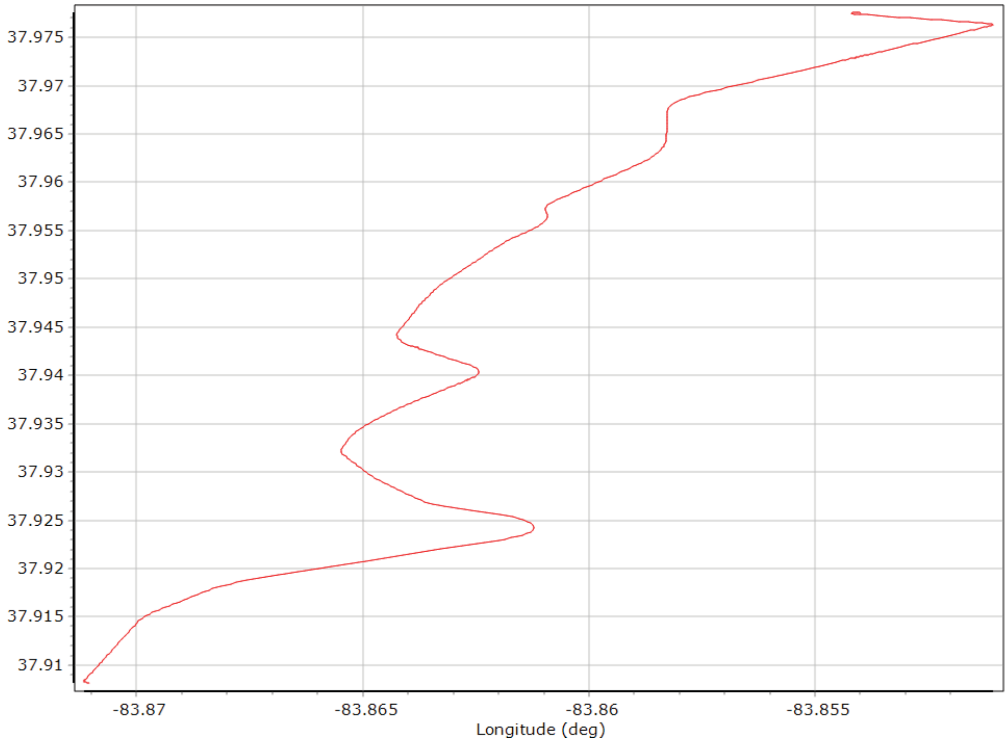


Satellite Lock/Elevation

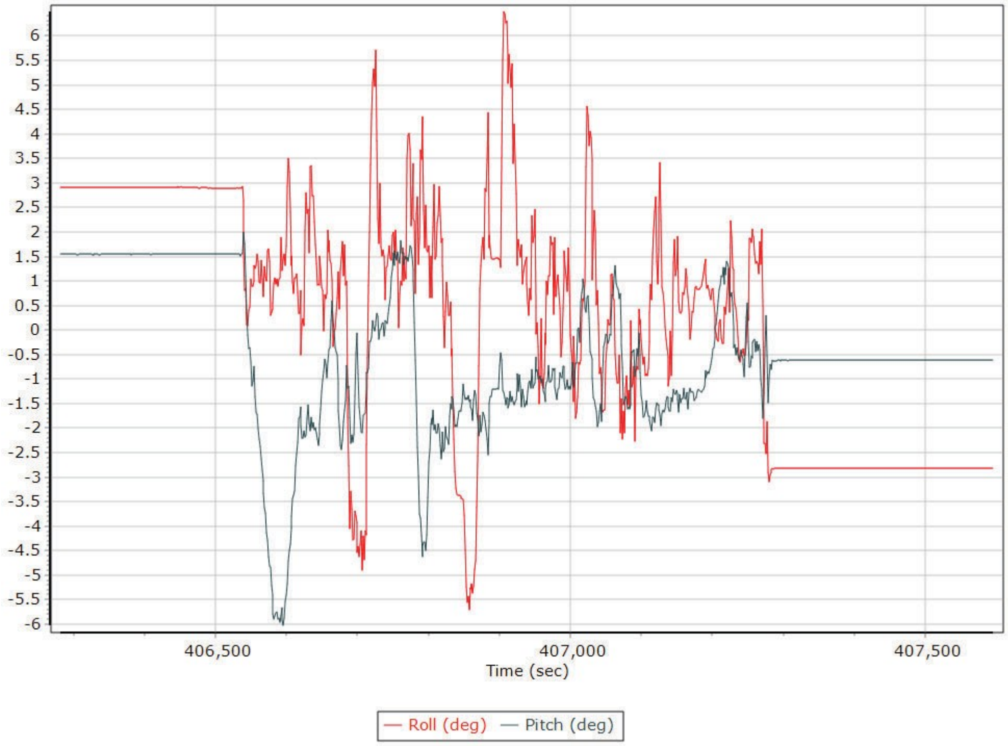


Smoothed Trajectory Information

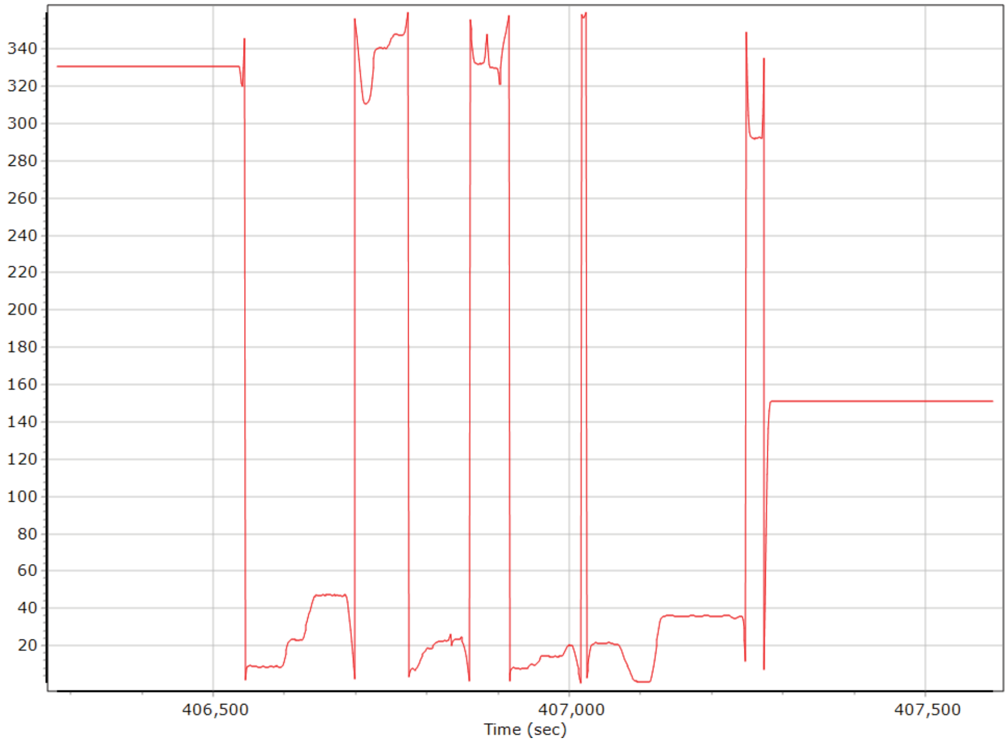
Top View



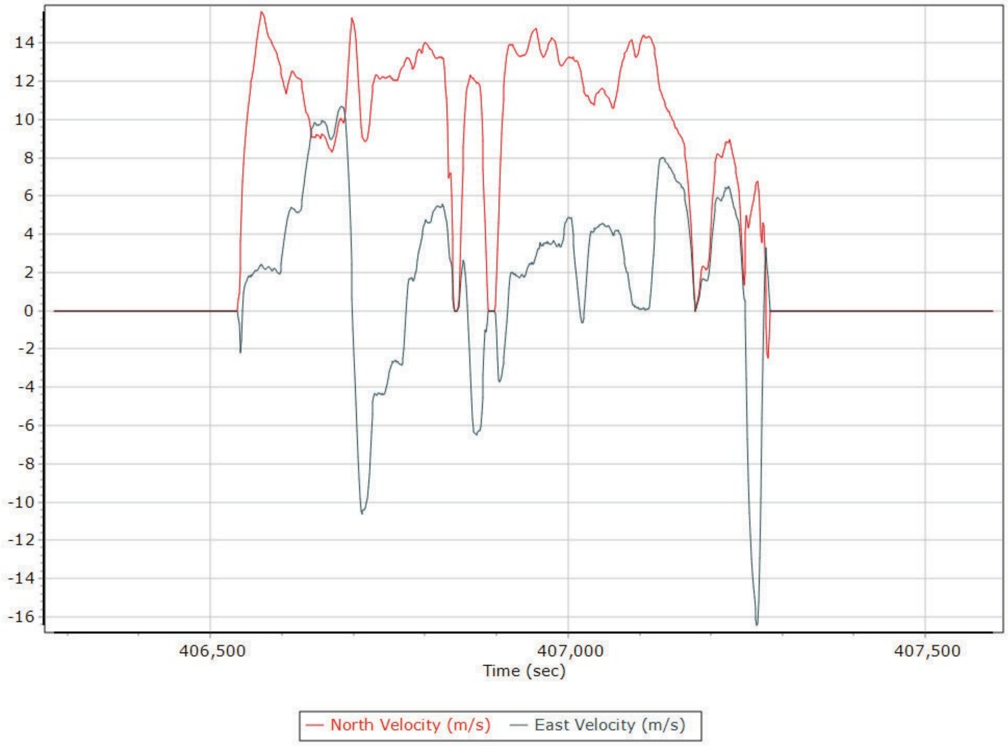
Roll/Pitch



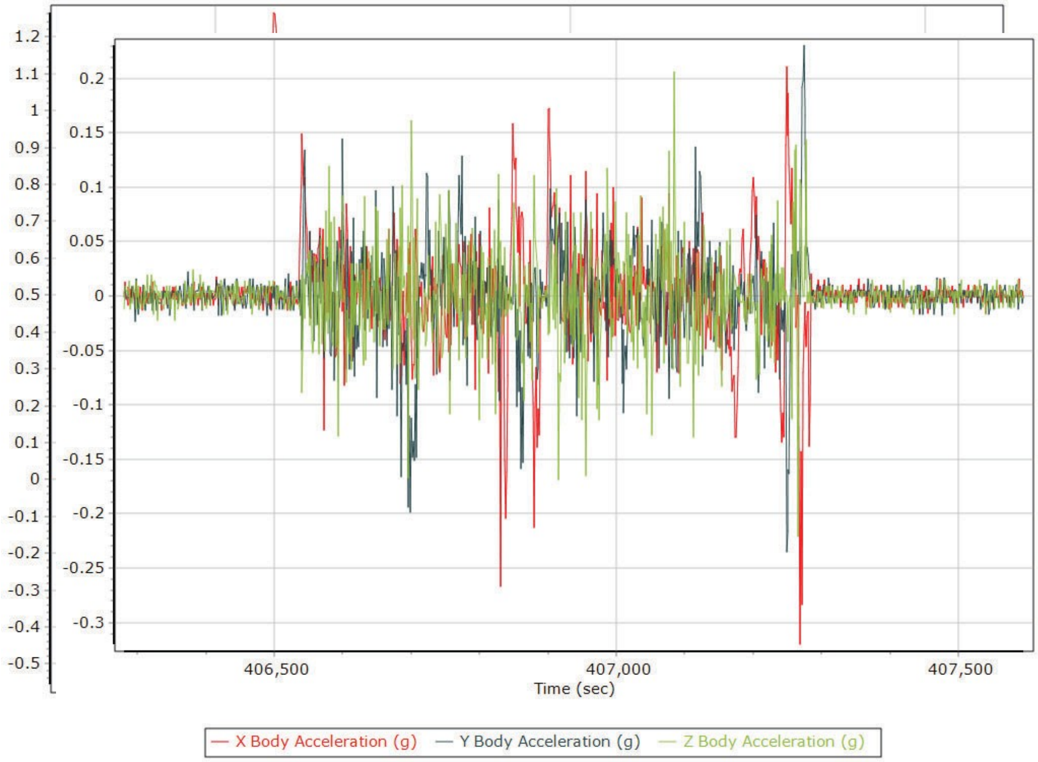
Heading



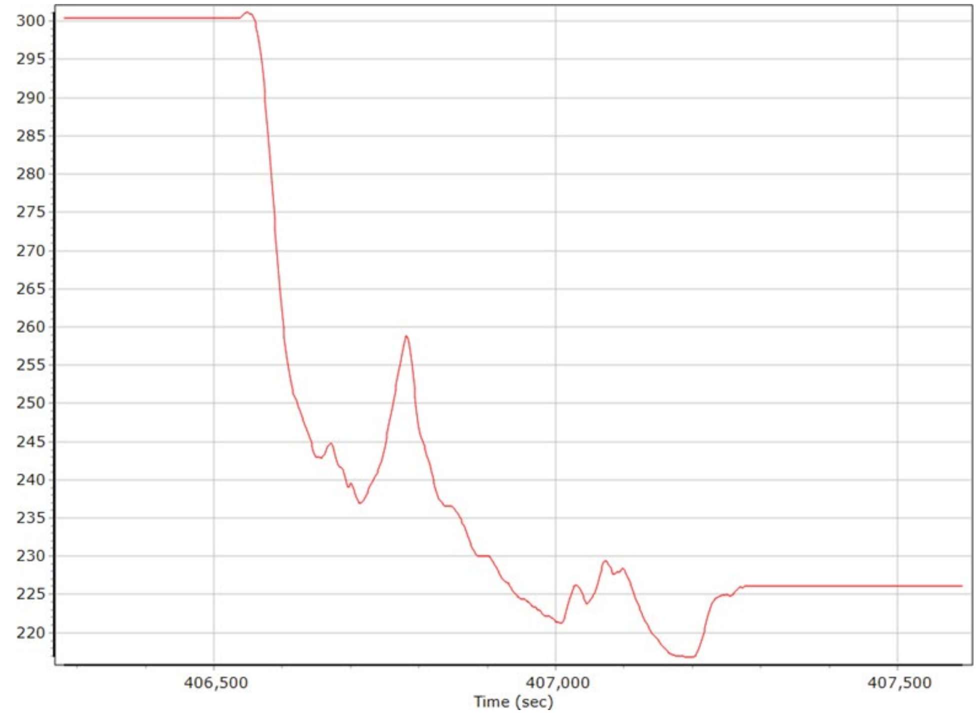
North/East Velocity



Down VelocityBody Acceleration



Altitude


300
295
290
285
280
275
270
265
260
255
250
245
240
235
230
225
220
406,500
407,000
407,500
Time (sec)

APPENDIX B

One-way Anova Descriptives and Boxplot.

Measurement

	Sum of Squares	df	Mean Square	F	Sig
Between Groups	.025	2	.012	.002	.998
Within Groups	200.345	33	6.071		
Total	200.369	35			

Measurement

				95% Confidence Interval for Mean			
	N	Mean	Std. Deviation	Lower Bound	Upper Bound	Minimum	Maximum
Laser Tape	12	18.02117	2.447189	16.44724	19.59510	15.655	21.889
REM	12	17.95842	2.433109	16.41249	19.41249	15.609	21.810
Mobile LiDAR	12	18.00058	2.481262	16.42406	19.57710	15.631	21.877
Total	36	17.99339	2.392662	17.18383	18.80295	15.609	21.889