LiDAR for Data Efficiency

WA-RD 778.1

Kin S. Yen
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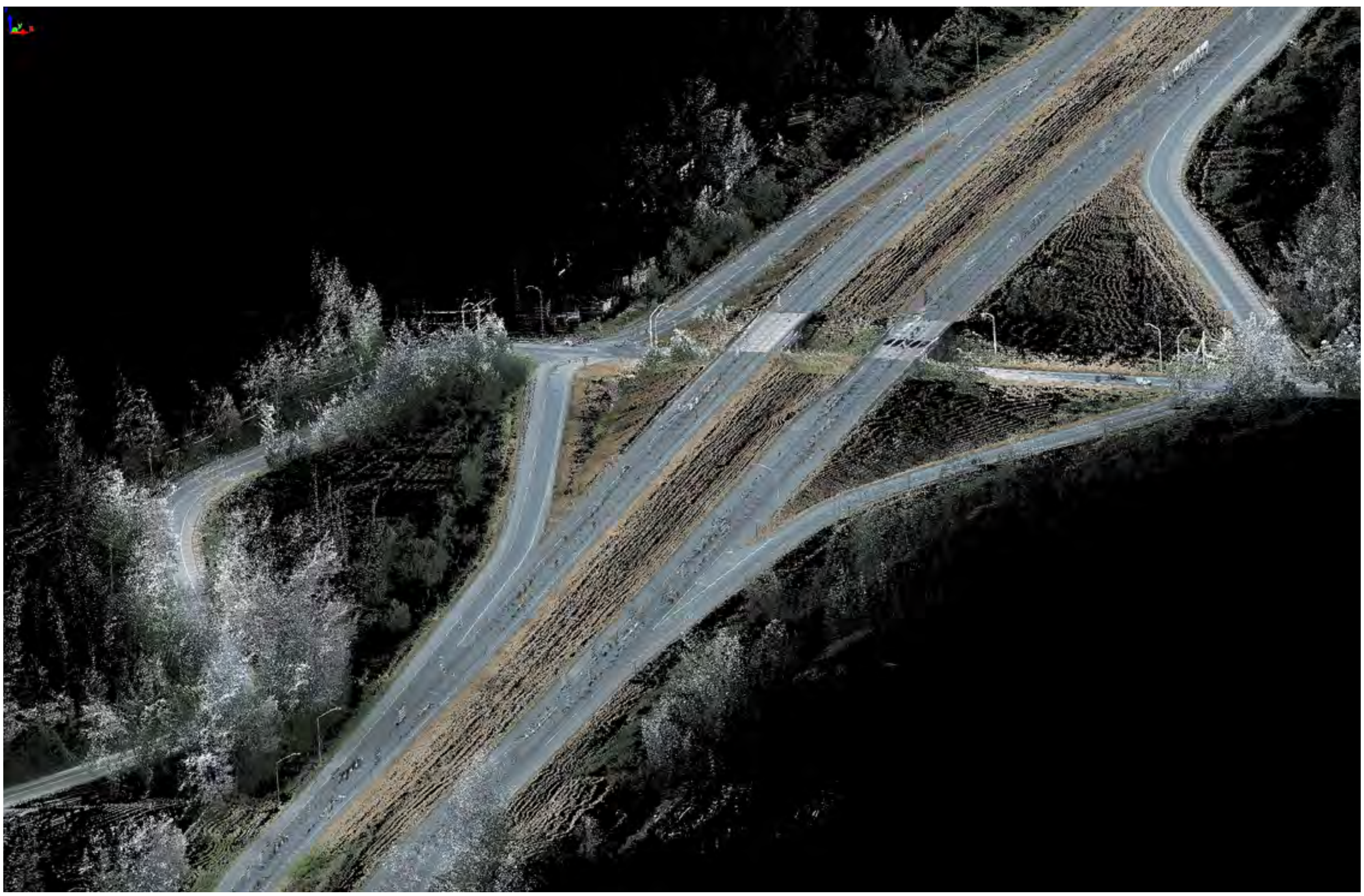
September 2011



Washington State Department of Transportation
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WSDOT Research Report

Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

LiDAR for Data Efficiency

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Ty A. Lasky, Principal Investigator

Report Number: WA-RD 778.1
AHMCT Research Report: UCD-ARR-11-09-30-01
Final Report of Contract: GCA6059

September 30, 2011

Washington State Department of Transportation

Prepared for:
The State of Washington
Department of Transportation
Paula J. Hammond, Secretary

Technical Documentation Page

1. Report No. WA-RD 778.1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LiDAR for Data Efficiency		5. Report Date September 30, 2011
		6. Performing Organization Code
7. Author(s): Kin S. Yen, Bahram Ravani, and Ty A. Lasky		8. Performing Organization Report No. UCD-ARR-11-09-30-01
9. Performing Organization Name and Address AHMCT Research Center UCD Dept. of Mechanical & Aerospace Engineering Davis, California 95616-5294		10. Work Unit No. (TRAIS)
		11. Contract or Grant GCA6059
12. Sponsoring Agency Name and Address Washington State Department of Transportation Transportation Building, KF-01 Olympia, Washington 98504 Rhonda Brooks, Project Manager, 360-705-7945		13. Type of Report and Period Covered Final Report June 2009 – Sept. 2011
		14. Sponsoring Agency Code WSDOT
15. Supplementary Notes		

16. Abstract

This report documents the AHMCT research project: "LiDAR for Data Efficiency" for the Washington State Department of Transportation (WSDOT). The research objective was to evaluate mobile LiDAR technology to enhance safety, determine efficiency gains, accuracy benefits, technical issues, and cost benefits of using this technology with a focus on collection, processing, and storage of the data into current WSDOT business processes. Vehicle mounted terrestrial mobile LiDAR systems have been developed to capture geospatial data of large highway areas at highway speed for highway surveying, asset management, as-built documentation, and maintenance operations. This tool presents an opportunity for WSDOT to consolidate geospatial data collection operations, and improve efficiency, safety for workers, and mobility of traveling public. A field pilot study was conducted to collect empirical data for feasibility evaluation and cost benefit analyses. While the pilot study demonstrated the potential positive impact in WSDOT business processes, it also highlighted the need for best practices documentation for using mobile LiDAR for DOT to ensure consistent and accurate results.

Details of data collection methods and cost for WSDOT Roadside Feature Inventory Program (RFIP), bridge clearance measurement, and ADA feature inventory were gathered. These programs would achieve direct cost saving in deploying mobile LiDAR system. Cost benefit analyses of seven mobile LiDAR deployment options are presented. Purchasing and operating a survey grade mobile LiDAR system produced the highest savings of $6.1 million in six years. Although deploying the survey grade mobile LiDAR system costs more, the benefits and cost saving from the bridge clearance operation and ADA feature inventory outweighs the higher cost and produces higher saving. Mobile LiDAR technology lowers the number of FTEs, vehicles, and carbon dioxide emissions for data collection. The major intangible benefactors are WSDOT's GeoMetrix Office, Geotechnical Office, Planning Office, Environmental Office, and Attorney Generals (AG) Office. The technology could also be useful in other state agency application areas such as cultural heritage preservation, homeland security, construction inspection, and machine guidance in construction. Deployment of a mobile LiDAR system is recommended.

17. Key Words	18. Distribution Statement
Mobile LiDAR, Asset Management, RFIP, Bridge Clearance Measurement, Mobile Mapping, WSDOT	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

20. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	98	

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EXECUTIVE SUMMARY

CURRENT ISSUES WITH GATHERING GEOSPATIAL DATA IN WSDOT

Currently there are multiple WSDOT business areas gathering geospatial data that is specific to their work that covers the same locations and using a variety of data collection standards and methods. Often times, the same features are being gathered and duplicated in separate databases. These decentralize data collection processes increase staff exposure to traffic and other hazards, add personnel equipment, & travel costs, and create unnecessary traffic delays for the traveling public.

ANOTHER WAY

This is where vehicle-mounted mobile Light Detection And Ranging (LiDAR) systems come in. Mobile LiDAR systems have been developed to capture geospatial data of highways including pavement and roadsides at highway speed to gather data for surveying, asset management, as-built documentation, and maintenance operations. The resultant point cloud is then post-processed to extract mapping data, roadside asset feature data, and various measurements. The extracted data can be readily imported into a database for analysis accessible by all WSDOT business areas, thus reducing duplicate data collection and storage. Also, the point cloud itself would be made available to Design Teams to extract existing project data elements, reducing the time needed in field surveys, reducing their exposure to traffic and the elements. This new tool presents an opportunity for WSDOT to consolidate geospatial data collection/storage and improve overall efficiency of resources and costs.

RESEARCH INTO MOBILE LiDAR

This research evaluated the mobile LiDAR technology to determine:

- The feasibility of using mobile LiDAR technology to fulfill WSDOT geospatial data requirements.
- The costs and benefits of mobile LiDAR technology to WSDOT business processes and the best deployment option to achieve maximum benefit.
- If any other state agencies’ existing business practices could benefit from mobile LiDAR technology.

THE RESERCH PROJECT

In the beginning the AHMCT researchers from UC Davis and the Technical Advisory Group (TAG) team, made up of WSDOT division representatives, researchers, and other state DOT representatives polled the divisions of WSDOT about their current geospatial data requirements and their surveying business practices. This information was then sorted, cataloged, and analyzed. The AHMCT researchers also presented what LiDAR is and constantly kept the TAG Team updated on the latest information on mobile LiDAR technology and research findings.

The TAG team also learned what other state DOTs have done and are doing with mobile LiDAR from other state DOT experts. A few state DOTs, such as TnDOT, Hawaii DOT, NVDOT, and TxDOT, have contracted with mobile LiDAR service providers for asset management. Caltrans has contracted with a mobile LiDAR survey firm to perform bridge clearance measurements and pavement survey on all Caltrans-maintained roads throughout California. Recently, ODOT has purchased a mapping grade mobile LiDAR system. In addition, mobile LiDAR vendors presented their latest state of LiDAR technology and workflow to deliver useful data to DOT.

THE PILOT STUDY

With support from the WSDOT GIS and Roadway Data Office, GeoMetrix Office, Maintenance, and, Bridge, Traffic, Pavement Management and Research, five vendors volunteered to operate their systems to collect data. One of the vendors also extracted features of interest from their resulting point cloud. The GeoMetrix Office then reviewed each of the vendor's point clouds.

This pilot study provided empirical data for the feasibility of LiDAR and demonstrated the mobile LiDAR system's benefits to WSDOT by eliminating worker's exposure to traffic by keeping them inside the vehicle or in the office, saving travel costs and delays to traffic. The study showed that this new technology would fit well into several WSDOT business processes, such as asset management, maintenance needs, engineering, and construction. The data can also be used for bridge vertical and horizontal clearances and to supplement the ADA feature inventory.

LiDAR DEPLOYMENT OPTION ANALISYS

Cost benefit analyses of seven mobile LiDAR deployment options were developed. These options are:

1. Contract for mobile LiDAR services (<u>mapping grade</u>)
2. Contract for bridge clearance measurement services
3. Rent and operate a <u>mapping grade</u> mobile LiDAR system
4. Purchase and operate a <u>mapping grade</u> mobile LiDAR system
5. Rent and operate a <u>survey grade</u> mobile LiDAR system
6. Purchase and operate a <u>survey grade</u> mobile LiDAR system
7. Purchase fractional ownership of a <u>survey grade</u> mobile LiDAR system

The cost of each option is broken down into: data collection cost, IT cost, and data extraction cost. The IT cost is dominated by the data storage costs and is relatively fixed across all options. Table 3.11 (page 30) provides a summary of the costs for each option. They range from $1.3 million to $10.7 million for the six year life span of the equipment allowing for three 2-year cycles of data. In all options, approximately half or more of the cost is the data extraction cost.

The RFIP, bridge vertical and horizontal clearance measurement, and ADA feature inventory program directly contribute to the dollar saving in mobile LiDAR deployment. Details of data collection methods and cost for RFIP, bridge clearance measurement, and ADA feature inventory are provided in Chapter 3. The first data collection cycle is generally more expensive than subsequent cycles due to higher data extraction costs in the first cycle and lower data extraction cost in subsequent cycles. Option 6, purchasing and operating a survey grade mobile LiDAR system, produced the highest savings of $6.1 million. Even though equipment rental options have lower initial cost and using a service has no initial cost, the purchase options have lower lifecycle cost and produce larger saving than the rental options.

The intangible benefits of deploying a mobile LiDAR system could be potentially larger than the tangible benefits. Mobile LiDAR technology lowers the number of FTEs, vehicles, and carbon dioxide emissions for data collection. In addition it increases the speed of data collection and reduces time to acquire the critical geospatial data for the data-driven decision making process. Long time delay between data requested and data provided is often the invisible cause of project delays and cost overruns. The major intangible benefactors are the WSDOT's GeoMetrix Office, Geotechnical Office, Planning Office, Environmental Office, and Attorney Generals (AG) Office and other state agencies, such as cultural heritage preservation, homeland security, construction inspection, and machine guidance in construction.

CONCLUSIONS AND RECOMMEDATIOMS

Mobile LiDAR presents a new technology to accomplish existing WSDOT operations and practices. It has the ability to modernize some WSDOT operations with efficiency and improved desirable outcomes such as improved employee safety and improved accuracy of data. The study shows a cost efficiency that could be realized over time with using Mobile LiDAR to supplement or replace existing WSDOT operations and processes. Purchasing and operating a Mobile LiDAR system has the potential to generate considerable savings, while meeting most WSDOT business requirements, although there are some key implementation issues that must be addressed. These include funding, procurement methods, organizational structure, compatibility, integration with existing data systems, best practices, accuracy standards, and universal user access to point cloud data. Further study to examine these and other implementation issues will provide the basis to best utilize this emerging technology of Mobile LiDAR in WSDOT business areas.

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DISCLAIMER/DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, and the Washington Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of Washington, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Meaning
ADA	Americans with Disabilities Act
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ARM	Accumulated Route Mile
ASPRS	American Society for Photogrammetry and Remote Sensing
ASTM	American Society for Testing and Materials
BPO	Bridge Preservation Office
CAD	Computer-Aided Design
CORS	Continuously Operating Reference Station
COTS	Commercial-Off-The-Shelf
DMI	Distance Measuring Indicator
DOF	Degree-of-Freedom
DOT	Department of Transportation
DTM	Digital Terrain Model
FOV	Field-of-View
FTE	Full-Time Equivalent
GAMS	GPS Azimuth Measurement System
GB	Gigabyte
GIS	Geospatial Information System
GNSS	Global Navigation Satellite Systems
GLONASS	GLObal'naya NAvigatsionnaya Sputnikovaya Sistema
GTMA	Geospatial Transportation Mapping Association
IMU	Inertial measurement unit
ITAR	International Traffic in Arms Regulations
KF	Kalman Filter
LAS	Log ASCII Standard
LiDAR	Light Detection and Ranging
MP	Mile Post
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NGS	National Geodetic Survey
NIR	Near Infrared
ODOT	Oregon Department of Transportation
OEM	Original Equipment Manufacturer
QA/QC	Quality Assurance / Quality Control
RFIP	Roadside Feature Inventory Program
RTK	Real-Time Kinematic
SRMP	State Route Mile Post
SRView	State Route Viewer
TAG	Technical Advisory Group
TB	Terabyte
TIN	Triangulated Irregular Network
TnDOT	Tennessee Department of Transportation
TOF	Time-of-Flight
WSDOT	Washington State Department of Transportation
UV	Ultraviolet
VCMS	Vertical Clearance Measurement System

ACKNOWLEDGMENTS

The authors thank the Washington State Department of Transportation (WSDOT) for their support; in particular, the guidance and review provided by WSDOT Technical Advisory Group (TAG) members: Mark Finch, Heath Bright, Lori Beebe, Eric Jackson, Roger Caddell, Rhonda Brooks, Scott Campbell, Tom Clay, Marc Faucher, Kurt Iverson, David Luhr, Rick Mowlds, Steve Palmen, John Tevis, and Brent Schiller for their valuable participation and contributions. Moreover, the authors express gratitude to the mobile LiDAR vendors— Eagle Mapping, Earthmine, ESM Consulting, Mandli Communications, The PPI Group, Topcon, and Optech—for their pilot study participation, efforts, and generous support; this study would not have been feasible without their gracious assistance. In addition, we thank Autodesk, GeoAutomation, GeoCue, Riegl, Trimble, and Virtual Geomatics for presentation of their latest technologies and development to the TAG. We also thank Chris Harris of Tennessee DOT (TnDOT) and Ron Singh of Oregon DOT (ODOT) for their valuable input. The authors also acknowledge the dedicated efforts of the AHMCT research team members who have made this work possible.

CHAPTER 1:
INTRODUCTION

Background

Since the advent of total stations, static scanners, airborne scanners, GPS, and GIS, the WSDOT has been surveying and mapping more and more using digital data. WSDOT has been acquiring and using this data in a myriad of ways. Current data collection processes have some deficiencies:

- Multiple WSDOT business areas gather geospatial data covering the same highway locations, with many data overlaps using different methods and standards.
- Over the years, the same features have been gathered over and over again.
- Collecting data usually exposes personnel to traffic, the elements, and other hazards in the field.
- When personnel are collecting data in the field, many times they need to delay the traveling public by taking a lane or using flaggers, not to mention the cost of personnel or the time it takes to put up signs and/or set up vehicles.
- Typically after the data is collected, individual business areas process, store, and use the data to satisfy their own business needs, without sharing the data with other business areas. This creates the need for the other business areas to gather, process, and store similar data.

The above issues sound like database issues not data collection issues. But because the data required for WSDOT projects and maintenance is hazardous and expensive to collect, WSDOT only collects critical geospatial data with limited funds to update the data. If there were a way to safely, quickly, efficiently, and inexpensively collect all the data needed periodically, and then format it in a way that all WSDOT business areas could use, then WSDOT would be using the safest and most economical data available.

LiDAR systems have been developed to collect geospatial data [1,9]. Their high mobility and capturing ability of large highway areas (roadways, roadsides, structures) enables DOT users to collect massive amounts of data for highway surveying, asset management [15], as-built documentation, and maintenance operations [8,14,17,18]. The LiDAR scanner's resultant point cloud, shown in Figures 1.1, and 1.2, is then post-processed to extract mapping data, roadside asset feature data, and various measurements. The extracted data can then be readily imported into a database for analysis and be accessible by all WSDOT business areas, thus reducing duplicate data collection and storage in separate silos. Of course features like culverts ends, dry wells, regulatory outfalls, and anything underground are not visible in the point cloud; therefore, they cannot be extracted. However, these types of features are relatively safe to collect and they do not usually change position.

Mobile LiDAR systems inherently:

- Reduce workers' exposure to traffic, the elements, and other hazards in the field.
- Speed up the data collection of data.
- Increase the amount and accuracy of data collected.
- Eliminate the need for traffic control (flaggers, signs and/or vehicles), eliminating traffic delay for data collection.

Mobile LiDAR systems collect field data of up to 150 miles a day, removing the need for lane closures while increasing productivity. This new tool presents an opportunity for WSDOT to consolidate geospatial data collection and storage operations and improve overall efficiency by eliminating redundant work.

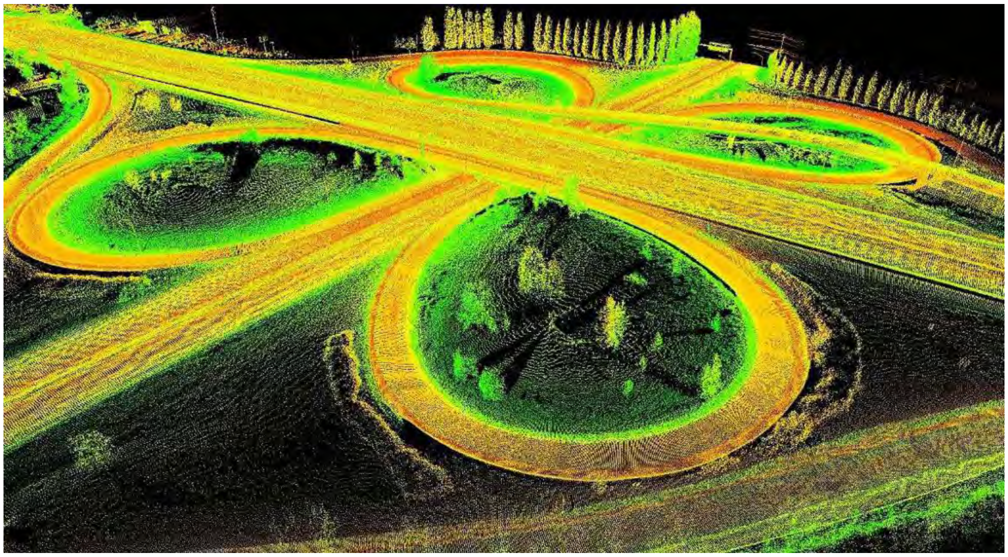

Figure 1.1: Example point-cloud of a highway interchange produced by a mobile LiDAR system (Data courtesy of David Evans & Associates)

Figure 1.2: Example point-cloud of a highway produced by a mobile LiDAR system (Data courtesy of Terrametrix)

Private contractors and services providers have been using mobile LiDAR extensively to collect geospatial data for mapping, asset management, and survey. Based on discussions with service providers, a few state DOTs, such as Tennessee DOT, Hawaii DOT, Nevada DOT, and Texas DOT, have contracted with mobile LiDAR service providers for asset management. Caltrans has contracted with a mobile LiDAR survey firm to perform bridge clearance measurements and pavement surveys. Recently, ODOT has purchased a mapping grade mobile LiDAR system. Survey service providers have been using survey grade mobile LiDAR systems to collect data for railroad and power transmission line management [18]. Research was needed to determine:

- The feasibility of using mobile LiDAR technology to fulfill WSDOT geospatial data requirements.
- If mobile LiDAR technology would improve WSDOT business operational efficiency.
- The best way to deploy mobile LiDAR technology for WSDOT to achieve maximum benefit.

Research Objective

The research objective is to evaluate the use of mobile LiDAR technology to determine safety enhancements, efficiency gains, accuracy, benefits, technical issues, and cost/benefit of using this technology, with a focus on collection, processing, and storage.

Research Approach

The Technical Advisory Group (TAG), composed of WSDOT experts from various department offices, other state DOT experts (Chris Harris from TnDOT, Kevin Akin from Caltrans, and Ron Singh from ODOT), and AHMCT researchers, governed and guided the research project. The TAG met biweekly, contributed data and information on current WSDOT business processes, and approved pilot study site selection and requirements. The TAG met with several system and service providers to gain better understanding of LiDAR in general and of their particular system, operation, services, and the cost/benefits of different options. During bi-weekly meeting, AHMCT researchers presented the latest information on mobile LiDAR technology and research findings to the Technical Advisory Group (TAG) team, made up of WSDOT division representatives, researchers, and other state DOT representatives. The TAG team also learned what others state DOTs have done with mobile LiDAR from other state DOT expert. A pilot study of employing mobile LiDAR technology was conducted to provide the mobile LiDAR data of an SR167 corridor section. The data supported feasibility evaluation of mobile LiDAR mapping technology. Several mobile LiDAR mapping deployment options were developed and compared with each other as well as the current processes. Each option's cost and benefit was analyzed. The tangible and non-tangible benefits were listed for each option.

CHAPTER 2:
WSDOT PILOT STUDY

Background

A pilot study was conducted with the generous support of five mobile LiDAR system manufacturers and service providers. The pilot study results were used to evaluate the cost benefit of this method of data collection. The test corridor (SR 167 MP 6.54 to MP 11.17) has been extensively mapped with fixed terrestrial scans, photogrammetry, traditional surveying, and roadside feature inventory. These datasets were used by WSDOT to validate the LiDAR results. A common set of geodetic controls were provided to the vendors. The pilot study began in March of 2010 and ended in January of 2011. The pilot study participants brought their systems and performed mobile data collection on the pilot study site. The data and productivity figures were then delivered to WSDOT after the vendors finished their data post-processing phase. The GeoMetrix Office committed resources to collect GPS data and perform data extractions.

Pilot Study Objectives

The pilot study provides empirical data for the selected Washington State Department of Transportation (WSDOT) corridor to support feasibility evaluation of mobile LiDAR technology. The feasibility evaluation included demonstration and documentation of efficiency and safety gains, ability to extract features, and the economic benefits to the DOT and traveling public, as well as any associated environmental benefits. In addition to evaluating the systems' accuracy and repeatability capabilities, the pilot study analyzed and documented the cost benefit of mobile LiDAR technology. The study also developed input cost/benefit information to support future funding decisions. The study was not a comparison of the various vendor products and their capabilities. A focus of the research was evaluation of the ability to identify (automatically or manually) specific features from mobile LiDAR data.

Pilot Study Test Site: State Route 167

The test site is located on SR 167 in east King County. WSDOT identified the segment of the SR 167 corridor, because they recently completed traditional data collection and surveys of the area. The beginning of the test section is located at 47° 12' 2".95"N, 122° 16' 1.20'W –Accumulated Route Mile (ARM) 7.82, and the end of the test section is located at 47° 15' 26.33"N, 122° 15' 34.50'W –ARM 12.45 (see Figure 2.1). The vendors scanned the test section in increasing and decreasing ARM directions, with multiple passes. The data collection included scanning of one interchange: the "Stewart Rd, 8th St E, and Milton". The interchange includes standard on and off ramps in both directions.

After the first data collection run by one of the participants, WSDOT developed a recommended route for the data collection. The efficient route starts at a gravel spot located at 47.250241 degree Latitude and -122.255137 degree longitude. Even though most data collection vehicles traveled at highway speeds during data collection runs, a

WSDOT shadow vehicle, traveling behind the data collection vehicle, is provided for extra safety. In some cases, the data was collected without a shadow vehicle. The data collection work for all participants was completed in a single day, mostly from 10 am to 2 pm since the traffic volume is the minimal in the day time.

Figure 2.1 Pilot study test site locations (courtesy of Open Street Map)

Route Description:

1. Start from the gravel area spot. Head west on 8^{th} under the overpass.
2. Take SB on ramp onto SR 167, stay in outside lanes. Near SR161 move left and return to,
3. 167 NB outside lanes to Ellingson. Take off ramp and return to,
4. 167 SB outside lanes to 161. Near SR161 move left and return to,
5. 167 NB inside lanes to Ellingson. Take off ramp and return to,
6. 167 SB inside lanes to 161. Near SR161 move left and return to 167 NB outside lanes to,
7. NB off ramp to 8^{th}, then straight ahead onto the,
8. NB on ramp to 167, then to Ellingson. Take off ramp and return to 167 SB outside lanes to,

9. SB off ramp to 8th,
10. Return to gravel spot.

Geo-referencing / Controls

WSDOT provided a list of available local control points as shown in Figure 2.2 in the red triangles. The full details of each monument point are available at: http://www.wsdot.wa.gov/monument. The pilot study participants were free to select and use one or more of the monument points. In some cases, WSDOT provided GNSS equipment and personnel for the GNSS base station setup. The goal was to provide a common set of geodetic controls with accurately known height, horizontal accuracy, and datum information. As a result of discussions with participants and the WSDOT, the control point GP27167-12, located next to an overpass, was used in most of the data collection runs. Detailed information about GP27167-12 may be found at: http://www.wsdot.wa.gov/monument/report.aspx?monumentid=6403. The GNSS baseline length is less than 4 miles when the GNSS base station is placed on the GP27167-12 monument point.

Figure 2.2: Photograph of the GP27167-12 monument ground control location (Courtesy of GeoMetrix Office)

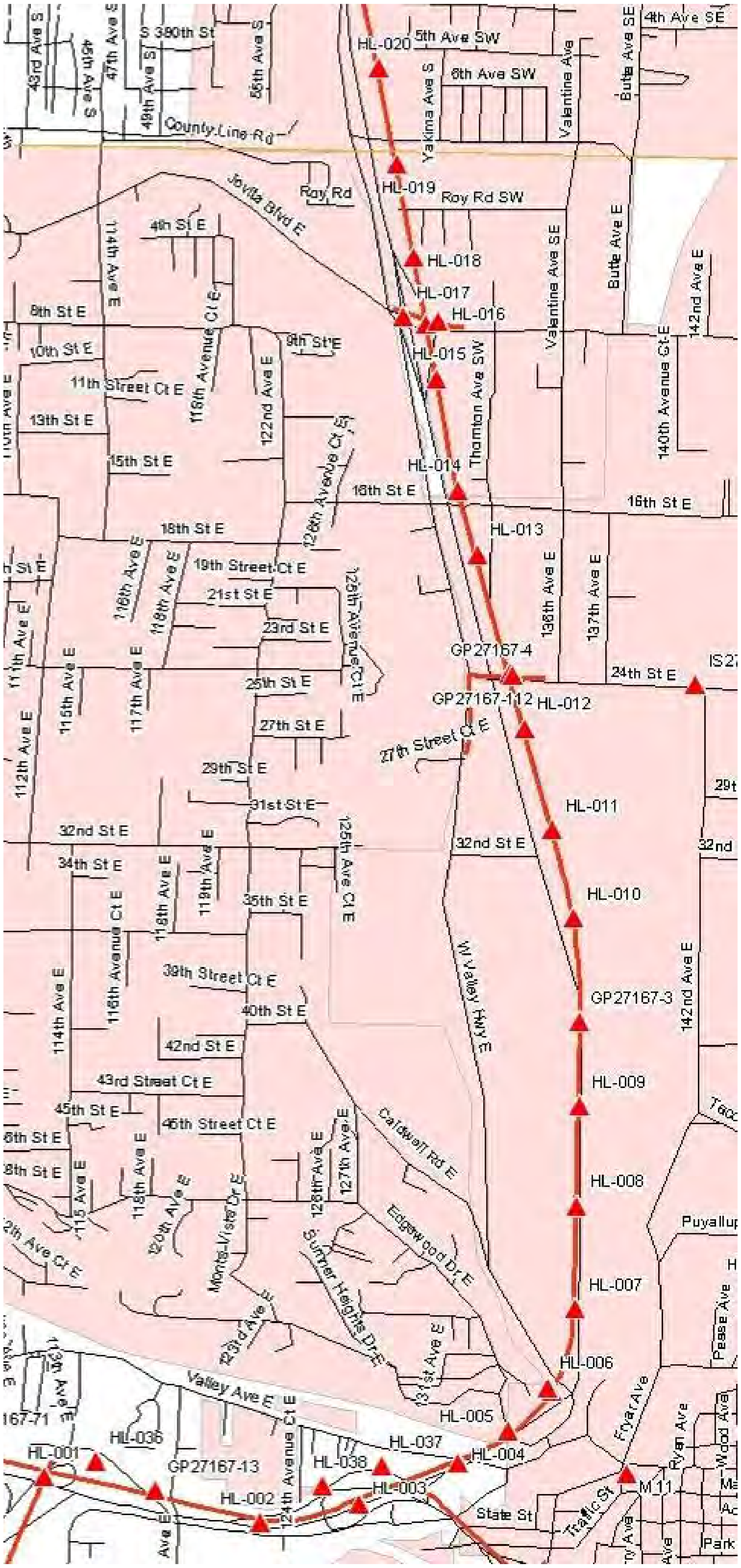

Figure 2.3 Pilot study site ground controls locations marked in red triangles (Courtesy of GeoMetrix Office)

Requested Data from the pilot study participants

The participants were asked to provide the results of any automated feature extraction available with the participant's system. Given the cost constraints, manual feature extraction was optional, at the participant's discretion. The participants presented their results to the research team as part of a subsequent teleconference. This teleconference included at a minimum WSDOT and AHMCT. Other DOT participants, such as FHWA, ODOT, TnDOT, and Caltrans, participated at times, along with research partners from the University of Washington. Federal agencies' and other states participated to learn about the results of the field test. Some of the required deliverables were not provided by the study participants because their systems were not designed to provide such data. The research team asked the participants for the following required and optional deliverables:

Required Deliverables:

1. LiDAR Point Cloud data (ASCII xyzirgb, ASCII xyzi, LAS, Cyclone, in order of preference).
2. Digital Camera image data, if collected.
3. GPS/IMU Post-processed data (including QA/QC statistics):
    a. Include xyz separation of forward and reverse processing
    b. Include flight-line (vehicle path)
4. Any automated extracted features, displayed in an Excel spreadsheet, comma-delimited text file, or GIS Shape file. All automatically extracted features were to be identified as such.
5. A cost estimate to collect, post process, and extract automatically extracted features, as if it were a service contracted by WSDOT. This information is to be used only for the research study; will not be shared outside of the context of the analysis; and is considered only an "estimate" for the purpose of the cost benefit analysis of the research study.
6. Test protocol description (System configuration information used, speeds used, total data collection time, and other information as the vender considers pertinent).

Optional / Voluntary Deliverables:

A. Manually extracted features, provided in an Excel spreadsheet, comma-delimited text file, or GIS shape file. All manually extracted features must be identified as such.

B. Bare-earth TIN of entire field-of-view with vegetation removed, in a compatible ASCII format.

C. An estimate of the cost of manual feature extraction, as if it were a service contracted by WSDOT. This information is to be used only for the research study; will not be shared outside of the context of the analysis; and is considered only an "estimate" for the purpose of the cost benefit analysis of the research study.

Pilot Study Results

Pilot Study Participants

There were five pilot study participants: Earthmine in partnership with ESM Consulting; Eagle Mapping Ltd.; Mandli Communications Inc.; Optech; and the PPI Group. The participants consisted of a diverse group of professionals, experienced in operating their equipment for various applications. With the exception of Eagle Mapping, all participants' data collection systems were land-based. Earthmine's system does not utilize any LiDAR technology. The details of pilot study participants' systems can be found in Appendix A.

Pilot Study Results

The pilot participants provided valuable empirical data for SR167 highway to support feasibility evaluation of mobile LiDAR technology. The pilot participants took about 2 hours with the vehicle speed mostly at 55 mph for data collection of the test section, a 5-mile divided 4-lane highway. This includes time that was taken to complete multiple passes, resulting in redundant test area data as well as capturing data of the two intersections. The multiple passes were valuable in examining system repeatability as well as filling in shadows created by large trucks blocking the LiDAR sensor's FOV. The short data collection time confirms high productivity of mobile LiDAR systems. In addition, the data collection personnel were safely protected inside the data collection vehicle.

All participants' data was delivered in the form of LAS and JPG formatted files except Earthmine. One participant had also provided their data in proprietary formats along with their proprietary data extraction software. The total data file size, given by each participant, ranges from 6 GB to 60 GB. The LAS formatted point-cloud files vary in size from 2 GB to 16 GB for the entire pilot study site. The total file size of the collected image ranges from 3GB to 59 GB. Given the pilot study area is 5 miles long 4-lane divided highway, the data storage requirement per highway mile varies from 1 GB/mile to 12 GB/mile. For comparison, the data file size of static laser scan of the test area is 26 GB or 5 GB/mile. Based on the pilot study data size, the data requirement for mobile scanning the entire WSDOT highway network was estimated. The detail calculation is shown in the following chapter.

Previously, GeoMetrix offices had performed 404 static laser scans to cover the entire pilot study site. The cost for static scan data collection is about $6,600 per mile. One mapping grade mobile LiDAR services provider provided their cost figure for the pilot study. The costs are $7,600 for project management, $9,600 for data collection, and $11,400 for data processing. The cost per mile is $1720 per mile for data collection and $1,140 for data processing. However, the cost would be much lower for a statewide data collection. Their estimate for data collection is about $70 to $140 per mile which is consistent with TnDOT statewide data collection cost figure. Based on the cost figure from a few Caltrans pavement survey contracts with survey service providers using survey grade mobile LiDAR, the cost is approximately $15,000 per mile. A significant portion of the costs are the equipment and mobilization cost. These contract projects cover a small area (5 miles or less), and therefore the cost per mile is unusually high. Survey grade mobile LiDAR data collection per mile cost would be much lower for a large area.

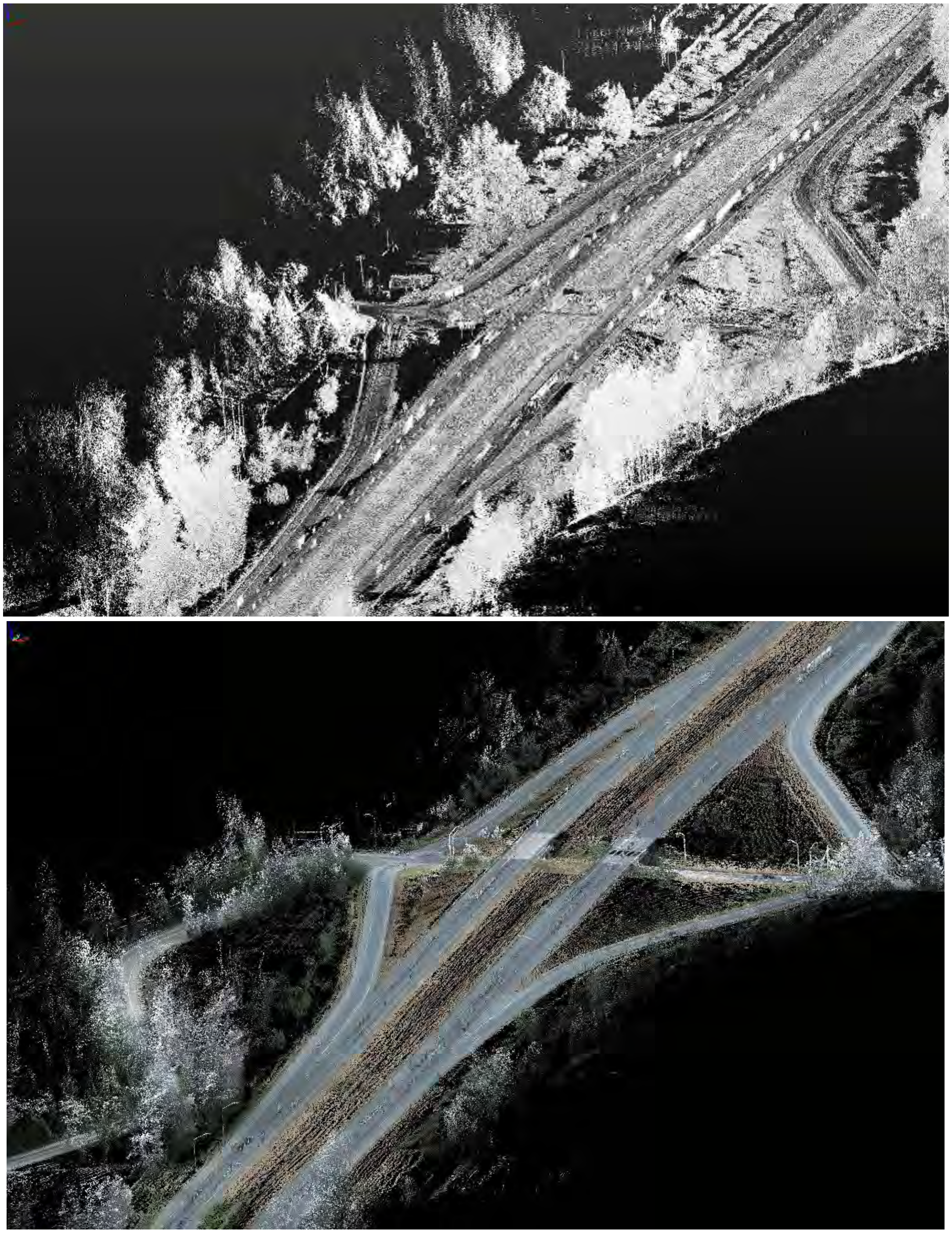

Figure 2.4: Point cloud of SR 167 pilot study site by two different systems (Courtesy of GeoMetrix Office)

Pilot Study Findings

The majority of the required features for the WSDOT RFIP (Roadside Features Inventory Program) can be extracted from test site point cloud and geo-referenced images. However, as expected, culverts are usually not visible in the point cloud data collected from the highway. Depending on the data accuracy, the data can be used for bridge vertical and horizontal clearances and ADA feature inventory applications.

The collected images from the pilot study were compared to high quality images collected by the WSDOT SR View Program. The SR View image quality was similar in some cases and better in other cases. The study result also validated the importance of proper camera orientation in order to capture text and symbol on road signs, post-mile marker, and advertising signs as well as identification of man-hole covers. In addition, it also illustrated the importance of proper LiDAR scanner mounting orientation on the data collection vehicle. One of the systems had LiDAR scanners mounted facing 90 degree to the vehicle direction of travel. Consequently, there was little to no LiDAR data collected on road signs compared to other systems, and signs features could not be extracted accurately with confidence.

Performing the comparison between participants' mobile LiDAR deliverables and WSDOT's existing mapping dataset of the SR167 test area revealed datum-related problem. There were large systematic horizontal and vertical offsets between the mobile map data and WSDOT's static scan data. Even though GNSS base station data on local ground control points were provided, some participants appeared to be holding fix with Continuously Operating Reference Station (CORS) data instead of the on-site furnished base station files for the GNSS/IMU position post-processing. As a result, this practice introduced horizontal and vertical offset between static scan and mobile scan data. The offsets are caused by using mismatched geoid models and reference earth ellipsoid models. CORS has its own system of reference that does not easily correlate to traditional datums.

Some mobile LiDAR system operators' processes seem to involve collecting the data; using the Internet to pull GPS data from the nearest CORS for processing; and using an NGS geoid model to achieve NAVD 88 elevations. The on-site base station data is apparently used as a check. The problem with this procedure is that the NGS geoid model is stated to contain up to 10 cm of uncertainty. WSDOT GeoMetrix Office has found that amount to be doubled in some circumstances. Since many of the CORS stations do not have accurate elevations there is no direct tie to the NAVD 88 datum.

All kinematic mobile platform positioning performed by WSDOT GeoMetrix Office utilizes direct survey ties to the datum by way of stationing a series of GPS base stations throughout the project area. If a CORS is used, it will have a previously established NAVD 88 elevation. Unfortunately, the WSDOT SR167 mapping project was completed before the NGS release of the NAD83/2007 adjustment. Consequently, the mapping was completed using the NAD83/91 datum/adjustment. NAD83/91 differs from CORS by about 7 cm in northing and 4 cm in easting. Because of upgrades to the GPS-referenced ellipsoid, an elevation discrepancy of up to 17 cm can be realized between NAD83/91 and NAD/07 if the proper correlating geoid model is not used.

Each vendor was supplied with exact datum, datum adjustment, state plane coordinates and zone, and unit values from the GeoMetrix Geodetic Survey Office prior to testing. The pilot study data revealed that CORS data and NAD83/91 datum will not be compatible and cannot be used interchangeably. The WSDOT Monument database lists the IS-labeled points in NAD83/91 only, while the GP-labeled points have both NAD83/91 and NAD83/07. To make a direct comparison between the mobile LiDAR data and WSDOT static scan data, both LiDAR datasets must have the same datum. In our pilot study's case, the datum should have been:

Datum: NAD 1983
Datum Adjustment: HARN-based 1991
Vertical Datum NAVD 1988
Coordinate System: Washington State Plane Coordinate System, South
Zone Units: US Survey Feet

In order to have consistent map data throughout the entire state highway network, mobile LiDAR system operators must be careful when selecting a GNSS base station for GNSS/IMU position post-processing to ensure the proper datum is used for the point-cloud data. Otherwise, large horizontal and vertical offsets may appear between the point-cloud and existing data surveyed by tradition methods. The accuracy of mobile LiDAR systems is lower than that of fixed scanners. However, mobile LiDAR accuracies are approaching those of static LiDAR especially when proper targeting techniques are used.

Conclusion

The pilot study has demonstrated the mobile LiDAR system's efficiency/safety gains, ability to extract features, the economic benefits to the DOT/traveling public, as well as associated environmental benefits. The study also shows that this new technology could fit well into several WSDOT business processes, such as asset management, maintenance needs, engineering, and construction. The study illustrated the need for best practices documentation for mobile LiDAR data collection for DOT. DOT users asking for LiDAR work done would need to carefully specify:

- The point-cloud point density (speed of vehicle)
- Surveying/mapping datum needed (State plane or some other)
- Deliverables (3D map, features, alignments, structures, etc.)

CHAPTER 3: COST BENEFIT ANALYSIS OF USING MOBILE LIDAR SYSTEMS FOR WSDOT

Business Program Background

The mission of the Washington State Department of Transportation is to keep people and business moving by operating, maintaining, and improving the State's transportation systems vital to our taxpayers and communities. WSDOT manages more than 7,000 highway miles (20,386 lane miles) of Federal and State of Washington highways and freeways. The WSDOT business process requires geo-spatial data for planning, maintenance, operation, and project delivery.

Business Problem and Opportunity

As discussed in detail in the previous chapter, gathering data using current traditional methods is relatively slow, labor intensive, and a potential safety risk. A mobile LiDAR system would significantly improve the speed and accuracy of the data collection. In some cases, due to budgetary constraints and limited personnel, the current data collection process is too slow or costly to meet the demand. The deployment of mobile LiDAR will also consolidate several data collection operations by various WSDOT offices. Despite the high initial costs of mobile LiDAR systems and data extraction software, the solution may be cost-effective compared to existing methods. The costs and benefits of mobile LiDAR solutions are examined below in detail, sorted by business functions. Not all business functions that would benefit from LiDAR are included, just the ones with tangible data.

WSDOT Business Functional Requirements

There are at least three existing WSDOT programs (RFIP, bridge clearance measurement, and ADA feature inventory) that would directly benefit from employing mobile LiDAR systems. These program's historical and current expenditures are used in this cost/benefit analysis. Their data and functional requirements are well-defined. There are other WSDOT functional groups that can greatly benefit from the data produced by these mobile systems. However, their program expenditures for geospatial data collection are not known well enough (or vary greatly from year to year) to do comparisons. For example, GeoMetrix Office had previously contracted with a survey service provider to use a mobile LiDAR system to collect survey data for a project. The GeoMetrix Office could use mobile LiDAR technology on many projects. Mobile LiDAR would simply be one of many tools, including mobile, terrestrial and aerial LiDAR, used by the technical experts in the GeoMetrix office. Currently, the GeoMetrix Office is recognized as WSDOT's LiDAR specialty group with the role and responsibility to implement and manage LiDAR technology. Furthermore, the Attorney General's Office had used contractors to collect geospatial data for accident investigations. In a meeting on mobile LiDAR technology, they had commented that they would greatly benefit from the data collected by a mobile LiDAR system. However, GeoMetrix Office and Attorney

General's Office demand for mobile LiDAR technology varies from year to year and is difficult to estimate and quantify.

Roadside Feature Inventory Program (RFIP) Requirements

The Roadside Feature Inventory Program (RFIP) is a statewide program for collecting, storing and reporting roadside features such as guardrails, culverts, signs, objects in clear zones, and other features from all WSDOT regions. This data is used for asset management, project and system design, and overall system analysis. Previously many individual business areas within WSDOT have collected similar information (e.g. utility poles, signs, guardrails, tree groupings, slope information, etc.) independently of one another. This caused duplicate effort and expense, which resulted in the data not being consistently stored in a statewide standard format that would allow shared use and maintenance of the data. Because of the advancements in technology, GIS applications and the creation of the RFIP, WSDOT has combined this information and thus created a single source for data retrieval. The data is more accurate, the ability to analyze and maintain the data increases exponentially, and it saves the agency time and money.

RFIP benefits:

- Having consistent data definitions, values and formats throughout the department
- Having reliable data collection methods and procedures to maintain standards with minimal variation
- Increased efficiency of projects through consistent data collection and reporting

Data customers:

- Maintenance: Uses the data to fulfill environmental requirements and inventory management
- Program Management: Uses it to strategically utilize safety, unstable slope, major electric, and drainage dollars
- Environmental: Regulatory compliance and inventory management
- Utilities: Uses it for system wide inventory and safety analysis
- Real Estate: Road approach inventory for access control

Bridge Clearance Requirements

The WSDOT Environmental & Engineering Programs, Bridge Preservation Office (BPO) is responsible for collecting bridge vertical and horizontal clearance as well as other bridge as-built structure information. The bridge clearance data are reported to WSDOT Commercial Vehicle Services, Region Bridge & Maintenance Crews, BPO and the Federal Government. The absolute accuracy requirement for bridge location is relatively low (~ 2'). The following are the relative accuracy requirements for bridge clearance data:

- Bridge Columns/Piers (horizontal clearance) – within 4 inches optimum
- Bridge Girders (vertical clearance) – within 1 in.
- Overhead Restrictions (including Truss Members) (vertical/horizontal clearance) – within 1 in. vertical; within 3 in. horizontal
- Bridge Rails / Guard Rails (horizontal clearance) – 3 in.

- Edge of Pavement (horizontal clearance) – 1.5 in. to 6 in.
- Sign Bridges (vertical clearance) – within 1 ft.

All of these measurements are achievable with a survey grade mobile LiDAR system. Beyond the clearance info needed to post heights, bridge strikes by over-height trucks happen about 12 times a year. Proving damage by having "existing condition" data would be extremely valuable in court. In addition, existing condition would be valuable in evaluating the effects of environmental hazards.

Americans with Disabilities Act (ADA) Feature Inventory Requirements

The WSDOT Project Development Office is responsible is collecting data on ADA ramps at intersections to ensure their compliance to ADA standards and regulations. The data customers are WSDOT Office of Equal Opportunity - ADA Compliance Officer, Project Development Office, Capital Program Development and Management Office, and Design Offices. The types of ADA features captured in this inventory are:

- All curb ramp types including detectable warning surface placement
- Bridge end sidewalk ramps
- Sidewalk
- Pedestrian Access Route (PAR) protruding objects and other obstructions
- Crosswalks
- Driveways
- Island and median cut-throughs
- APS push button types and locations
- APS signal type and location
- Shared use paths
- Independent walkways
- Facility Ramps
- Edge Protection
- Handrails
- Railroad Crossings
- Stairs
- Parking Stalls

Each of these ADA features have numerous elements that need to be measured and documented such as: sub types, running slopes, cross slopes, widths, lengths, clearances, alignments, etc. A detailed list of the above features and their elements may be found in the WSDOT ADA Data Dictionary Diagrams 2nd edition written by the WSDOT HQ Design Office. The required accuracy for horizontal and vertical measurements for these elements is 0.01 feet and the angular accuracy for slope measurements is 0.01 percent. All angles must be relative to level.

Figure 3.1 illustrates a typical ADA ramp and a few of the measurements that would be required to be made from the point cloud. For this type of work, the relative accuracy for horizontal and vertical measurements is 0.01 feet, and the angular accuracy for slope measurement is 0.01 percent. The absolute position accuracy for the intersection is 1 to 5 feet.

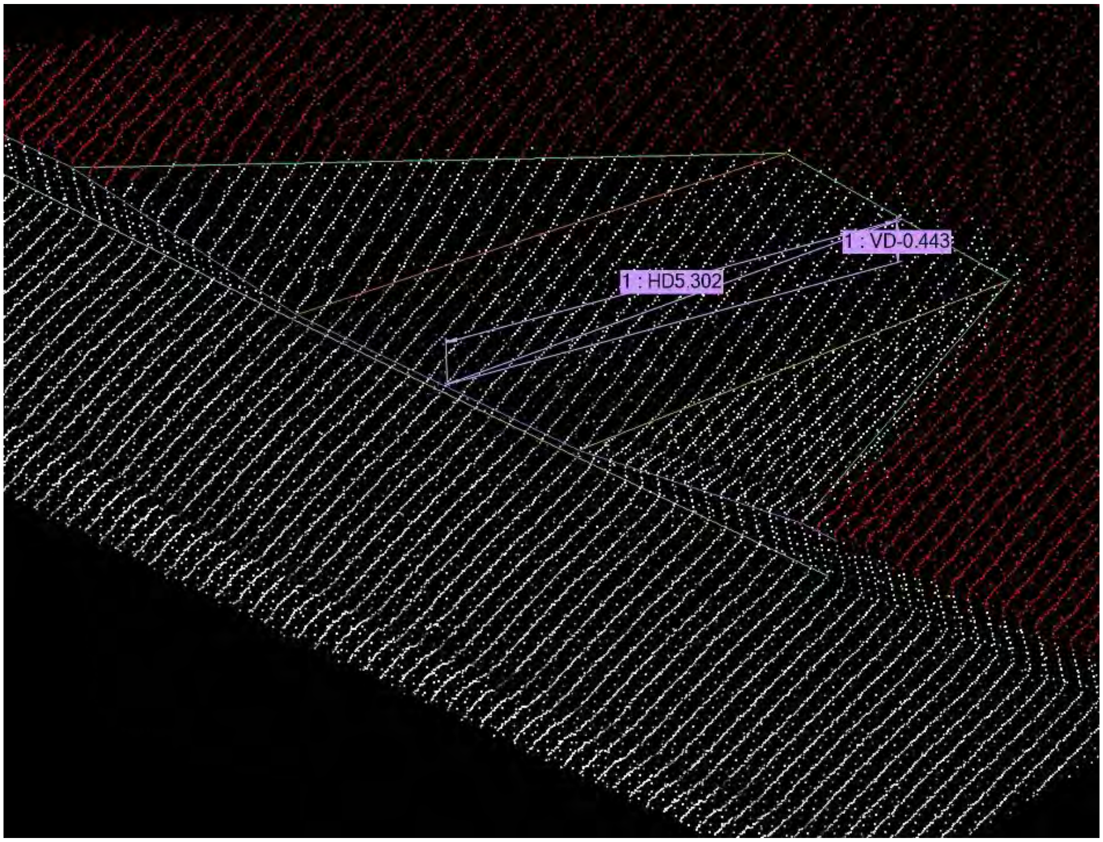

Figure 3.1 Making ADA ramp measurements from point cloud (Courtesy of GeoMetrix Office)

Current Data Collection Methods and Cost

This section provides details of the current methods of data collection for WSDOT RFIP, Bridge Clearances, and ADA feature inventory. In addition, the program cost, equipment used, productivity figures, full-time equivalent (FTE) personnel and vehicles involved in data collection are listed for each program.

Roadside Features Inventory Program (RFIP) Data Collection Methods and Cost

WSDOT is divided into 6 regions. Each region has a crew for RFIP data collection. A typical regional RFIP crew consists of 2 persons. To increase the speed of data collection, some regions in some situations run a 4 person crew. Typically, a crew member proceeds to the feature on foot or by car and inputs the feature's attributes into the data logger. Each crew shares a laptop computer and a vehicle. On average, the each crew collects:

- 137 features per day in rural areas
- 491 features per day in urban areas.

Data collection location and collection schedule is left up to the individual regions. The feature mile post (MP) location is determined by a WSDOT custom-developed application that calculates MP location from GPS location. Since all feature locations should be fairly close to the roadway, this rule is used to help mitigate errors. A total of 12 FTE and 6 vehicles are typically utilized statewide for RFIP data collections.

The itemized field data collection cost is listed in Table 3.1. The collected field data is processed in the office by a Transportation Planning Specialist, with assistance from an Information Technology Specialist when required. The program is managed by a Transportation Technical Engineer. Total estimated yearly program cost is $1,340,000. Table 3.2 shows the historical yearly expenditure and productivity of the RFIP since 2006. The yearly RFIP expenditure varies. However, the survey and data management cost per highway mile is relatively constant, with an average of $1,355 per mile. The RFIP data is used to create the future safety program for WSDOT. Even though almost 4,000 highway miles of data have been collected and processed, the program still has approximately 3059 miles to go to completion. The information can be used in preliminary design and scoping. The more information that is collected and placed in the database increases the demand for the information and better information.

Table 3.1 Itemized RFIP field data collection cost

Description	**Cost**
Vehicle	$600 per month
Laptop	$1500 per crew
Data logging equipment (one per crew member)	$6000 per unit
Estimated travel expenses	$3600 per year per region
Misc. cost (cell phone, supplies, repair, etc.)	$1000 per month per crew
Transportation Technician 2	$4,200 per month
Transportation Technician 3	$4,800 per month
GIS Pathfinder Office software maintenance	$3,500 per year

Table 3.2 Historical RFIP yearly cost

Year	**Annual RFIP Program Cost**	**Number of Miles Surveyed**	**Cost per mile**
2010	$638,381	443	$1,442.41
2009	$836,960	644	$1,299.63
2008	$1,179,356	709	$1,831.30
2007	$1,319,550	911	$1,448.46
2006	$884,504	879	$1,006.26
Sub Total	$4,858,752	3585	Ave. cost: $1,355.20

Bridge Clearance Measurement Data Collection Methods and Cost

Bridge clearance data is collected by a crew of a Bridge Geometry Engineer and a co-inspector traveling in a vehicle with a hitch-mounted Vertical Clearance Measurement System (VCMS). In addition to the vehicle, the Vertical Clearance Measurement System

(VCMS) requires a converter unit and laptop for control. The time required for vertical clearance data collection depends on number of lanes under structure, density of the structures, and exits/turnaround availability. In an urban area where the highway typically has numerous lanes and ramps, it takes about 1.5 hours per structure to collect all necessary data. In a rural setting, it is estimated the data collection generally takes about 45 minutes for each structure. In addition to using VCMS to collect vertical clearances, bridge inspectors also collect bridge structure horizontal clearances during routine bridge inspections.

Figure 3.2 Hitch-mounted Vertical Clearance Measurement System (courtesy of Mandli Communications Inc.)

The personnel hourly cost is $45. Traveling throughout the state, the crew requires additional lodging and per diem cost. The lodging and per diem cost is approximately $15/hour per person in addition to the labor rates. After the data collection, it generally requires an hour in office processing time per structure at $45 per hour. The vehicle is roughly $20/hour. The Bridge Preservation Office (BPO) estimated that it costs $300 per structure including labor, lodging, per diem, and basic vehicle costs. The Bridge Preservation Office also estimated that it spends $80,000 per year to collect data on the 270 structures/records per year. Consequently, it takes BPO about 10 years to complete a full cycle of data collection for all WSDOT bridge structures. Their goal is to maintain this current data collection rate of 270 structures per year or more to maintain or improve the 10 year cycle.

Americans with Disabilities Act (ADA) Feature Inventory Data Collection Methods and Cost

As part of WSDOT’s ADA transition plan, WSDOT has started collecting data for an ADA feature database of what features exist or are missing in the field. A survey crew (borrowed from one of the Regions) collects data on a wide array of ADA features and their elements (see the WSDOT ADA Data Dictionary Diagrams 2nd edition). The precise measurements of the ADA elements are the primary objectives of the crew.

For example, at a curb ramp, the ADA Data Collection crew will locate the ramp by placing a mapping-grade GPS unit at the center of the ramp cut along the back of the curb. The mapping grade GPS has an absolute positional accuracy of 5 feet. Once the ramp location is located logged, the ramp attributes are measured by hand tapes and digital levels (Stabila or Smart Level) and entered into the Trimble data collector using a data dictionary created specifically for the ADA collection program. Digital range finders are also used to measure the horizontal/vertical differences of remote features. The field crew shares a pickup truck, digital camera, a laptop computer, a digital level, and tape measures. The crew size is typically two people. A three person crew is sometimes needed in heavily urbanized areas primarily to provide a traffic spotter.

This process at a curb ramp takes a well-trained crew about 10 minutes to complete. The time required for measuring all the ramps in the entire intersection depends on the number of ramps in the intersection. Usually, there are only ADA ramps and crosswalks in each quadrant. However, more data is required to be collected in some intersections that have traffic islands, pedestrian facilities, obstructions, etc. (see the WSDOT ADA Data Dictionary Diagrams 2nd edition for a complete list). The estimated time to complete an entire intersection with minimal attributes is one to two hours. However, an intersection with extensive collection points and a lot of traffic may take four hours for the crew to complete all the measurements of all the feature elements. Typically, in-office post processing time is 1 hour per intersection per data collector used.

Table 3.3 Itemized ADA feature inventory data collection cost

Description	Cost
Pickup truck	$800 per month
Trimble data logger, laptop, digital camera, digital rangefinder, and software	$20,000 per crew
Transportation Technician 2	$30 per hour
Transportation Technician 3	$45 per hour

The program cost from July 2009 to June 30, 2010 was $118,414, and the cost from July 2010 to March 2011 was $237,321. Due to the availability of the ADA Survey Crew, survey of ADA features was not completed on a continuous basis.

Summary of Current Cost

The estimated annual costs of the three programs are summarized in Table 3.4.

Table 3.4 Summary of Current Cost

Program Description	Estimated Annual Program Cost	Estimated Cost per mile or structure	Number of vehicles used	Annual FTE for data collection
RFIP	$1,340,000	$1,355.20 per mile	6	12
Bridge Clearances	$80,000	$300 per structure	1	2
ADA Feature Inventory	$180,000	Not available	1	2

Mobile LiDAR Deployment Options Detail and Cost

To collect data for the entire WSDOT network, a mobile LiDAR system vehicle would need to be at least driven in both directions on each roadway and, depending on the range of the LiDAR scanner, some multi-lane highway segments may have to be driven one or two more times. In addition, extra travel mileage is required to capture highway interchanges. Thus, it was assumed that there are about 15,000 miles that would need to be driven by the data collection vehicle in order to pick up the whole state's network. The cost/benefit analysis is based on this 15,000 mile estimate. Because of Washington State's typical weather conditions, it was assumed that the data collection can only be conducted for 6 months of the year. The SRView program shows that a single vehicle can collect data of the whole WSDOT highway network in two years. To simplify calculation, it was further assumed a uniform labor rate of $50 per hour for all of the personnel needed for data collection and processing.

Each options cost may be broken down into three categories:

1. **Information Technology (IT) cost –** cost of data extraction software, storage, server, backup, and workstations for data extractions. The current WSDOT IT charges $7.3 per gigabyte (GB) for storage and associated backup cost. A virtual server would cost $1,000. Based on the pilot study result, the estimated data requirement is about 3 GB per mile. Thus, the total data storage requirement is 45 terabyte (TB) (15,000 mi x 3 GB/mi) and cost $328,500 for each two year data collection cycle. If WSDOT performs the data post-processing, new workstations are required (QTY=5 at $3,000 each, total cost is $15,000). Based on discussions with point cloud post-processing software makers, the workstation base configuration should have multi-core CPU, a 64-bit OS with 16 GB of memory, a few TB local storage, and dual high-resolution monitors (2560x1440 or more). In addition, data extraction software licenses and yearly renewal costs are $80,000 and $20,000 per year. It should be noted that the GeoMetrix Office has already invested in both software and high-end workstations and currently has the knowledge and skills capable of processing and extracting LiDAR data. The estimated cost for new workstations and software may need to be revised depending on the chosen option and software.

2. **Data collection cost** - the total costs associated with data collection which is composed of the equipment cost, equipment maintenance cost, personnel cost, and vehicle cost. $700 per month is used for vehicle cost.
3. **Data extraction cost** – the total cost of the personnel to extract the required geospatial data for various WSDOT programs. The data extraction cost depends highly on the number of features required to be extracted.

There are seven major of options in deploying mobile LiDAR technologies. They are:

1. Contract for mobile LiDAR services (<u>mapping grade</u>)
2. Contract for bridge clearance measurement services
3. Rents and operates a <u>mapping grade</u> mobile LiDAR system
4. Purchase and operate a <u>mapping grade</u> mobile LiDAR system
5. Rent and operate a <u>survey grade</u> mobile LiDAR system
6. Purchase and operate a <u>survey grade</u> mobile LiDAR system
7. Purchase fractional ownership of a <u>survey grade</u> mobile LiDAR system

Option #1 Contract for mobile LiDAR services (<u>mapping grade</u>)

There are a few service providers who provide statewide highway network mapping services using a Mobile LiDAR system. The advantage of this option is that the contractor will supply the equipment, personnel, and the final needed output. DOT would not be burden with training, data post-processing, technological obsolescence of equipment, and equipment maintenance. On the other hand, contracting process is often complicated and takes a long time, and DOT would not have a mobile LiDAR system available at a moment's notice. This option provides data with "mapping grade" accuracy, and the service provider also provides feature extraction services as well. Most DOTs contract mobile LiDAR data collection from service providers for their asset management. Some DOTs perform their own data extraction as needed, while other DOTs rely on contractors to extract their data. For example, Tennessee DOT (TnDOT) had a contract with Mandli Communications, Inc. to perform a mobile LiDAR scan of their entire state highway network. The total size of resulting point-cloud and digital images data was 15 TB. The operation took two years to complete at cost of about $70 per mile. The data extraction cost an extra $62 per mile for a total of $132 per mile not including data storage costs. Note that data extraction cost depends on the number of features to be extracted and can vary greatly.

Feature extraction takes about 2 to 5 man-hours per mile. Table 3.5 lists the cost break down for contract services. Each data collection will take two years. The average data collection cost per mile includes all cost associated with data collection such as vehicle, personnel, and fuel. The data extraction cost is usually higher for the first cycle since most assets are not in the database. The data extraction cost of subsequent cycles is much smaller since most assets have been extracted and inserted into the database. The estimated total cost for both data collection and extraction asset management (RFIP) for the first cycle is $2.9 million, and the total cost for subsequent cycles is $2.1 million. The total cost for all 3 cycles (6 years) is $7.1 million.

Table 3.5 Itemized cost for mobile LiDAR contract services (mapping grade)

Description	**Year 1 & 2 1st Cycle**	**Year 3 & 4 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
IT data storage cost	$328,500	$328,500	$328,500	$985,500
IT server cost	$1,000	$0	$0	$1,000
Total IT cost	**$329,500**	**$328,500**	**$328,500**	**$986,500**
Data collection cost per mile	$70	$70	$70	
Total data collection cost	**$1,050,000**	**$1,050,000**	**$1,050,000**	**$3,150,000**
Data extraction cost/mi	$100	$50	$50	
Total data extraction cost	**$1,500,000**	**$750,000**	**$750,000**	**$3,000,000**
Total cost	**$2,879,500**	**$2,128,500**	**$2,128,500**	**$7,136,500**

Option #2 Contract for bridge clearance measurement services

Some survey/engineering grade mobile LiDAR system operators provide contract service to collect and extract bridge vertical and horizontal clearances. Like Option 1, the advantage of this option is that the contractor will supply the equipment, personnel, and the final needed output. DOT would not be burden with training, data post-processing, technological obsolescence of equipment, and equipment maintenance. The disadvantage is that DOT would not have a mobile LiDAR system available at a moment's notice. The cost is about $100 to $150 per structure. The service provides only the bridge vehicle, and horizontal clearances and clearance diagrams as deliverable. Point cloud data is not part of the deliverable. The cost depends on the number of structures to be surveyed and their geographic separation. For example, Caltrans (California Department of Transportation) had a contract with a service provider for such services. Terrametrix processed 589 bridges for Caltrans and is currently documenting 7,250 additional bridges for horizontal and vertical clearance. The Bridge Office also needs accurate as-built of existing bridge structure conditions to address litigation concerning ongoing accidental bridge strikes, which average about one a month. Bridge repair and court costs include proving damage (change detection, based on existing scans). All structures would not require the same detail. For example, over/under crossings would be different than river crossings. The deliverable of this option does not provide accurate as-built data. WSDOT has total of 2,700 structures. Thus, the total cost of surveying all structures in WSDOT is about $337,500 assuming a cost of $125 per structure.

Option #3 Rent and operate a <u>mapping grade</u> mobile LiDAR system

Some mapping grade mobile LiDAR system manufacturers work with their dealers to provide a rental option. The advantage of this option is the elimination of equipment technological obsolescence risk and the burden equipment maintenance and warranty as well as higher system availability. It also has a lower cost of entry compared to the purchase option, but the lifecycle cost of this option is higher than the purchase option. For example, A Topcon IP-S2 is available for rental from the PPI group for approximately $25,000 per month or more depending on the system configuration. In this scenario, WSDOT rents and operates a mapping grade mobile LiDAR system for data collection and performs data collection and extraction with in-house personnel. The IT cost includes data hosting, virtual server, five data post-processing workstations, data extraction software and its maintenance. The majority of the IT cost is the data storage cost. The data collection cycle duration is estimated to take two years, at 6 months/year due to Washington State weather limitations.

The data collection cost is composed of equipment rental for 12 months (six months per year for two years), one-time training cost, vehicle cost, and personnel cost. The data extraction takes about 2.5 hours per mile at $50 per mile. Table 3.6 lists the cost breakdown for this option. The data extraction cost is higher for the first cycle since most assets are not in the database. The data extraction cost of subsequent cycles is much smaller since most assets have already been extracted and installed into the database. The estimated total cost for both data collection and extraction for the first cycle is $2.9 million, and the total cost for subsequent cycles is $1.75 million. The total cost for all 3 cycles (6 years) is $6.3 million.

Table 3.6 Cost for renting and operating a mapping grade mobile LiDAR system

Description	**Year 1 & 2 1st Cycle**	**Year 3 & 4 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
IT data storage cost	$328,500	$328,500	$328,500	$985,500
IT server cost	$1,000	$0	$0	$1,000
Data post-processing workstations (QTY=5 at $3,000 each)	$15,000	$0	$0	$15,000
Data extraction software	$80,000	$0	$0	$80,000
Annnual Data extraction software maintenance	$20,000	$40,000	$40,000	$100,000
Total IT cost	**$444,500**	**$368,500**	**$368,500**	**$1,181,500**
Mapping grade mobile LiDAR system rental cost for 12 months @ $30,000/month	$360,000	$360,000	$360,000	$1,080,000
Training	$50,000	$0	$0	$50,000
Vehicle cost (6 months/year, =$700/month x 12 months)	$8,400	$8,400	$8,400	$25,200
Personnel cost ($8650/month, 2 person crew for 12 months)	$207,600	$207,600	$207,600	$622,800
Total data collection cost	**$626,000**	**$576,000**	**$576,000**	**$1,778,000**
Data extraction cost/mi (2.5 hr/mi for 1st cycle, 1 hr/mi for subseqent Cycle, @ $50/hr)	$125	$50	$50	
Total data extraction cost	**$1,875,000**	**$750,000**	**$750,000**	**$3,375,000**
Total cost	**$2,945,500**	**$1,694,500**	**$1,694,500**	**$6,334,500**

Option #4 Purchase and operate a mapping grade mobile LiDAR system

The numbers of choices of purchasing mapping grade mobile LiDAR systems are more than the choices available for rental. The advantage is lower lifecycle cost compared to rental option, and mobile LiDAR system is available at a moment's notice. The disadvantage of this option is the technological obsolescence of equipment, higher entry cost, and the burden of equipment maintenance and warranty. Typical mapping grade system costs from $250,000 to $350,000 depending on the LiDAR and camera configuration. In this case, WSDOT purchases and operates a mapping grade mobile LiDAR system for data collection and performs data collection and extraction with in-house personnel. The data collection cycle duration is estimated to take two years, operating 6 months for each year. The data collection cost is composed of mobile LiDAR equipment cost, annual maintenance cost, one-time training cost, vehicle cost, and personnel cost. The annual maintenance cost includes firmware/software upgrade, calibration and extended warranty. The two person crew would take six months per year for two years to complete a single data collection cost cycle. The data extraction is estimated to take about 2.5 hours per mile at $50 per hour. Table 3.7 lists the cost break down for this option. The estimated total cost for both data collection and extraction for the first cycle is $2.97 million, and the total cost for subsequent cycle is $1.4 million. The total cost for all 3 cycles (6 years) is $5.78 million.

Table 3.7 Cost for purchasing and operating a <u>mapping grade</u> mobile LiDAR system

Description	**Year 1 & 2 1st Cycle**	**Year 3 & 4 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
IT data storage cost	$328,500	$328,500	$328,500	$985,500
IT server cost	$1,000	$0	$0	$1,000
Data post-processing workstations (QTY=5 at $3,000 each)	$15,000	$0	$0	$15,000
Data extraction software	$80,000	$0	$0	$80,000
Data extraction software maintenance	$20,000	$40,000	$40,000	$100,000
Total IT cost	**$444,500**	**$368,500**	**$368,500**	**$1,181,500**
<u>Mapping grade</u> mobile LiDAR Equipment cost	$350,000	$0	$0	$350,000
<u>Mapping grade</u> mobile LiDAR equipment maintenance cost (10% equipment cost per year)	$35,000	$70,000	$70,000	$175,000
Training	$50,000	$0	$0	$50,000
Vehicle cost (6 months/year, =$700/month x 12 months)	$8,400	$8,400	$8,400	$25,200
Personnel cost ($8650/month, 2 person crew for 12 months)	$207,600	$207,600	$207,600	$622,800
Total data collection cost	**$651,000**	**$286,000**	**$286,000**	**$1,223,000**
Data extraction cost (2.5 hr/mi for 1st cycle & 1 hr/mi for subsequent cycles, @ $50/hr)	$125	$50	$50	
Total data extraction cost	**$1,875,000**	**$750,000**	**$750,000**	**$3,375,000**
Total cost	**$2,970,500**	**$1,404,500**	**$1,404,500**	**$5,779,500**

Option #5 Rent and operate a <u>survey grade</u> mobile LiDAR system

Some survey/engineering grade mobile LiDAR system manufacturers work with their dealers to provide a rental option. The advantage of this option is the elimination of equipment technological obsolescence risk and the burden of equipment maintenance and warranty as well as higher system availability. The data accuracy is higher, and it is suitable for more WSDOT applications. It also has a lower cost of entry compared to the purchase option, but the lifecycle cost of this option is higher than the purchase option. For example, Trimble MX8 is available for rental for approximately $150,000 for three months duration. In this option, WSDOT rents and operates a survey grade mobile LiDAR system for data collection and performs data collection and extraction with in-house personnel. The data collection cost is composed of equipment rental for 12 months (six months per year for two years data collection cycle), one-time training cost, vehicle cost, and personnel cost. The personnel time required for high-accuracy data collection and raw data post-processing time is higher than mapping grade because more complex setup and raw GNSS/IMU data post-processing. To achieve best accuracy, more GNSS base stations setup at closer spacing and placement of ground targets are required. Thus, one extra personnel per year is added the data collection cost calculation. The additional data extraction time is also added because of additional feature extraction for bridge clearances and ADA feature inventory. It takes about 3 hours per mile instead of 2.5 hours per miles. Table 3.8 lists the cost break down for this option. The total cost for all 3 cycles (6 years) is $8.5 million.

Table 3.8 Cost for renting and operating a survey grade mobile LiDAR system

Description	**Year 1 & 2 1st Cycle**	**Year 3 & 4 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
IT data storage cost	$328,500	$328,500	$328,500	$985,500
IT server cost	$1,000	$0	$0	$1,000
Data post-processing workstations (QTY=5 at $3,000 each)	$15,000	$0	$0	$15,000
Data extraction software	$80,000	$0	$0	$80,000
Data extraction software maintenance	$20,000	$40,000	$40,000	$100,000
Total IT cost	**$444,500**	**$368,500**	**$368,500**	**$1,181,500**
Survey grade mobile LiDAR equipment rental cost for 12 months @ $50,000/month	$600,000	$600,000	$600,000	$1,800,000
Training	$50,000	$0	$0	$50,000
Vehicle cost (6 months/year, =$700/month x 12 months)	$8,400	$8,400	$8,400	$25,200
Personnel cost ($8650/month, 3 person crew for 6 months/yr for 2yrs)	$311,400	$311,400	$311,400	$934,200
Total data collection cost	**$969,800**	**$919,800**	**$919,800**	**$2,809,400**
Data extraction cost (3 hr/mi for 1st cycle, 1.5 hr/mi for subseqent Cycle, @ $50/hr)	$150	$75	$75	
Total data extraction cost	**$2,250,000**	**$1,125,000**	**$1,125,000**	**$4,500,000**
Total cost	**$3,664,300**	**$2,413,300**	**$2,413,300**	**$8,490,900**

Option #6 Purchase and operate a survey grade mobile LiDAR system

There are more purchase options available for survey grade mobile LiDAR systems than there are rental options. The advantage is lower lifecycle cost compared to rental option, and mobile LiDAR system is available at a moment's notice. The data accuracy is higher, and it is suitable for more WSDOT applications. The disadvantage of this option is the technological obsolescence of equipment, higher entry cost, and the burden of equipment maintenance and warranty. Typically, a survey grade system costs from $500,000 to $850,000 depending on the LiDAR and camera configuration. In this scenario, WSDOT purchases and operates a survey grade mobile LiDAR system for data collection and performs data collection and extraction with in-house personnel. Similar to the previous options, the data collection cycle duration is estimated to take two years at 6 months/year with a three person crew. The data collection cost is composed of equipment cost, annual maintenance cost, one-time training cost, vehicle cost, and personnel cost. The annual maintenance cost includes firmware/software upgrade, calibration and extended warranty. The personnel time required for high-accuracy data collection and raw data post-processing time is higher. Thus, one extra personnel time per year are added to the data collection cost calculation. The data extraction is estimated to take about 3 hours per mile at $50 per mile. Table 3.9 lists the cost break down for this option. The total cost for all 3 cycles (6 years) is $8.0 million.

Table 3.9 Itemized cost for purchasing and operating a survey grade mobile LiDAR system

Description	**Year 1 & 2 1st Cycle**	**Year 3 & 4 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
IT data storage cost	$328,500	$328,500	$328,500	$985,500
IT server cost	$1,000	$0	$0	$1,000
Data post-processing workstations (QTY=5 at $3,000 each)	$15,000	$0	$0	$15,000
Data extraction software	$80,000	$0	$0	$80,000
Data extraction software maintenance	$20,000	$40,000	$40,000	$100,000
Total IT cost	**$444,500**	**$368,500**	**$368,500**	**$1,181,500**
Survey grade mobile LiDAR Equipment cost	$850,000	$0	$0	$850,000
Survey grade mobile LiDAR equipment maintenance cost (10% equipment cost per year)	$85,000	$170,000	$170,000	$425,000
Training	$50,000	$0	$0	$50,000
Vehicle cost (6 months/year, =$700/month x 12 months)	$8,400	$8,400	$8,400	$25,200
Personnel cost ($8650/month, 3 person crew for 6 months)	$311,400	$311,400	$311,400	$934,200
Total data collection cost	**$1,304,800**	**$489,800**	**$489,800**	**$2,284,400**
Data extraction cost (3 hr/mi for 1st cycle, 1.5 hr/mi for subseqent Cycle, @ $50/hr)	$150	$75	$75	
Total data extraction cost	**$2,250,000**	**$1,125,000**	**$1,125,000**	**$4,500,000**
Total cost	**$3,999,300**	**$1,983,300**	**$1,983,300**	**$7,965,900**

Option #7 Purchase fractional (50%) ownership of a mapping grade mobile LiDAR system

3D Laser Mapping and GeoDigital International Inc. offer fractional ownership plans for a StreetMapper 360 system for U.S. customers. Fractional ownership plans are common in the aviation industry where asset costs are high. Fractional ownership reduces the cost of entry and risk of technological obsolescence. The advantage of this option is that the contractor will supply the equipment, personnel, and GNSS/IMU post-processing. DOT would not be burdened with training and equipment maintenance. On the other hand, the contracting process could be complicated and take a long time, and DOT would not have a mobile LiDAR system available at a moment's notice. The equipment availability is lower than rental or purchase option. Under the fractional ownership plan, customers purchase a fraction (20%, 30%, 40% or 50%) of the system. The customer (WSDOT) pays an initial fractional equipment cost based on the percentage of the fractional ownership. The plan also requires a monthly management and maintenance fee ($17,654/month for 50% ownership). The fee covers insurance and maintenance costs. The customer also pays a fixed per mile usage and data processing fee ($75 per mile) for the point cloud data. The plan provider will supply the personnel and vehicle for data collection (100 days per year for 50% ownership) and raw data post-processing. The customer (WSDOT) will have to perform their own data extraction using in-house personnel and software. Similar to previous "survey grade" options, the data extraction is estimated to take about 3 hours per mile at $50 per mile. The total cost for all 3 cycles (6 years) is $10.7 million.

Table 3.10 Itemized cost for partial ownership (50%) of a mapping grade mobile LiDAR system

Description	**Year 1 & 2 1st Cycle**	**Year 3 & 4 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
IT data storage cost	$328,500	$328,500	$328,500	$985,500
IT server cost	$1,000	0	0	$1,000
Data post-processing workstations (QTY=5 at $3,000 each)	$15,000	0	0	$15,000
Data extraction software	$80,000	0	0	$80,000
Data extraction software maintenance	$20,000	$40,000	$40,000	$100,000
Total IT cost	**$444,500**	**$368,500**	**$368,500**	**$1,181,500**
Initial 50% survey grade mobile LiDAR equipment purchase	$403,000	0	0	$403,000
Mobile LiDAR equipment maintenance / management cost (for 2 yrs cycle @ $17,654/month)	$423,696	$423,696	$423,696	$1,271,088
Data collection and processing cost ($75/mile)	$1,125,000	$1,125,000	$1,125,000	$3,375,000
Total Data collection cost	**$1,951,696**	**$1,548,696**	**$1,548,696**	**$5,049,088**
Data extraction cost (3 hr/mi for 1st cycle, 1.5 hr/mi for subseqent Cycle, @ $50/hr)	$150	$75	$75	
Total Data extraction cost	**$2,250,000**	**$1,125,000**	**$1,125,000**	**$4,500,000**
Total cost for first cycle with data extraction	**$4,646,196**	**$3,042,196**	**$3,042,196**	**$10,730,588**

Cost Summary of all mobile LiDAR deployment options

Table 3.11 provides a summary of the costs for each option. In all options, approximately half of the cost is data extraction cost. It is difficult to estimate the data extraction cost because it depends on the software used, number of features to be extracted, and whether the highway is in rural or urban area. The feature extraction time estimate is based on discussion with contractors and feature extraction software makers. To obtain a better estimate, the DOT must perform an in-depth study to determine a realistic productivity figure for data extraction for their asset management program. Recently, data extraction software has made significant improvement in increasing productivity. The 1st cycle cost for rental and purchase options are very close. However, the subsequent cycle cost for the purchase options are much lower. Thus, in the long run, the purchasing options are better. On the other hand, if the data collection cycle is changed from 2 years to 3 or 4 years, the rental options may be better. The fractional ownership does not seem to offer any cost advantage due to the high monthly management and maintenance cost and the per mile data processing cost. In addition, it would be shared 50% of the time so the work output would be 50% of all the other options. Data hosting cost may reduce in the future with advances in storage technology. However, the data demand may increase with high-speed LiDAR scanner and higher-resolution cameras offsetting storage cost reduction. Fractional ownership of survey grade mobile LiDAR system option can be rejected based on cost. Base on cost-only comparison, purchasing and operating a mobile LiDAR system (either mapping grade or survey grade accuracy) are the two lowest-cost options.

Table 3.11 Cost Summary of all seven options

Option Description	**Year 1 & 2 1st Cycle**	**Year 2 & 3 2nd Cycle**	**Year 5 & 6 3rd Cycle**	**Total 6 yrs (3 cycles)**
1: Contract for mobile LiDAR services (**mapping grade**)	$2,879,500	$2,128,500	$2,128,500	**$7,136,500**
2: Contract for bridge clearance measurement services	$337,500	$337,500	$337,500	**$1,012,500**
Combine option 1 & 2	$3,217,000	$2,466,000	$2,466,000	**$8,149,000**
3: Rent and operates a **mapping grade** mobile LiDAR system	$2,945,500	$1,694,500	$1,694,500	**$6,334,500**
4: Purchase and operate a **mapping grade** mobile LiDAR system	$2,970,500	$1,404,500	$1,404,500	**$5,779,500**
5: Rent and operate a **survey grade** mobile LiDAR system	$3,664,300	$2,413,300	$2,413,300	**$8,490,900**
6: Purchase and operate a **survey grade** mobile LiDAR system	$3,999,300	$1,983,300	$1,983,300	**$7,965,900**
7: 50% fractional ownership of a **survey grade** mobile LiDAR system	$4,646,196	$3,042,196	$3,042,196	**$10,730,588**

Benefits and Cost Savings of Each Solution

The benefits of mobile LiDAR technologies can be divided into tangible benefits and intangible benefits. The tangible benefits come from the direct cost savings from using mobile LiDAR technologies over current data collection methods. Other tangible benefits are FTEs reduction, vehicle fleet reduction, and carbon dioxide (CO_2) emission from less vehicle usage and miles travel. The intangible benefits are increased safety, higher data collection speed, higher accuracy data, and an up-to-date (every 2 years) data rich geospatial point-cloud data for use in other WSDOT business processes. Not all options satisfy all WSDOT programs requirements. Table 3.12 summarizes compatibility of each option with WSDOT programs. The "check" indicates compatibility.

Table 3.12 Solutions Compatibility with WSDOT programs

	RFIP	Bridge Clearance	ADA Compliance
Mobile LiDAR Deployment Options			
Contract for mobile LiDAR mapping services **(Mapping Grade)**	✓		
Contract for bridge clearance measurement services		✓	
Rent and operate **mapping grade** mobile LiDAR system	✓		
Purchase and operate **mapping grade** mobile LiDAR system	✓		
Rent and operate **survey grade** mobile LiDAR system	✓	✓	✓
Purchase and operate **survey grade** mobile LiDAR system	✓	✓	✓
Purchase fractional ownership of a **survey grade** mobile LiDAR system	✓	✓	✓

Tangible Benefits

This section calculates the cost savings of mobile LiDAR technology over the current methods for each of the four WSDOT programs: RFIP, bridge clearance measurement, and ADA feature compliance. Each section lists the assumptions for cost, FTE, and vehicle savings. The assumptions may have large effects on cost saving calculation.

Roadside Feature Inventory Program (RFIP)

Some RFIP data, such as culvert type, size, and location, would not be collected using mobile LiDAR system because culvert ends cannot be reliably seen by the scanners. These features would still require the traditional process to collect, utilizing field personnel with GPS units for collection. However, culvert type, size, and location do not change. Therefore, once collected these would not need to be collected again. RFIP data collection must retain some FTEs (Full-time Equivalent) to collect feature data that the mobile LiDAR system cannot reliably provide. Nevertheless, it is estimated that the number of vehicles required would still be reduced from six to two, and number of FTE for data collection would reduce from twelve to two. In addition some of the RFIP cost is devoted for back office data management and support for its customers. This analysis assumes that 60% of the current RFIP cost is associated with feature data collection. Table 3.4 shows that the average RFIP cost is $1,355/mile. Thus, $813/mile ($1,355/mi * 0.6) is the current RFIP feature data collection cost, and the total feature data collection cost for the entire Washington State is $5,691,000 ($813/mile * 7000 mile) for the first cycle of data collection. The cost for subsequent cycle of data collection will be less because most data has been collected in the first cycle. The analysis assumes data collection of subsequent cycles cost ($2,845,500) would be half of the first cycle.

Bridge Clearance Measurement

Based on BPO's estimate, WSDOT BPO spends $80,000 a year to collect bridge clearance data, and data collection cycle for the entire WSDOT's bridge clearances takes 10 year to complete. Therefore, if a survey grade mobile LiDAR system is used, the saving would be $800,000 for each data collection cycle. Besides measuring bridge clearance data, the bridge inspectors also perform the critical task for inspecting bridges for their integrity which occupies most of their time.

Americans with Disabilities Act (ADA) Feature Inventory

The expenditure for WSDOT ADA compliance survey varies from year to year, and it is hard to predict. It was assumed that it would continue year after year. It was estimated that the average annual cost is $180,000, and also assumed that 60% of the program cost is associated with data collection. Thus, using a survey grade mobile LiDAR system would save $108,000. It would also save 1 vehicle and 2.5 FTE.

Carbon Dioxide Savings

For the CO_2 emission savings calculation, it is assumed each vehicle travels 15,000 mile per year with average gas mileage of 25 mile per gallon (mpg). The annual gasoline usage is 600 gallon, and the equivalent CO_2 emission is 11,640 lbs per year (5.8 ton per year) for each vehicle.

Benefit summary

It was estimated that the point cloud feature extraction requires 2.5 hr/mile to 3 hr/mile for the first cycle, and therefore the man-hour required for the entire Washington State is estimated to be 37,500 to 45,000 hours over two years or 9 to 11 FTEs/year for the first cycle. Table 3.13 summarizes the data collection and processing cost for RFIP, Bridge Clearance measurement, and ADA feature inventory programs.

Table 3.13 Itemized savings for each program

	A	B	C	D	E	F
Current Operations	**Estimated 1st Cycle Cost**	**Estimated Subsequent Cycle cost**	**Annual FTE for data collection**	**Estimated FTE for data collection after Mobile LiDAR**	**Current Vehicle Usages**	**Vehicle needed after Mobile LiDAR**
RFIP	**$5,691,000**	**$2,845,500**	12	2	6	2
Bridge Clearance Measurement	**$800,000**	**$800,000**	2	2	1	0
ADA Feature Inventory	**$108,000**	**$108,000**	2.5	0	1	1

Table 3.14 shows the benefits for each mobile LiDAR system deployment option. The 1st cycle savings (Table 3.14 Column I) is the estimated monetary savings produced by implementing the option in the first data collection and processing cycle. It was calculated by subtracting the option's 1st cycle data collection and processing cost (Table

3.14 Column A) from the total estimated 1st cycle cost (Table 3.13 Column A) of the WSDOT operations (RFIP, Bridge clearance measurement, and ADA feature inventory) that benefited from that option. The subsequent (2nd and 3rd) cycle savings (Table 3.14 Column J) is equal to the total of estimated subsequent cycle cost of affected WSDOT operations (Table 3.13 Column B) minus the option's subsequent cycle data collection and processing cost (Table 3.14 Column B). The expected monetary savings of all three cycles in 6 years (sum of Table 3.14 column I and 2 times column J) is shown in Table 3.14 Column K. Even though deploying the survey grade system costs more, the benefits and cost saving from the bridge clearance and ADA feature inventory operations outweighs the higher cost and produces higher savings.

Table 3.14 Column F shows the estimated FTE savings produced by each option in their first cycle of data collection and processing. This was calculated by adding Column C and subtracting Column D of Table 3.13 of the WSDOT operation that benefited from the option, and subtracting the sum of Table 3.14 Column C and D of the option. The vehicle savings was calculated similarly.

Table 3.14 Itemized savings for each mobile LiDAR option

	A	B	C	D	E	F	G	H	I	J	K
Option Description	**1st cycle data collection & processing cost**	**Subsequent cycle data collection & processing cost**	**FTE required for data collection**	**Annual FTE required for data Post-pocessing**	**Annual vehicle(s) for data collection**	**FTE savings**	**Vehicle savings**	**CO2 savings (tons)**	**1st cycle savings**	**Subsequent cycle savings**	**Total 6 yrs (3 Cycles) savings**
1: Contract for mobile LiDAR services (**mapping grade**)	**$2,879,500**	**$2,128,500**	**0**	**0**	**0**	**8**	**4**	**23**	**$2,811,500**	**$717,000**	**$4,245,500**
2: Contract for bridge clearance measurement services	**$337,500**	**$337,500**	**0**	**0**	**0**	**0**	**0**	**0**	**$462,500**	**$462,500**	**$1,387,500**
Combine option 1 & 2	**$3,217,000**	**$2,466,000**	**0**	**0**	**0**	**8**	**4**	**23**	**$3,274,000**	**$1,179,500**	**$5,633,000**
3: Rent and operates a **mapping grade** mobile LiDAR system	**$2,945,500**	**$1,694,500**	**1**	**9**	**1**	**0**	**3**	**23**	**$2,745,500**	**$1,151,000**	**$5,047,500**
4: Purchase and operate a **mapping grade** mobile LiDAR system	**$2,970,500**	**$1,404,500**	**1**	**9**	**1**	**0**	**3**	**23**	**$2,720,500**	**$1,441,000**	**$5,602,500**
5: Rent and operate a **survey grade** mobile LiDAR system	**$3,664,300**	**$2,413,300**	**1.5**	**11**	**1**	**0**	**4**	**29**	**$2,934,700**	**$1,340,200**	**$5,615,100**
6: Purchase and operate a **survey grade** mobile LiDAR system	**$3,999,300**	**$1,983,300**	**1.5**	**11**	**1**	**0**	**4**	**29**	**$2,599,700**	**$1,770,200**	**$6,140,100**
7: 50% fractional ownership of a **survey grade** mobile LiDAR system	**$4,646,196**	**$3,042,196**	**0**	**11**	**1**	**2**	**4**	**29**	**$1,952,804**	**$711,304**	**$3,375,412**

Intangible Benefits

Intangible benefits are the unquantifiable benefits without any cost and data from previous history. Intangible benefits could be potentially larger than the tangible benefits. Using a mobile LiDAR system reduces worker exposure to traffic and environmental hazards because all personnel are inside a vehicle. It also improves mobility of the traveling public by eliminating lane closures and other temporary work zones for survey workers. It also lowers the number of FTEs, vehicles, and carbon dioxide emission for data collection. In addition it increases the speed of data collection and reduces time to acquire the critical geospatial data for the data-driven decision making process. Long time delay between data requested and data provided is often the invisible cause of project delays and cost overruns. The major intangible benefactors are the WSDOT's GeoMetrix Office, Geotechnical Office, Planning Office, Environmental Office, Design and Construction, and Attorney Generals (AG) Office. The intangible impact by a mapping grade mobile LiDAR system is less than that of a survey grade system as shown in Table 3.15, which provides a list of applications that could benefit from mobile LiDAR technology.

Mobile LiDAR technology provides an effective means to collect as-built data on bridges and structures. Bridge and structure detailed as-built data before any man-made accident or natural disaster is critical in assessing the damage caused by the accident or disaster. Good documentation and proof of the damage would significantly improve the likelihood of WSDOT recovering repair cost from the individual who caused the accident without lengthy litigation. In addition, the AG Office currently relies on outside contractors to provide LiDAR data for accident reconstruction. The deployment of mobile LiDAR technology would provide them with LiDAR data before and after the accident. Thus, AG Office would save money from not having to pay contractors for scanning the roadway at the accident area.

GeoMetrix Office and their customers, such as design and construction, could be the biggest intangible benefactors. Currently, the cost of survey grade mobile LiDAR data from survey services contractors is about $10,000 to $15,000 per mile. One quarter to one third of the cost is associated with the equipment cost. GeoMetrix Office could save at least $100,000/year if the survey grade mobile LiDAR system is used to scan 40 miles of roadway a year. The cost of the survey grade mobile LiDAR system would be recovered from GeoMetrix Office's projects over six years. A mobile LiDAR system could also be used for construction inspection and as-built documentation throughout different construction stages. Thus, as-built data of utilities conduits, drainage pipes, pavement sub-grade, and pavement thickness are accurately captured for future maintenance and retrofit. Having accurate as-built data would significantly reduce the need for ground penetrating radar survey for utilities before retrofit or change order during retrofit construction in the future.

Table 3.15 WSDOT business areas benefit from mobile LiDAR

WSDOT Business Areas
RFIP
Bridge Clearances Measurement
ADA feature inventory
Archeological site scanning.
Project planning and scoping
Bridge and structural asbuilt
Construction inspection documentation
Earth-moving volume surveys for contracts dispute and compliance
Maintenance quantities (mowing areas, tree trimming, slopes, etc)
Safety surveys such as guardrail location and height determination, and line-of-sight analysis for safety and engineering studies
Before and after disaster damage for bridge and roadway structure damage and risk assessment
Geotech Engineering: Unstable slopes monitoring
Legal (AG office) – accident reconstruction, tort liability
Right of Way and Access Encroachment
Outdoor Advertizing Monitoring and Violation Detection
GeoMetrix Office Projects
Lane channelization
Cable barrier asbuilts
Roadway prism asbuilt
Topographical mapping
Tunnel asbuilts
Railroad surveys
Power lines and utilities/luminaires/signals
Pavement surface areas

WSDOT Mobile LiDAR System Deployment Challenges and Considerations

The selected system/solution must meet the diverse business objectives of WSDOT while balancing the costs, benefits, and ease of implementation. The mode of operation has a significant effect on cost. The best deployment option is not just based on maximum cost/benefits. It also depends on other factors such as ease of implementation, risks, and economic feasibility [25]. Even though mobile LiDAR systems improve worker safety and are cost-effective, deployment of mobile LiDAR mapping technology presents several challenges for DOT:

- Extensive knowledge, skills and mission planning are required to operate a mobile LiDAR system and properly post-process the raw GNSS/IMU/LiDAR data.

- Management has to address integration issues with existing WSDOT business processes.

- The high initial cost of the system may require a special legislative approval to purchase the equipment. In addition, funding is also required for software, computing infrastructure upgrades, system maintenance, and creating a new funding program with personnel to operate the system and process the data. A "Decision package" must be written to put together the program and seek legislative approval for extra funding.

- Best practices and workflow procedures must first be created to ensure data is collected consistently and achieves the needed accuracy as well as guiding users on the proper use of the data. At the same time, the best practices and workflow procedures should be integrated into WSDOT standards manuals and policy documents.

- IT Challenges:

    - Mobile LiDAR systems can produce a huge amount of data in a short time, requiring upgrade of the entire computing infrastructure (software, workstations, servers, data storage, and network backbone). The unusually large data storage requirement could put a large strain on existing DOT IT infrastructure. Server room, network bandwidth and backbone may have to be upgraded to accommodate the data demand.

    - The feature extraction will require new software and high-end workstations. The GeoMetrix Office has already invested in both software and high-end workstations and currently has the knowledge and skills needed for processing and extracting LiDAR data.

    - A data management system is needed in the long run to allow diverse groups of users to access the current and historical data in order to extract the needed information. A simple and easy to use point cloud viewer will be needed.

    - A large training program may be required in order to train a larger work force to take advantage of the point cloud data. The latest version of MicroStation supports point cloud, and it could be one of the software for WSDOT personnel to view and extract data.

Risks and Mitigation

Technological obsolescence is one of the major risks of purchasing a mobile LiDAR system. The GNSSs (GPS, GLONASS, Galileo, and Compass) are currently going through major modernization or are in the middle of deployment. More satellite navigation frequencies and signals will be made available soon. Most GNSS receivers are designed to be compatible with GNSS modernization. Their firmware may be upgraded to improve compatibility. However, the new generation of GNSS receivers with much higher number of channels for GNSS signal tracking may be needed to take advantage of over 80 satellites in the sky when all the GNSSs are fully operational. The cycle of new GNSS receiver development is about 1 to 2 years. Higher accuracy IMUs are also made available at “affordable” price for mobile LiDAR system. However, the development cycle for IMU sensors are usually longer than 3 years.

LiDAR scanners have made rapid improvement recently. For example, the Optech Lynx LiDAR scanner’s maximum measurement rate has increased from 100,000 points per second (pts/s) to 500,000 pts/s, and its maximum scan rate has also increased from 150 Hz to 200 Hz when the system first offered over 4 years ago. Nevertheless the total system cost remains the same. Other mapping grade LiDAR scanners are made available with higher performance and lower cost. In addition, digital camera has also made technological improvement over the years in term of cost, frame rate, and resolution.

To mitigate risk of technological obsolescence, customers may obtain data from mobile LiDAR service providers using service contract. In addition, mobile LiDAR system manufacturers have recognized their customer’s concern of risk of technological obsolescence and high initial system cost. They have partnered with dealer or services provider to offer equipment rental and partial ownership options. Both options enable lower cost of entry and provide a cost-effective option for low utilization. To determine which options may be most cost effective, users should consider the expected utilization rate of the mobile LiDAR system. If the anticipated system utilization rate is low, then renting, partial ownership, or service contracts may be a better options.

The uncertainty in the high feature extraction cost presented ambiguity in the cost benefit analysis. Realistic feature extraction productivity data is not available. The cost / benefit analysis is based on estimates given by services providers and DOT users. The feature extraction productivity fluctuates greatly depending on the software, user skill level, feature requirement, and geographical location. However, it could also be an opportunity for improvement in savings through better software and workflow.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

Mobile LiDAR technology enables WSDOT to collect geo-spatial data once, with the data being used by many of the WSDOT business process as well as other State departments. Table 3.14 summarized the cost and saving for all seven mobile LiDAR deployment options. Over 3 cycles and 6 years lifecycle, the savings range is from $1.3 million to $6.1 million.

- Although equipment rental options have lower initial cost, the purchase options have lower lifecycle cost and produce larger saving than the rental options.

- Option 6, purchasing and operating a survey grade mobile LiDAR system, produced the highest saving of $6.1 million. Even though deploying the survey grade mobile LiDAR system costs more, the benefits and cost saving from the bridge clearance operation outweighs the higher cost and produces higher saving.

- The first data collection cycle is generally more expensive than subsequent cycles due to higher data extraction cost in the first cycle and lower data extraction cost in subsequent cycles.

- The intangible benefits of deploying mobile LiDAR system could be potentially larger than the tangible benefits. The major intangible benefactors are the WSDOT's GeoMetrix Office, Geotechnical Office, Planning Office, Environmental Office, and Attorney Generals (AG) Office. A survey grade mobile LiDAR system meets the requirements of more types of work than a mapping grade mobile LiDAR system. The technology could also be useful in other WSDOT application areas such as cultural heritage preservation, homeland security, construction inspection, and 3D digital world models for machine control and guidance in construction.

The system/solution selection process must also consider diverse business objectives while balancing costs, benefits, and ease of implementation. Other factors, such as integration into existing WSDOT business processes, risks, and economic feasibility, should be considered. The cost benefit analysis offers a guide to which option may be the best for WSDOT. Further internal discussion with WSDOT management is needed to examine the advantages and disadvantages of these solution options in order to select the prime candidate for deployment.

Recommendations

Purchasing and operating a mobile LiDAR system is the recommended option because:

- It generates savings and meets most WSDOT business requirements.

- The number of survey grade mobile LiDAR systems available for rental is quite limited. Appendix A shows a few mobile LiDAR systems available for purchasing and thus avoids sole source rental scenario.

On the other hand, renting and operating a mobile LiDAR system should be considered if:

- The data collection cycle duration is increased from two to four years and the equipment utilization rate is low.

- The lower initial cost is required for lack of funds.

Appendix A provides mobile LiDAR system selection considerations with explanations. In general, a mobile LiDAR system should be configured with dual LiDAR scanners with two digital cameras pointing forward and two cameras pointing sideways.

Future Work

AHMCT researchers will continue to monitor the standardization efforts and results produced by ASPRS and ASTM. NCHRP has initiated a new project to develop best practices and guidelines for the use of mobile LiDAR system. The ASPRS mobile systems committee, chaired by Dr. Craig Glennie, is working on a best practices and guidelines document, with the goal of having an initial draft prepared for ASPRS 2012. Best practices and workflow documentation are crucial in producing accurate and reliable data consistently and efficiently.

A documented cost benefit analysis and "Decision Package" will need to be developed to help convince the legislature to approve funding deploying mobile LiDAR mapping technology. Additional analysis and internal discussion may be required to determine which deployment options may best fit for WSDOT. It is suggested to select one or two options from this report for approval.

Future research should examine the best approaches to combine digital images with LiDAR data to increase data extraction productivity. In addition, a software tool should be developed to stream data to the user to visualize data and do measurements at their desk PC.

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APPENDIX A: COMMERICALLY AVALABLE MOBILE LIDAR SYSTEMS

Background

Terrestrial mobile LiDAR systems—a new class of survey instrument—have recently become commercially available for roadway surveys including roadside asset inventory, bridge structures, bridge clearance and highway pavement surveys. AHMCT had experimented with a vehicle-mounted laser scanner system for bridge clearance measurement for Caltrans Structures Maintenance. A mobile LiDAR system was used for terrain mapping of Highway 1 in Afghanistan [21] as well as US highways [8]. In the system used in Afghanistan, a ground-based 2-D laser scanner was mounted on a truck with a GPS and IMU. These systems measure millions of data points and generate a very detailed "point cloud" data set. Since then, several manufacturers have developed and offer commercial systems. Several service providers have purchased these systems and provide mobile LiDAR services for many different applications. Mobile LiDAR technology availability and accuracy have increased.

General Mobile LiDAR System Description

The basic system architecture of a Land-based mobile LiDAR scanning system [1,3,10,13,16,17,19,21,26], illustrated in Figure A.1, consists of:

- A dual-frequency Real-Time Kinematic (RTK) GNSS receiver(s)
- A six Degree-Of-Freedom (DOF) Inertial Measurement Unit (IMU) (typically three accelerometers and three gyros orthogonally (xyz directions) mounted)
- A Distance Measuring Indicator (DMI),
- LiDAR scanner(s)
- Data synchronization electronics
- Data logging computer(s)
- Digital camera(s).

The computer(s) collects the synchronized data of the GNSS carrier-phase measurements, IMU and DMI outputs, digital photographs, and LiDAR scanner data for the post-processing software. Combining GNSS base station raw data collected at the same time, the GNSS measurement, IMU, and DMI data of the rover, the software will provide position and orientation solution (at 100 to 1,000 Hz update frequency) of the sensor platform containing the LiDAR scanners and digital cameras. To achieve the highest possible accuracy, the raw GNSS/IMU data is post-processed with GNSS base station(s) raw data with high accuracy satellite orbital measurements. Furthermore, the system may have multiple LiDAR scanning sensors with digital cameras in visible light wavelength, Near Infrared (NIR), or Ultraviolet (UV) wavelength. Near Infrared (NIR) and Ultraviolet (UV) cameras may be used to better identify certain plant species or in poor lighting conditions.

The land-based LiDAR scanners are usually shorter in range but higher in accuracy than those used in airborne systems. The LiDAR scanner produces distance and angular measurement to the target as well as the amplitude of the light return signal. The amplitude depends on the reflectance of the target surface as well as range and incidence angle to the target. It allows the software to identify the highly reflective painted lane lines, signs, and raised pavement markers. By combining the GNSS/IMU and laser range scanner data, the global coordinate of every scan point can be calculated. Thus, the position of the painted lane line will also be established. In addition, other roadside and roadway features can be identified and located using the resulting point cloud and geo-referenced photographs.

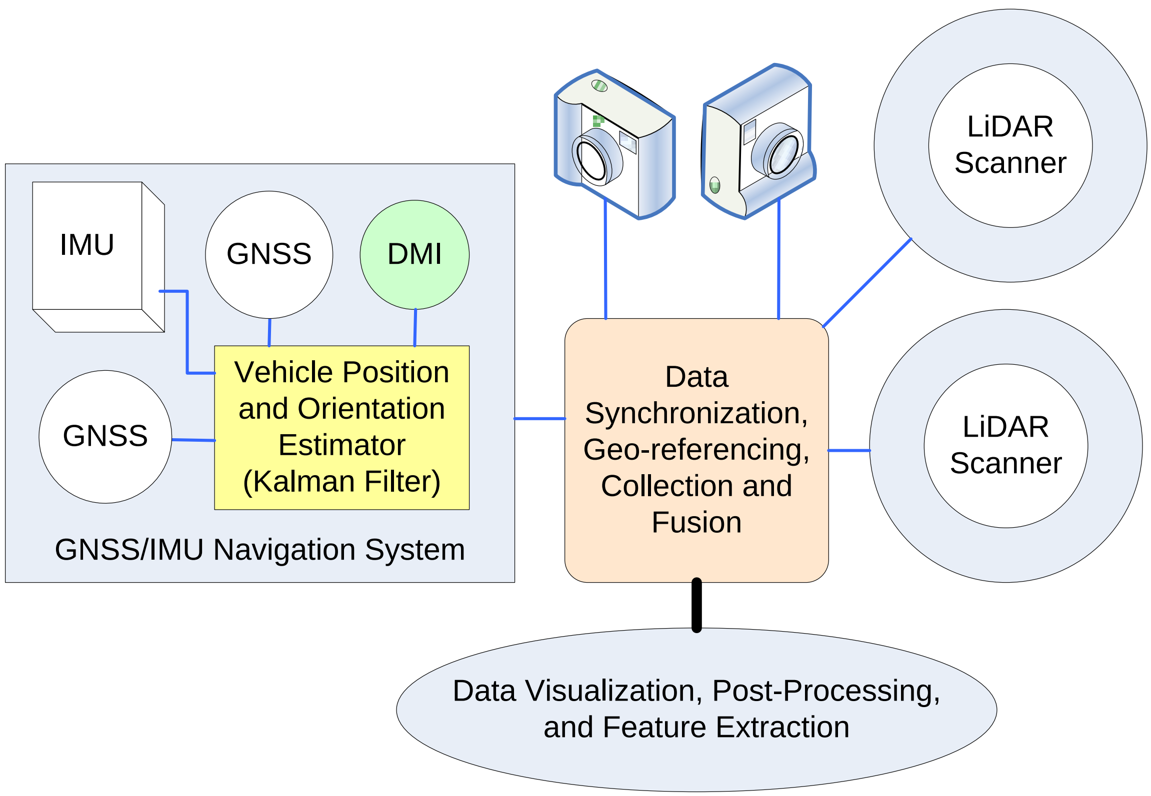

Figure A.1: Mobile LiDAR system architecture block diagram

2D LiDAR Scanner Overview

The 2D LiDAR scanner uses advanced laser measurement technology capable of obtaining hundreds of thousands of point measurements per second. The 2D LiDAR scanner system consists of a motorized spinning mirror with encoder and a LiDAR sensor. Its accuracy depends on the rangefinder accuracy and the encoder resolution. Moreover, some scanner performance can be adversely affected by surface reflectivity, edges, temperature, atmospheric conditions, and interfering radiation such as bright lights or direct sunlight [2]. 2D LiDAR scanners for mobile LiDAR systems use either the

Time-of-Flight (TOF) measurement method or phase-based measurement to obtain target point distance.

Time-of-Flight measurement technology works by sending out a laser pulse and observing the time taken for the pulse to reflect from an object and return to the instrument. Advanced high-speed electronics are used to measure the small time difference and compute the range to the target. The LiDAR scanner also has a high-resolution angular encoder to provide orientation of the rotating mirror at the time of each range measurement. This type of technology is similar to that used in Total Stations. However, the difference between 2D LiDAR scanners and Total Stations is the speed of measurement. Typical Total Stations may measure up to eight distances per second. In contrast, the 2D LiDAR scanner is capable of measuring up to half a million distances per second. Some LiDAR sensors can detect and provide range measurement for multiple light returns from a single light pulse. This technology enhances the LiDAR sensor's ability to detect the structure or an object positioned behind vegetation.

Phase-based measurement technology works by the phase difference measured between the reflected beam and the transmitted amplitude modulated continuous wave laser beam. The target distance is proportional to the phase difference and the wavelength of the amplitude modulated signal. In addition, the amplitude of the reflected beam provides the reflected power. Typically, phase-based scanners are capable of achieving a much higher number of point measurements in a second relative to time-of-flight scanners—their point measurement rate is from about five to one hundred times greater. However, they have shorter useful range, typically 25-100 m (80-330 ft). Time-of-flight scanners have the technological adaptability to provide longer range, typically between 75 m to 1000 m (245 ft to 3280 ft). Currently available phase-based LiDAR sensors do not have multiple return capability.

Figure A.2: Working principle of phase-based and time-of-flight 3D laser scanners

Table A.1 lists some of the most common 2D LiDAR scanning systems used by mobile systems. Their detailed specifications may be found on their manufacturer's websites listed in Table A.1. While scanner measurement rate (points per second) is often used to promote the superiority of a LiDAR scanner technology, the "scan rate" is more critical in affecting the vehicle's speed in data collection. The "scan rate" is the LiDAR scanner's mirror rotational rate. The points in the point-cloud produced by mobile LiDAR system are not evenly spaced as shown in Figure A.3. The point-cloud in Figure A.3 is produced by a system with two LiDAR scanners mounted orthogonal to each other and approximately 45 degrees to the vehicle travel direction. Each dot represents a single LiDAR measurement, and each line of dense dots corresponds to a series of measurements from a single sweep of the LiDAR scanner mirror. The high LiDAR measurement rate creates small point spacing within each "line". The spacing between the lines of points is equal to the vehicle speed divided by the "scan rate". For example, a "scan rate" of 100 Hz and vehicle speed of 25 m/s (56 m/h) would produce a line spacing of 25 cm (10 inches). The maximum line spacing depends on the application. Generally, it should be below 15 cm (6 inches). Therefore, higher "scan rate" is more important than LiDAR measurement rate in mobile mapping applications. While most LiDAR scanners have only one laser emitter and detector, the Velodyne LiDAR scanner has multiple sets of emitters and detectors mounted at different angles. For example, their HDL-64E has 64 sets of emitters and detectors covering from $+2^{o}$ to -24.8^{o} ($\sim 0.4^{o}$ spacing). It produces dense line spacing despite low scan rate of 15 Hz. However, the line space increases with the measurement range.

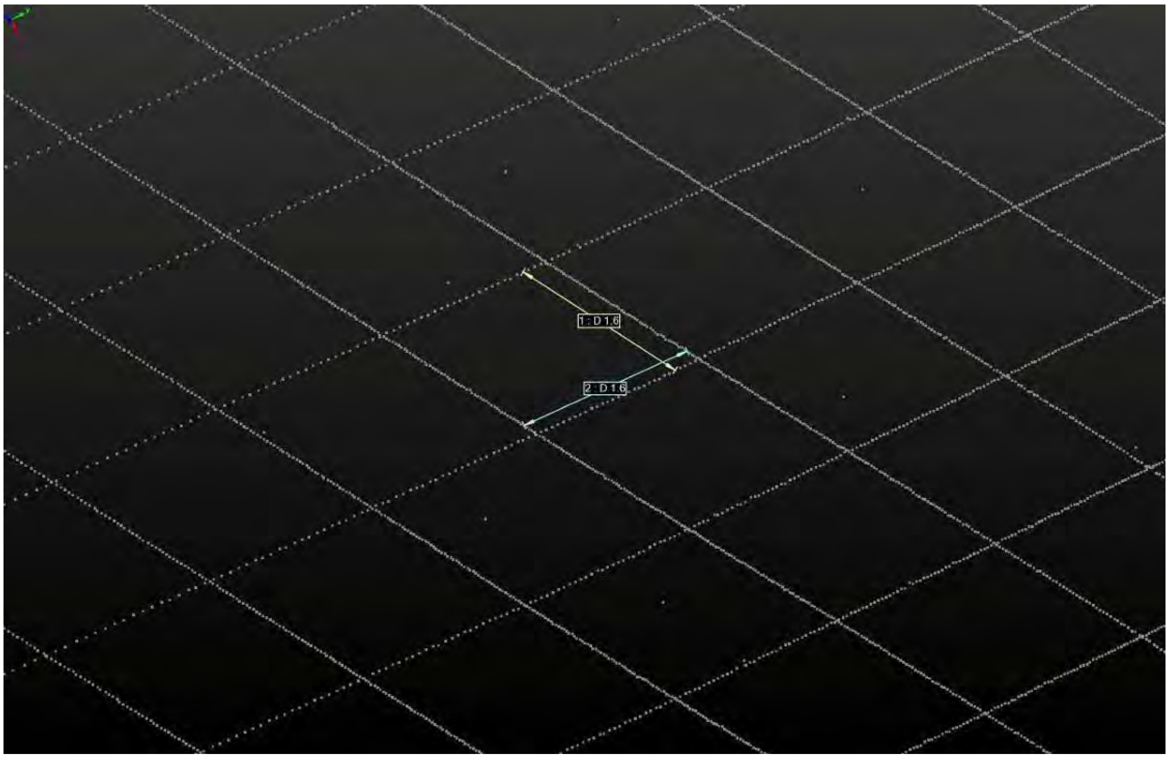

Figure A.3: Typical "scan line" produced by mobile LiDAR systems, dimensions in feet (Courtesy of GeoMetrix Office)

LiDAR requires an unobstructed line-of-sight to the measurement surface. Obscured by the internal structure and scanner body, some 2D LiDAR scanners have less than 360 degree field of view (FOV) by design. New generations of 2D LiDAR scanner designs enable 360 degree FOV. Thus, the number of scanners on a mobile system may be reduced, resulting in a smaller and more compact system. In real-life applications, the LiDAR measurement range generally is smaller than 1/3 to 1/2 the maximum range claimed in vender's specifications. The maximum measurement range is degraded by the object's surface reflectivity and the laser light angle of incidence.

Since these mobile systems are operated on public highways, the laser on the LiDAR scanner must be rated "eye-safe". Human retinas can be damaged by concentrated coherent laser light beams emitted by the LiDAR scanner. Most modern LiDAR scanners have a Class I laser which produces low power invisible infrared laser light incapable of damaging the human retina.

Maker	Optech	Riegl	Riegl	Z+F	Phoneix Sci	Sick	Sick	Faro	Velodyne	Velodyne
Photo										
Model	Lynx V200 Lynx M1	LMS-Q120i	VQ-250	5010 Imager / Profiler	PPS-2000	LMS291	LMS511	Focus 3D	HDL-64E	HDL-32E
Range Accuracy	+/- 7 mm (1 σ) (0.02 ft)	20 mm (0.07 ft)	10 mm (0.03 ft)	~ 3 mm (0.01 ft)	0.15mm (0.05 ft)	+/- 35 mm (0.11 ft)		~ 3 mm (0.01 ft)	+/- 15 mm (0.05 ft)	+/- 20 mm (0.07 ft)
FOV (degree)	360	80	360	320	90	180 or 90	190	305	360	360
Scan Freq.	80-200 Hz	100 Hz	100 Hz	Imager: 50 Hz Profiler: 100 Hz	1000 Hz	75 Hz	100 Hz	97 Hz	15 Hz	5-20 Hz
Long Spacing @ 55mph	0.12 m (0.4 ft)	0.25 m (0.8 ft)	0.16 m (0.5 ft)	0.16 m (0.5 ft)	0.03 m (0.08 ft)	0.32 m (1 ft)	0.16 m (0.5 ft)	0.16 m (0.5 ft)	0.03 m (0.8 ft)*	0. m (0. ft)**
Point/s	Up to 500,000	10,000	Up to 300,000	1,016,000	945,000	13,500	19,000	Up to 976,000	1,000,000	800,000
Practical Range	~ 75 m	~ 50 m	~ 75 m	~ 50 m	~ 3 m	~ 25 m	~ 40 m	~60 m	~ 75 m	~ 75 m
Eye Safety	Class 1, Yes	Class 1, Yes	Class 1, Yes	Class 1, Yes	Class IIIb, No	Class 1, Yes	Class 1, Yes	Class 3R, Yes	Class 1, Yes	Class 1, Yes
Multi-return	Yes	No	Yes	No	No	No	Yes	No	No	Yes
Cost	~ $200,000	N/A	~ $200,000	~ $150,000	N/A	~ $5,000	~ $5,000	$40,000	$75,000	$30,000
Website	Optech.com	Riegl.com	Riegl.com	Zf-laser.com	Phnx-sci.com	Sickusa.com	Sickusa.com	Faro.com	Velodyne.com/ lidar	Velodyne.com/ lidar

Table A.1 Commerially-available 2D LiDAR scanning systems

GNSS/INS Land Vehicle Positioning Systems Overview

Land vehicle positioning systems, composed of GNSS receiver(s), IMU, and DMI, are crucial in providing accurate continuous vehicle position and orientation for the mobile system. Tightly-integrated RTK GNSS receivers and IMU systems have been developed and used in mapping and vehicle guidance. Performance has significantly improved, and many COTS systems have recently become affordable. The accuracy of the final point-cloud largely depends on the GNSS/IMU system accuracy.

Global Navigation Satellite System (GNSS) Modernization

Today, GNSS provides autonomous geo-spatial positioning with global coverage. GNSS receivers determine their location and precise time using time signals transmitted along a line-of-sight by radio from GNSS satellites. Today, there are four GNSS systems (GPS, GLONASS, Galileo, and Compass) in operation or initial deployment phase.

The United States Global Position System (GPS) has been operational since 1994. It is current being modernized and upgraded. RTK GPS has become the standard survey tool for large areas. It is capable of delivering centimeter accuracy under ideal conditions. Producing a high-accuracy RTK GPS solution requires data from two dual-frequency (L1 and L2) GPS receivers—one stationary base station and one rover—collecting signals from at least five GPS satellites at the same time. The solution may be calculated in real-time by the rover GPS if it receives the base station data in real-time through a radio data link. The solution may also be calculated by post-processing software using the coordinated data collected by the base station and rover GPS after the end of the survey. Real-time solutions allow the surveyor to see the accuracy of the solution at the time of survey occupying the location point of interest. However, this requires live radio data to the GPS station. Post-processing does not require live radio link, but the surveyor does not know they have an accurate solution until the solution is post-processed in the office at the end of the survey. In this case, the surveyor runs the risk of not having enough satellite signals to generate good survey data. The RTK GPS solution accuracy depends on many factors, such as GPS data processing algorithms, GPS receiver noise, multi-path of GPS satellite signals caused by buildings or terrain, ionosphere conditions, troposphere conditions, the number of visible GPS satellites, GPS satellite geometry, and the distance between the base station and rover GPS. The error relationship is quite complex and difficult to quantify. Significant efforts have been made by the U.S. government, research institutions, and GPS equipment makers to reduce the error and improve the speed to resolve and calculate the RTK solution.

The current GPS system is undergoing a major modernization. The ground control and monitoring station facility are being upgraded, and new GPS satellites are being launched with new civilian and military signals, including L1C, L2C and L5 frequencies. The current GPS constellation consists of 32 satellites. At the same time, new GPS receivers have been developed to take advantage of the new signals. The GPS industry expects to see GPS accuracy and availability improve continuously throughout the next several years as a result of this modernization effort.

The former Soviet Union and now Russia developed and deployed GLObal'naya NAvigatsionnaya Sputnikovaya Sistema (GLONASS). It had a fully functional navigation constellation. However, it fell into disrepair after the collapse of the Soviet Union resulting in gaps in coverage and only partial availability. Recently, the restoration and modernization of the GLONASS satellite constellation is in process. Currently, there are 23 operational satellites. The modernized GLONASS satellite will transmit new signals in L1, L2, L3 and L5 frequencies. The majority of new survey-grade GNSS receivers support GLONASS. Mobile LiDAR system operators found that combining GPS and GLONASS significantly improved satellite availability and position solution accuracy in GNSS-challenged areas such as urban canyons.

In addition, the European Union (EU) is expected to bring Galileo, a Global Navigation Satellite System (GNSS) similar to GPS, online in the next several years. The recent agreement between the EU and the U.S. ensures both GNSS systems will be compatible and interoperable. As a result, Galileo effectively doubles the number of GPS satellites in the sky with its 30 satellite constellation. This compatibility will certainly improve the overall performance of GPS and Galileo receivers. Two experimental Galileo satellites are currently in orbit; however, the full operational date of Galileo has been delayed several times and is quite uncertain at this time. Nevertheless, modern GNSS receivers are designed and produced to support Galileo.

Lastly, the COMPASS system, also known as Beidou-2, is a GNSS being developed by China as an independent global satellite navigation system. It will be a constellation of 35 satellites, which include 5 geostationary orbit (GEO) satellites and 30 medium Earth orbit (MEO) satellites. The ranging signals are based on the CDMA similar to Galileo or modernized GPS. The full operational constellation covering the entire globe is expected to be completed in 2020.

When all four GNSS systems are deployed as planned in the next several years, there will be a combined constellation of 90+ satellites, which will significantly improve the signal availability and position accuracy, especially in urban canyons, forest, and high-latitude areas. While the availability of these new and improved GNSS is welcomed by users, it also presents a risk of technological obsolescence to the users. To take full advantage of new and modernized GNSS, users may have to upgrade their expensive survey grade GNSS receivers more often than in the past. Upgrading the GNSS receiver(s) on a highly-integrated mobile LiDAR system may not be an option, making the entire system obsolete.

Inertial Measurement Unit (IMU)

Inertial Measurement Units (IMUs) are composed of accelerometers and gyros. The most common configuration is three accelerometers and three gyros mounted orthogonally (on the xyz axes) to each other. More inertial sensors may be used to provide redundancy and increased accuracy. Accelerometers give body acceleration data in three directions, and gyros provide yaw rate (body rotational rate) data in three directions. By integrating this sensor data, the body position and orientation may be calculated at all times. The integration process does introduce cumulative errors. Therefore, the error of this dead-reckoning method increases as the integration duration increases, i.e. the solution drifts. The IMU system cost varies enormously from a few hundred dollars to several hundred thousand dollars depending on accuracy and drift rate. Unlike GNSS which provides positional solutions at a low rate of 1 to 20 Hz (1 to 20 solutions per second), the IMU provides positional and orientation updates at a high rate 256 Hz to 1000 Hz (256 to 1000 per second).

IMUs are used in airplanes, ships, submarines, and missile navigation. The Honeywell HG1700 and Litton LN200 IMU are often used in the GNSS/IMU positioning system for mobile systems. Since these IMUs are used in military applications, they are subjected to International Traffic in Arms Regulations (ITAR). Besides regulating the import and export of these components, ITAR also restricts the access of the IMU created data to a "foreign agent." A foreign agent could be a non-US citizen or a foreign country. In other words, the IMU data must be guarded from access from any non-US citizen. In addition, laptop or USB drives storing the IMU data must not be taken outside U.S. ITAR details can be found at the U.S. State Department website. The users should educate themselves so that ITAR is not breached. Recently, higher-accuracy, non-ITAR restricted IMUs were made available with competitive prices. Lately, most mobile LiDAR system operators chose to buy systems with higher-accuracy IMUs without ITAR restrictions.

IMU accuracy plays a curial role in the orientation accuracy of LiDAR scanners, and in turn affects positional accuracy of each point in the final point-cloud. There are several parameters used to describe performance of the accelerometers and gyros inside an IMU. Typically, IMU designers choose accelerometers with performance specifications complementary to that of the gyros used in an IMU. To determine the IMU accuracy, users can focus on one key performance parameter, the gyro bias. The IMU gyro bias should be less than or equal to 1 degree/hr for mobile LiDAR mapping applications. Some "survey grade" mobile LiDAR systems utilize fiber optic gyro (FOG) with gyro bias less than 0.5 degree/hr. These tactical and navigation grade IMUs cost from $40,000 to over $100,000. Higher IMU accuracy enables GNSS/IMU system to maintain accurate positional and orientation solution accuracy for longer GNSS signal outages.

Integrated GNSS/IMU Navigation System

Integrated GNSS/IMU systems are often used in mobile mapping, aerial photogrammetry mapping, and navigation applications. GNSS data align and calibrate the IMU sensors when GNSS satellites and solution are available. The IMU provides positional solution when a GNSS solution is not achievable. It also "smooths" out the GNSS solution, and provides a high sample-rate solution between relatively sparse GNSS samples. Without the GNSS positional solutions, the IMU integrated positional solution will drift out of bound over time. The integrated GNSS/IMU system may provide an accurate positional solution from up to 1000 Hz while a standalone GNSS system may only yield a 20 Hz positional solution. The Kalman Filter (KF) proved to be the optimal method for the estimation and compensation of the system errors in GNSS/IMU system integration [20]. Several KF approaches have been put into practice, such as the Linearized KF, Extended KF, and the sigma-point or Unscented KF. Much research has been conducted in GNSS/IMU integration in significant depth [5-7,20,23]. GNSS/IMU systems may be classified as tightly-coupled and loosely-coupled. In a loosely-coupled system, the GNSS position solution is calculated independent of the IMU. Both IMU and

GNSS positional solutions are combined by a KF to give an optimal position. In a tightly-coupled system, the GNSS positional solutions are calculated with the aid of the IMU data. Thus, the GNSS may still be able to provide a positional solution with four or less satellites where a stand-alone GNSS receiver may not.

Regardless of system integration methods, the positional solution may be calculated in real-time or post-processed depending on the availability of the real-time GNSS base station data. In a post-processing environment, the KF may be run forward and backward in time, and the combined forward and backward solution could effectively cut the effect of a GNSS outage interval by more than half. Positional solution error can be reduced significantly. Figure A.4 shows a typical error reduction by combining the forward and backward KF solution in post-processing. Post-processing of the GNSS/IMU data can yield much better results especially if the GNSS outage is long.

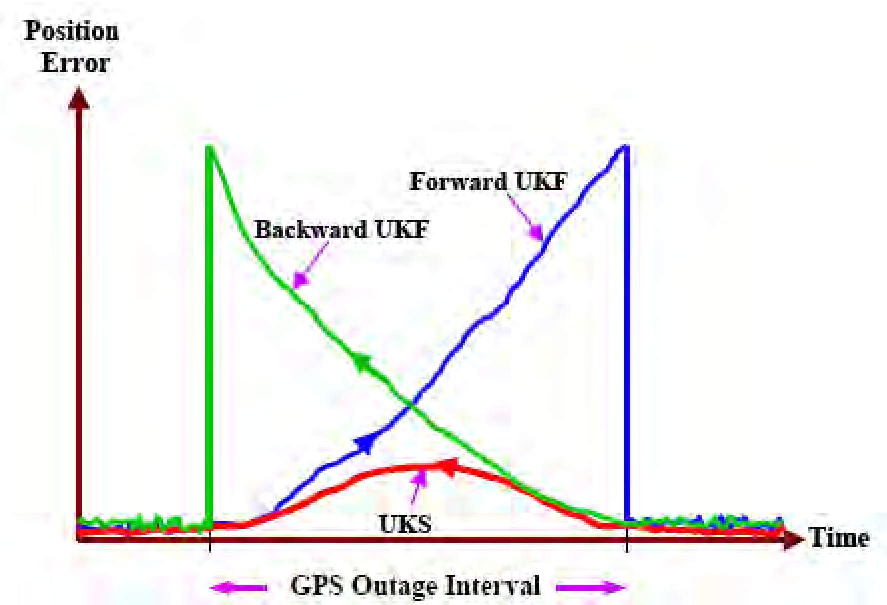

Figure A.4: Positional error comparison of Forward KF, Backward KF, and Combined Forward and Backward KF (UKS) solutions [20]

There are a limited number of commercial-off-the-shelf (COTS) GNSS/IMU system hardware and post-processing software providers. NovAtel, a GNSS/IMU system provider, recently purchased Waypoint Consulting Company, which provides a wide array of post-processing GNSS/IMU software. In addition, Applanix, a Trimble company, has both GNSS/IMU system and post-processing software for land and aerial survey applications. Over half of mobile LiDAR system manufacturers use the Applanix POS LV GNSS/IMU in their systems.

Table A.2 provides a summary of various Applanix POS LV GNSS/IMU model performances with and without GPS outage for 1 minute. The Applanix with the higher model number has a better IMU. The Applanix POS LV 420 system has Litton LN200 IMU containing FOGs of 1 degree/hr gyro bias. It is subjected to ITAR restrictions. Both Applanix POS LV 520 and 510 systems have an IMU that is more accurate than the one employed by the POS LV 420 system, and they are not subjected to ITAR restrictions. The POS LV 610 system has the best IMU of all POS LV models. Table A.2 shows that the X, Y, Z position accuracy is not improved by higher accuracy IMU when there is no GNSS signal outage. However, the better IMU improves the system orientation (roll, pitch, and heading) accuracy. The better orientation accuracy increases the accuracy of the LiDAR mirror orientation in the global coordinate, and thus improved the overall point-cloud accuracy. On the other hand, the better IMUs provide significant system performances when there is a long GNSS signal outage as shown in Table A.2. Recently, most "survey / engineering grade" mobile LiDAR system operators have chosen to purchase their system with GNSS/IMU system with higher-accuracy IMU such as the Applanix POS LV 520 or 510.

	Accuracy without GPS outage			Accuracy with 1 km or 1 min GPS outage		
Applanix POS LV Model	420	510 / 520	610	420	510 / 520	610
X, Y Position (m)	0.02	0.02	0.02	0.12	0.1	0.1
Z Position (m)	0.05	0.05	0.05	0.1	0.07	0.07
Roll & Pitch (degree)	0.015	0.005	0.005	0.02	0.005	0.005
Heading (Degree)	0.02	0.015	0.015	0.02	0.015	0.015

Table A.2 Applanix GNSS/IMU system performance with post-processing

Before performing data collection by the mobile LiDAR system, the GNSS/IMU system must carry out an alignment process in which the system determines the IMU orientation with respect to local gravity and true North. The GNSS can provide orientation using multiple antennas, such as the GPS Azimuth Measurement System (GAMS) with second GNSS Receiver. Some GNSS/IMU systems, such as the Applanix POS LV 420 and 520, have two GNSS receivers and antennas to provide direct heading aiding. These systems could recover accurate heading faster than a system with same IMU with GAMS after GNSS signal outage. A system with a single GNSS receiver can implement gyrocompass and dynamic heading alignment. Gyrocompass technique makes use of the IMU gyro to measure the earth rotation to determine the IMU heading relative to true North. Alternatively, the system could determine its orientation by moving in a long straight line, a figure-8 maneuver, or a circle on the ground. Most GNSS/IMU system providers recommend a 5 to 10 minute static session for the alignment process. It is performed before and after the LiDAR and photo data collection. During the static session, the vehicle remains stationary for the session duration, and the operator should not disturb the vehicle.

Digital Camera

Digital images or video are often collected in conjunction with LiDAR data by mobile systems. The camera shutter is synchronized with the GNSS/IMU clock. Consequently, the collected digital images are accurately georeferenced. The color images are often used to overlay / colorize the points in the point-cloud. In addition, they are instrumental in helping users to identify features that are not possible by using the point-cloud alone. For example, point-cloud density is often too sparse to determine text printed on a road sign. The digital images are critical to resolve and establish the Manual on Uniform Traffic Control Devices (MUTCD) code of road signs. Furthermore, they help users to recognize features such as drainage and advertising billboards. Therefore, the quality and performance of the digital camera on-board of a mobile LiDAR system is equally important as the LiDAR sensors in system selection. They are particularly important for roadside asset inventory and mapping applications. In addition, some systems apply photogrammetric techniques on the images to provide position of features in the images without the aid of data from a LiDAR scanner.

The orientation of the camera mounted on the vehicle should be determined by the applications of the final data. A forward looking camera is important in capturing details of road signs. Side looking cameras are better in attaining features of building facade, drainage, sound walls, and median barriers. In most cases, users may select the photograph spacing. The minimum image spacing will depend on the vehicle speed and the camera maximum frame rate (number of photograph per second). Typical image spacing is between 25 to 50 feet. The optimum image spacing would depend on the user application. While lower image spacing will capture more detailed information, it will also drastically increase the size of the data because multiple high-resolution cameras are often used. In fact, the digital image data size is often 2 to 10 times bigger than that of the LiDAR data. While data storage is not a big issue for a small project, the estimated LiDAR point cloud and digital images data size for an entire State of Washington roadway network would add up to more than 50 TB.

Commercially-Available Mobile LiDAR Systems

Recently, several mobile LiDAR systems are commercially available for purchase, contract services, and rental through their dealers. Their cost and performance varies and depends on their target applications and configurations. In general, they may be classified into two classes: “mapping grade” systems and “survey/engineering grade” systems. However, some systems can be configured into either class based on the LiDAR scanner(s) and IMU employed. Mapping grade systems are designed to provide data with adequate accuracy at a low cost for mapping and asset inventory purposes. Their data’s absolute and relative accuracy are 1 foot and 0.1 foot representatively. However, in practice, these systems often achieve higher accuracy, particularly when GNSS signal conditions are good. Their IMU and LiDAR scanner(s) are less accurate than that of the “survey/engineer grade” systems. Some mobile systems even eliminate the use of LiDAR scanner and rely on digital cameras and photogrammetric techniques to generate a “point-cloud." A deliberate engineering decision was made to trade off performance with cost to provide cost-effective solutions.

Figure A.5: Available mobile LiDAR systems

On the other hand, "survey/engineering grade" systems are designed to achieve maximum possible accuracy with current available state-of-the-art GNSS receivers, IMU, digital cameras, and LiDAR scanners [13]. These systems produced centimeter-level absolute accuracy data, and could maintain data accuracy with short GNSS signal outage [8,12,13,22,24]. In addition, their LiDAR scanners' range accuracy is 7 to 8 mm. They are designed for survey applications which require the system to deliver highly-accurate and precise data reliably and consistently. DOT surveying and engineering applications have unique requirements that other applications do not share. Accuracy of the work product carries certain financial and legal liability implications. These systems cost 2 to 5 times more than that of the "mapping grade" system. Some mobile LiDAR systems are shown and discussed in detail below, and other systems are either not available in U.S., designed for other applications, or in prototyping stage [3].

Eagle Mapping System

Eagle Mapping operated a low-level aerial (not land-based) LiDAR system for the pilot study. Their objective was to determine the feasibility of using their system to meet WSDOT application requirements as well as examining their system capability and accuracy. Based in Port Coquitlam, British Columba, Canada, Eagle Mapping has provided high-quality digital mapping, data and imagery using remote sensing techniques since 1985. Recently, they have developed their own aerial LiDAR system, as shown in Figure A.6, for a low-flying airplane or helicopter. Compared to other aerial systems developed for high flying aircrafts, this new class of aerial systems produces a high-density point cloud (~30 points per square meter) with higher accuracy. The system is composed of a RIEGL VQ-480 LiDAR scanner and a NovAtel SPAN-SE with a tactical-grade IMU-FSAS IMU from iMAR GmbH. The IMU and LiDAR scanner are rigidly mounted in a small, portable unit that can be easily transported and mounted to any helicopter or airplane, quickly with minimum calibration and sensor bore-sight process. The RIEGL VQ-480 LiDAR scanner has an effective measurement rate of up to 150,000 points per second, and its range measurement accuracy is 25 mm. In addition, RIEGL's online waveform analysis provides virtually unlimited returns for every laser pulse emitted. Detailed VQ-480 specifications may be found at the RIEGL website (http://www.riegl.com/). The system produces up to 50 measurements/sq. meter in a single pass covering their entire highway corridor including right of way area. It captures drainage and ditches better because of its point of view. However, it does not capture road signage well. Figure A.7 shows the point cloud of the pilot study area, produced by the Eagle Mapping system. The entire pilot study site point cloud Log ASCII Standard (LAS) file size created is 1 gigabyte (GB). Compare to land based mobile systems, their coverage is much wider, and it provides better point-cloud data in the wide median, road shoulder, and area beyond right of way. Eagle mapping has planned to integrate their LiDAR system with a 60 MP aerial image camera. Eagle Mapping provides aerial LiDAR and photography services. The system cost is not available. The contract services cost depends on various factors: mobilization cost, system cost, airplane/helicopter rental and operating cost, and deliverable requirements. Estimated average cost is not available.

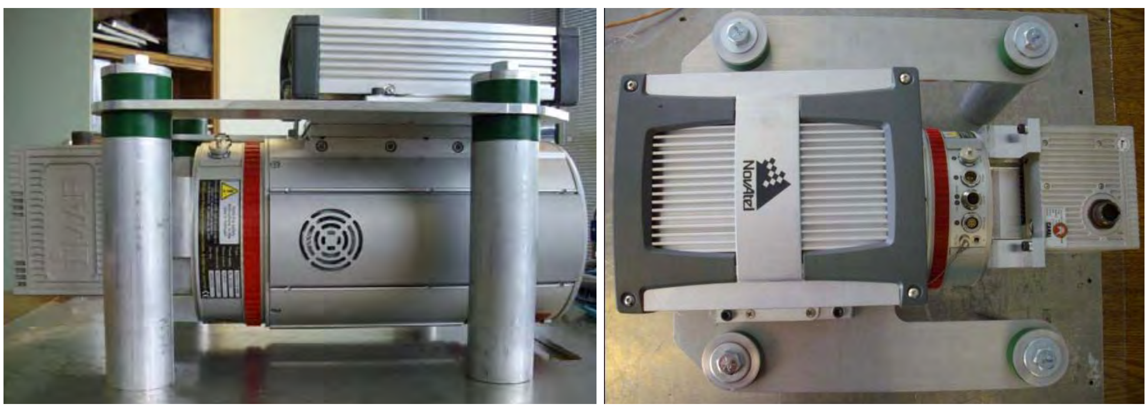

Figure A.6: Eagle Mapping aerial LiDAR system

Figure A.7: Point cloud of SR 167 pilot study site by Eagle Mapping system

Earthmine Mars Collection System

Earthmine was founded in 2006 and is based in Berkeley, California. Earthmine has developed the Earthmine Mars Collection System [4] and back office computer technologies to collect, process, and host detailed and accurate 3D street-level imagery of streets, alleys or highways. It also supplies developer tools for creating and distributing applications that benefit from this data. Their services are used for GIS and asset management applications.

The Earthmine Mars Collection System, shown in Figure A.8, is composed of four pairs of 8-megapixel stereo cameras, a NovAtel SPAN-CPT GNSS/IMU positioning system, and computer data collection system. It does not have any LiDAR sensors. The system usually is mounted on the roof of a vehicle or a custom “bicycle” platform for pedestrian accessible areas. It takes high-resolution stereo 360-degree panoramic images at about a 10-meter spacing interval at vehicle speed up to 120 km/h. Combining the four stereo camera pairs; the system creates 32 megapixel 360°(H) x 180°(V) stereo panoramic imagery at every interval. Based on the stereo imaging technology developed by JPL and Caltech for the Mars Rovers, the 3D location of each pixel in each stereo pair of the images relative to the stereo camera position can be determined. By combining the global position solution provided by the GNSS/IMU system, the global position of each pixel is found. The position accuracy depends on the distance from the stereo camera and GNSS/IMU solution accuracy. The GNSS/IMU solution and the stereo images pixel location are post-processed in the Earthmine elastic cloud computing environment using proprietary software and technology exclusively licensed from JPL and Caltech. Therefore, the collected data must be first post-processed by Earthmine. Data customer may then choose to store the processed data on their server for their own exclusive use. Alternatively, the post-processed data could be stored on the Earthmine elastic cloud and shared with other data costumers at a reduced cost.

Earthmine provides contract data collection services as well as data extraction services. Their data collection system is not available for sale. The contract data collection services cost ranges from $140 per mile to $275 per mile. The data extraction service cost ranges from $160 per mile to $330 per mile depending on the number of features to be extracted. In addition, there are associated annual data hosting and server software maintenance costs.

Figure A.8: Earthmine MARS mobile system

To extract the features and roadside asset location data from the post-processed imagery and “point-cloud” data, users may use an existing add-in tool for ArcMap with internet connection to the Earthmine cloud or data server. Alternatively, custom software may be developed using Earthmine’s API and Adobe Air interface to extract the final deliverable data. The ArcMap add-on software and API are optimized for web-based delivery of the data. Figure A.9 shows a screen shot of a custom Earthmine data viewer and extraction software developed for the Oregon DOT. Further detail about the Earthmine system may be found at their website (www.earthmine.com).

Figure A.9: Custom Earthmine viewer screen shot

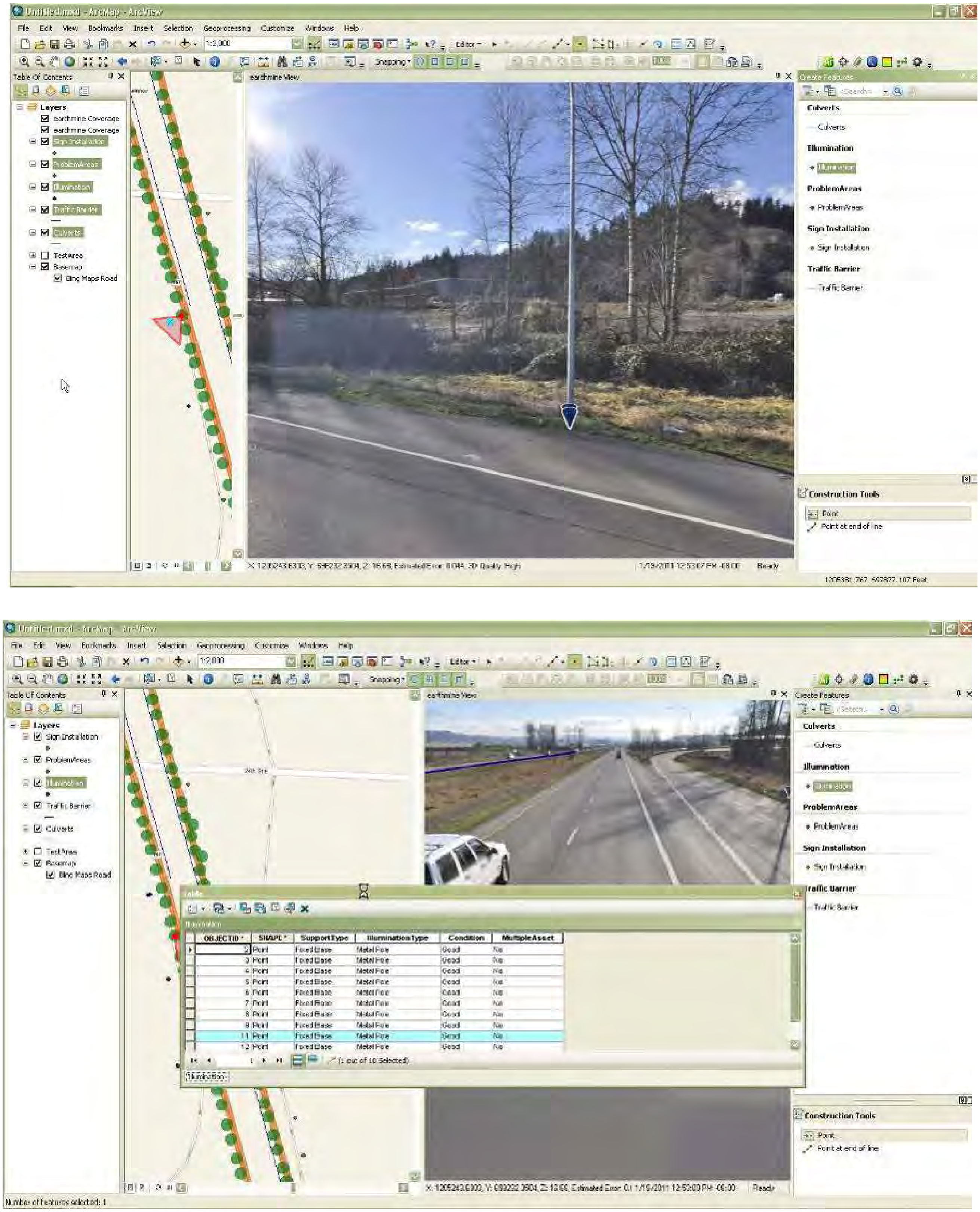

Figure A.10: Earthmine ArcMap add-on screen shots

Mandli Communications mobile LiDAR system

Mandli Communications Inc., based in Madison, Wisconsin, has been providing services for the transportation industry since 1983. It has designed and developed integrated specialized data collection systems that tightly integrate digital image cameras, LiDAR scanners, GNSS/IMU positioning systems, and other remote sensing devices for use in various Departments of Transportation applications such as pavement condition surveying, asset management, GIS, photologging, bridge clearance measurement, and measuring road sign retro-reflectivity. In addition, they have developed a suite of post-processing software tools for GIS, pavement condition survey, asset management, and other DOT applications. The company sells data collection systems and provides data collection and post-processing services for many U.S. DOTs such as Caltrans, Nevada DOT, Tennessee DOT, Texas DOT, and Hawaii DOT.

The Mandli Communications mobile data collection system is highly-configurable [17]. It can be upgraded to the latest state-of-the-art LiDAR scanners, digital camera, and other sensors at a later time. The system configuration depends on the application. The base system has an Applanix POS LV 220 positioning system with OmniSTAR real-time satellite differential service. In addition, the data collection system has a robust computing system with large data storage capacity for extended period on a DOT highway network. A Velodyne HDL-64E LiDAR scanner (located near top-right corner of Figure A.11) and 1600x1200 resolution digital cameras were used in previous data collection system as shown in Figure A.11. Since then, the system, shown in Figure A.12, has been upgraded to use two Velodyne HDL-32E LiDAR scanners. The twin scanner configuration reduces obstruction shadows in the point-cloud created by objects near the LiDAR sensor. In addition, it increases the point density of the point-cloud created, resulting in a realistic representation of the scanned area.

Mandli Communications has built an extensive computing infrastructure to store and post-process the LiDAR and photolog images collected by their system. Their Roadview$^{X®}$ software enables users to quickly and effectively visualize and extract feature data from the point-cloud and images. Their custom post-processing workflow and semi-automated feature extraction routines reduce their post-processing time and cost. Further detail about the Mandli Communication data collection system and their services may be found at their website (www.mandli.com).

Mandli Communications provides contract data collection services as well as data extraction services. Their custom data collection system is also available for sale. The system cost depends on the configuration. The estimated system cost is not available. The contract data collection service cost ranges from $70 per mile to $150 per mile. The data extraction service cost ranges from $80 per mile to $160 per mile depending on the number of features to be extracted.

Figure A.11: Mandli Communications mobile LiDAR system with a Velodyne HDL-64E LiDAR scanner

Figure A.12: Mandli Communications mobile LiDAR system with two Velodyne HDL-32E LiDAR scanners (copyright The American Surveyor Magazine© 2011)

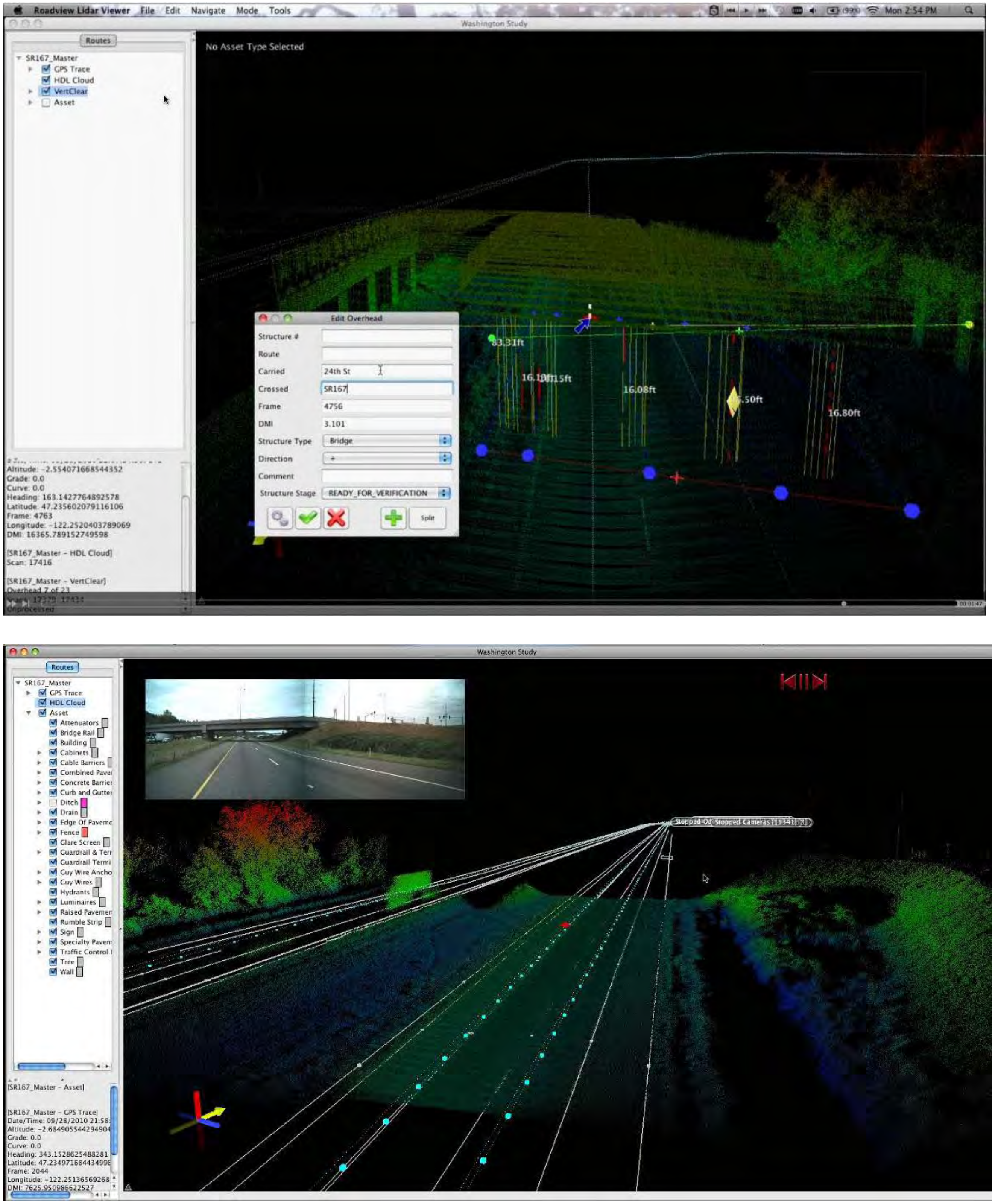

Figure A.13: Screen shot of Mandli Communications Roadview$^{X®}$ software

Optech Lynx

Optech develops, manufactures, and supports advanced LiDAR and imaging-based survey instruments. Based in Toronto, Canada and with operations throughout the world, Optech provides LiDAR sensors and camera solutions in airborne mapping, airborne laser bathymetry, mobile mapping, mine cavity monitoring, and industrial process control, as well as space applications.

The Optech Lynx M1 system is highly-configurable, and users may choose to have up to four LiDAR scanners, four cameras, and accuracy grade of the IMU [18,22]. The system sensors (LiDAR scanners, cameras, GNSS antennae, and GNSS/IMU positioning system) are mounted on rigid platform which can be fixed to the roof of an automobile or golf cart, or a boat. It is designed for the engineering grade survey market. The current Lynx M1 system is Optech's third generation mobile LiDAR system following their Lynx V100 and V200 system. The scan rate and point measurement rate has been increased in each subsequent generation. The Lynx M1 scan rate is user selectable. Its maximum scan rate is 200 Hz, the highest among commercially available 360^o FOV LiDAR scanners. Higher scan rate allows the data collection vehicle to travel at higher speed while maintaining high point density with even distribution. However, the maximum LiDAR sensing rate reduces as the scan rate increases. A typical Lynx configuration has two 360^o FOV LiDAR scanners mounted orthogonal to each other to reduce shadow caused by line of sight obstruction from objects. It captures all three sides of a building facet in a single pass. If only one LiDAR scanner is used, one side of the building facet is blocked from view of the scanner by the other building facet. The M1 LiDAR scanner is also capable of detecting up to 4 returns from a single laser pulse. This feature permits the system to detect and measure surfaces obstructed by light vegetation. As indicated in Table A.1, the Lynx LiDAR scanner has range accuracy of 7 mm.

Users may choose any available Applanix POS GNSS/IMU positioning system for their Lynx. Survey services providers often choose either the POS LV 420 or 520. Recently, Lynx systems have been delivered with the POS LV 520 system. Both the POS LV 420 and 520 have GAMS for better heading accuracy, as well as DMI. In addition, the user has two options for the on-board cameras: camera with 2 megapixel (MP) resolution with a frame rate of 5 frames/s or camera with 5 MP resolution with a frame rate of 3 frame/s. Higher frame rate permits the system to take pictures at a closer distance interval.

Optech sells and provides support for the hardware and post-processing software. Their DASH Map post-processing software processes the raw GNSS/IMU and LiDAR data to output point-cloud data in Log ASCII Standard (LAS) format file for 3^{rd}-party post-processing data extraction software. Their user-friendly data collection software utilizes Google Earth for mission planning and data collection execution. The estimated system cost is from $500,000 to $850,000 depending on the system configuration. Leasing options are available. The majority of survey/engineering grade mobile LiDAR systems in U.S are made up of different generations of Lynx system. North American survey services provider with Lynx systems include: Aerial Data Services, Inc.; McKim & Creed, Inc.; Michael Baker, Jr., Inc.; Photo Science Inc.; Sanborn Map Company;

Surveying and Mapping, Inc.; WHPacific, Inc.; and Woolpert, Inc. Further detail about the Optech Lynx M1 system may be found at their website (http://optech.ca/lynx.htm).

Figure A.14: Optech Lynx mobile LiDAR system

Figure A.15: Optech Lynx mobile LiDAR system mounted on a boat (Courtesy of GeoMetrix Office)

Figure A.16: Point-cloud produced by Optech Lynx mobile LiDAR system

RIEGL VMX-250

Based in Horn, Austria with operations and staff worldwide, RIEGL has 30 years of experience in the research, development and production of laser rangefinders, distance meters and scanners. RIEGL also cooperates with OEM-partners to deliver turnkey solutions for multiple fields of application. RIEGL has regional offices located in Orlando, Florida to provide sales, training, support, and services for U.S. customers.

The Riegl VMX-250 system is a compact and portable system that delivers engineer grade survey data for users. The system sensors (two VQ-250 LiDAR scanners, GNSS antenna, and IMU) are mounted rigidly to each other in a compact package as shown in Figure A.17. The sensor platform can be easily taken out of the protective transportation case and installed on the vehicle roof by two persons. The VQ-250 LiDAR scanner's scan rate is user selectable with a maximum scan rate of 100 Hz. Its maximum point measurement rate is 300,000 points/s. A typical VMX-250 system configuration has two 360^o FOV VQ-250 LiDAR scanners mounted orthogonal to each other in order to reduce shadows caused by line of sight obstruction from objects. It captures all three sides of a building facet in a single pass. If only one LiDAR scanner is used, one side of the building facet is blocked from view of the scanner by other building facet. The VQ-250 LiDAR scanner is also capable of detecting multiple returns from a single laser pulse. The full waveform analysis capability of the VQ-250 provides a practically unlimited number of target returns per pulse. However, the number of returns for a single laser pulse is less than four in most practical situations. This feature permits the system to detect and measure surface obstructed by light vegetation. As indicated in Table A.1, the Riegl VQ-250 LiDAR scanner has range accuracy of 10 mm. Other VQ-250 specifications are listed in Table A.1.

The standard VMX-250 system is configured with the POS LV 510 system. Compared to the POS LV 520, the POS LV 510 does not have GAMS. The current system provides mounting points for digital cameras or video equipment. Nevertheless, a tightly-integrated digital camera option is not yet available for the VMX-250 system.

RIEGL sells and provides support for their hardware and post-processing software. The system is bundled with RIEGL's user friendly software suite (RiACQUIRE, RiPROCESS, and RiWORLD) for data collection, sensor alignment adjustment, and GNSS/IMU/LiDAR raw data post-processing. Their RiPROCESS post-processing software processes the raw GNSS/IMU and LiDAR data to output point-cloud data in standard LAS format file for 3rd-party post-processing data extraction software. The estimated system cost is about $700,000 depending on the system configuration. Currently, R.E.Y. Engineers, Inc. is the only U.S. survey service provider with the RIEGL VMX-250 system. Further detail about the Riegl VMX-250 system may be found at their website (http://riegl.com/).

Figure A.17: RIEGL VMX-250 mobile LiDAR system

Figure A.18: Point-cloud produced by RIEGL VMX-250 system

3D Laser Mapping StreetMapper 360

Based in Nottinghamshire, United Kingdom, 3D Laser Mapping (3DLM) provides LiDAR software and hardware, and support for both RIEGL LMS and third-party products. Working with RIEGL and IGI mbH, 3D Laser Mapping developed the StreetMapper 360 system. Located in Kreuztal, Germany, IGI mbH specializes in the design and development of guidance, navigation, precise positioning, and attitude determination systems.

The 3DLM StreetMapper 360 system is designed to deliver engineer grade survey data for its users [8,9,14,16]. It is a 2nd generation mobile LiDAR system developed by 3DLM. The StreetMapper 360 system is composed of two VQ-250 LiDAR scanners, digital cameras, GNSS antenna, and an IGI IMU rigidly-mounted in a compact package as shown in Figure A.19. The VQ-250 LiDAR scanner specifications are listed in Table A.1 and were discussed previously. Like the RIEGL VMX-250, the StreetMapper 360's twin VQ-250 LiDAR scanners are also mounted orthogonal to each other minimized shadows caused by line-of-sight obstruction. However, their scanner mounting orientation is slightly different from the Riegl VMX-250.

Figure A.19: StreetMapper 360 system mounted on a Terrametrix vehicle (copyright The American Surveyor Magazine© 2011)

The StreetMapper 360 employs a highly-accurate IMU with FOG bias of 0.1 degree/hr. The IMU has an update rate of 256 Hz. The current system provides up to four 4 MP resolution digital cameras operating at 7.5 frame/s. The cameras are synchronized and time-stamped with the GNSS/IMU system. The resulting geo-referenced images are stored in the data logging computer along with the LiDAR scanners and GNSS/IMU raw data.

3DLM sells and provides support for their hardware and post-processing software. Their post-processing software outputs point-cloud data in standard LAS format file for

3rd party post-processing data extraction software. Moreover, TerraPhoto or PHIDIAS may be used to extract information from the geo-referenced images. Currently, Terrametrix is the only U.S. survey service provider with a StreetMapper 360 system. Terrametrix has scanned over 400 bridges in Nevada to provide the NV DOT with bridge clearance data. It has also performed similar services for Caltrans as well.

StreetMapper is now being offered on a Fractional Ownership basis. The plan aims to reduce entry cost and allow owners to achieve high utilization rates on their fractional asset. In addition, the risk of technological obsolescence is significantly curtailed, since a much smaller investment needs to be recouped on a fractional share. The detail of StreetMapper 360 Fractional Ownership is available at 3DLM website (http://3dlasermapping.net/). The estimated system cost is about $780,000 depending on the system configuration.

Ambercore's Titan

Ambercore is headquartered in Ottawa, Canada. Ambercore's first kinematic terrestrial LiDAR system (called TITAN®) was developed in 2002 for helicopter-based low-level aerial LiDAR survey. In 2003, the system was modified to be mounted on a truck to perform survey of Highway 1 in Afghanistan between Herat and Kandahar. Since then, a 2^{nd} generation TITAN was developed to overcome the short comings of the first generation system.

The current Titan system has four Riegl LMS-Q120i LiDAR scanners, a high-accuracy navigation grade IMU, GPS antenna, and up to 4 digital cameras mounted in a rigid assembly [10-12,26]. The entire assembly can be deployed on a variety of moving platforms such as trucks, sport utility vehicles, or boats. Figure A.20 shows the system mounted on a hydraulic lift platform at the rear of a truck. The evaluated platform provides better line of sight for the LiDAR scanners, particularly the downward facing LiDAR scanner. As shown in Figure A.20, the quad LiDAR configuration consists of one upward and one downward facing LiDAR scanner as well as two sideway facing scanners angled slightly forward on each side of the enclosure. As a result, the TITAN system has a total of 360º field of view. Each LMS-Q120i has 80^{o} FOV and maximum scan rate of 100 Hz. The LiDAR scanner measurement rate is 10,000 points/s with 20 mm range accuracy. Other LMS-Q120i specifications are listed in Table A.1. In addition, the TITAN system has integrated cameras with a 1280x1024 resolution. They were upgraded with better integrated cameras in 2010.

Figure A.20 Ambercore Titan mobile LiDAR system

Ambercore developed its own proprietary GPS/IMU post processing package, CAPTIN (Computation of Attitude and Position for Terrestrial Inertial Navigation) to process the GPS/IMU data. Their custom post-processing software processes the raw GNSS/IMU and LiDAR data to output point-cloud data in standard LAS format file for 3rd party post-processing data extraction software. Ambercore sells and provides support for the hardware and post-processing software. David Evans and Associates (DEA) is one of the U.S. survey service providers with the Titan system. The detailed system cost is not available. The estimated system cost is $500,000 to $800,000 depending on the system configuration.

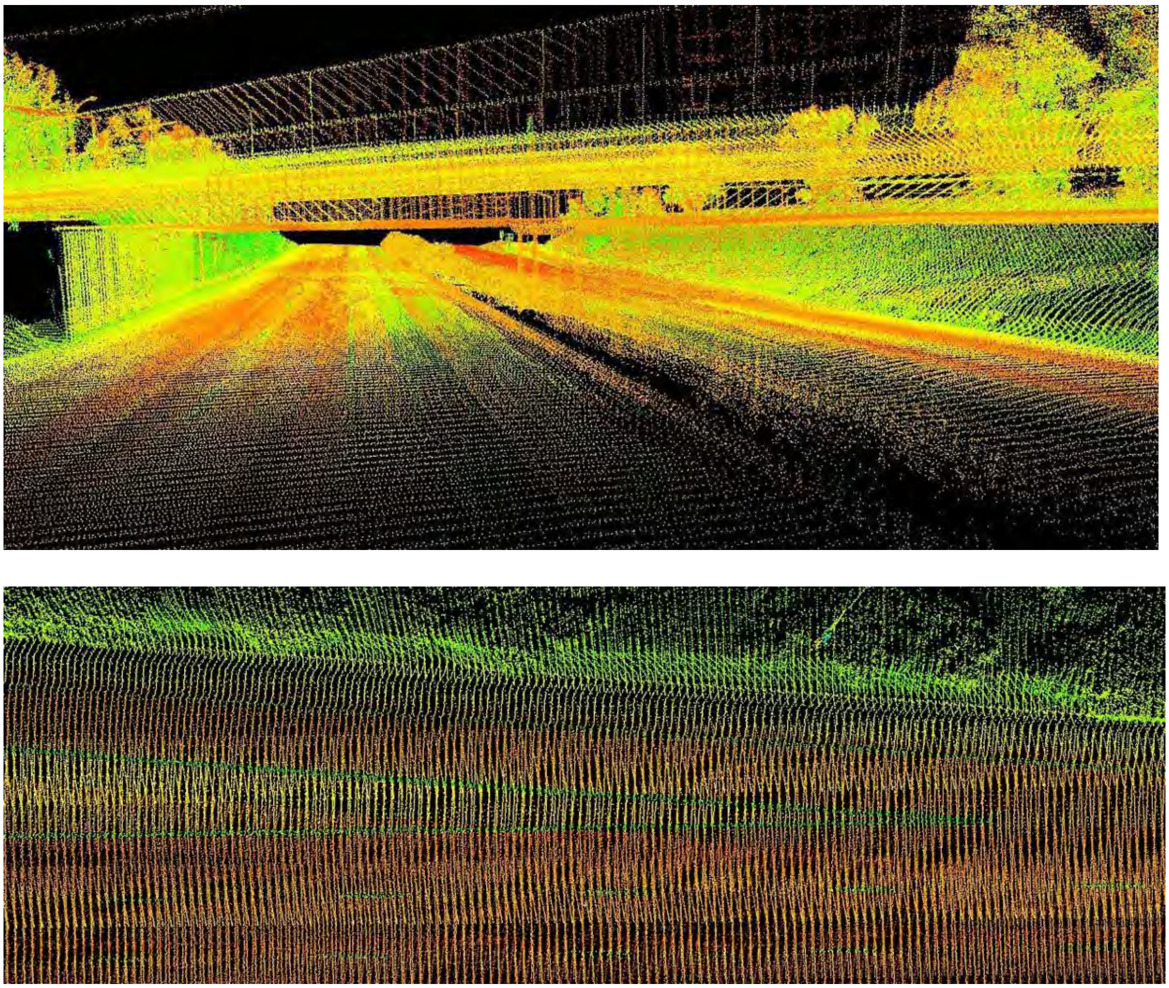

Figure A.21 Point-cloud produced by TITAN® system

Topcon IP-S2

Based in Livermore, California with operations and staff worldwide, Topcon Position System, Inc. provides survey instruments such as GNSS receivers, total stations, and digital levels, as well as machine guidance equipment for construction equipment.

The Topcon IP-S2 system is a low-cost, highly-configurable system designed primarily for GIS and mapping applications [15]. Users have a variety of digital camera and LiDAR scanner option available. The base system has a Point Grey Research, Inc. Ladybug®3 camera system, an embedded computer, a Topcon GNSS receiver, and a Honeywell HG 1700 IMU. Higher accuracy IMU options are available. The system does not have GAMS.

Figure A.22 Topcon IP-S2 system configured with Velodyne HDL-64E

The Ladybug3 spherical digital video camera system has six 2 MP cameras that enable the system to collect video or photographs. Figures A.22 and A.23 show the Ladybug3 camera located next to the square GNSS antenna on top of the sensor assembly. The Ladybug3 is enclosed in a weather-resistant case. Through the system's IEEE-1394b (FireWire) interface, the JPEG-compressed 12MP resolution images are streamed to a data collection computer disk at 15 frames per second (fps). The six images are stitched together to produce a 6144x3072 panorama photo during post-processing. The image stitching process is computationally intensive and could take a long time. Software options are available to stitch the images on a server farm to speed up this process. Additional digital cameras may be added using the available camera interfaces on the system. As shown in Figure A.22, five more cameras are installed to the system in addition to the Ladybug3 camera. The IP-S2 system's embedded computer provides a digital interface for time synchronization, a time stamped camera shutter and LiDAR scanner with the GNSS receiver. Consequently, the collection images are geo-referenced.

The flexible architecture of IP-S2 enables it to interface and integrate various LiDAR scanners available in the commercial market. Currently, the system is available with the SICK LMS291, Riegl VQ-250, Velodyne HDL-64E, and HDL-32E LiDAR scanner. Detailed specifications of these scanners are listed in Table A.1. The SICK LMS291 scanner's scan rate and measurement rate are too slow for a vehicle to travel at highway speeds and maintain high enough point density for feature identification and data extraction. Configurations with other LiDAR scanners, such as the Velodyne HDL-63E, HDL-32E, or Riegl VQ-250, are recommended for highway mapping applications in which the data collection vehicle is traveling over 55 mph.

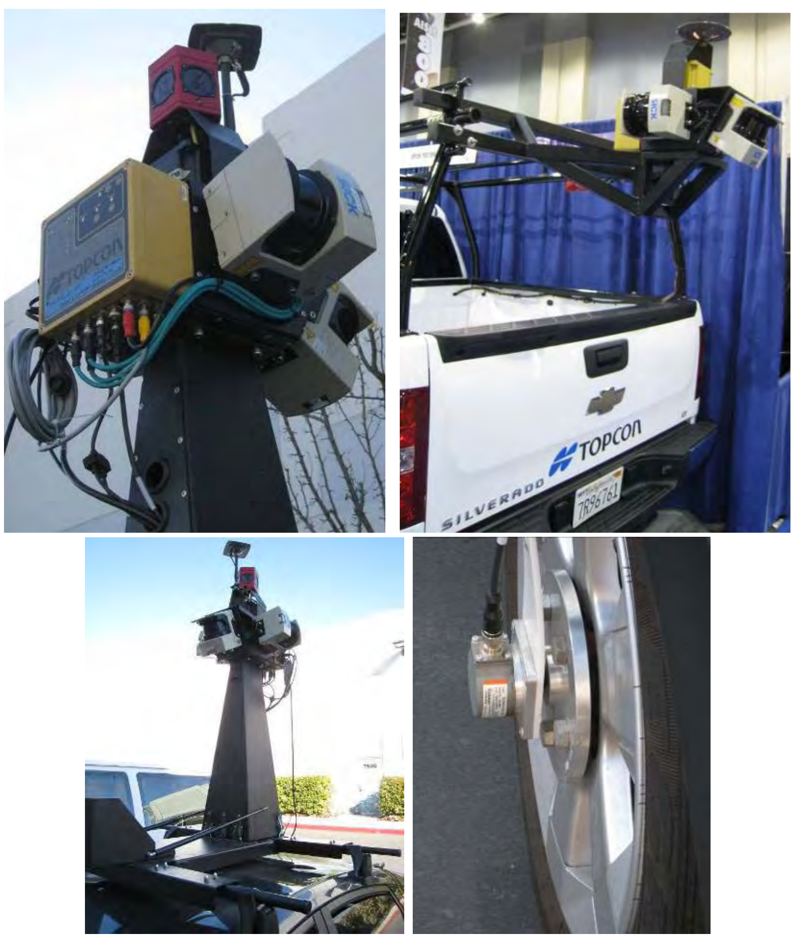

Figure A.23 Topcon IPS-2 system configured with SICK LiDAR scanners

The system is bundled with a software suite for data collection and GNSS/IMU/LiDAR and imagery raw data post-processing on a workstation or on a server farm. Spatial Factory is used for basic feature extraction and data visualization. It could be used to perform elevation adjustment, pass-to-pass adjustment, and vehicle trajectory adjustment using external ground control points. Spatial Factory can also output point-cloud data in standard LAS format file for 3rd party post-processing data extraction software. The estimated system cost is about $250,000 to $350,000 or more depending on the system configuration. The PPI Group is one of the Topcon IP-S2 dealers who provide sales, mapping services, support, training, and equipment rental. Further detail about the Topcon IP-S2 system may be found at their website (http://www.topconpositioning.com/products/mobile-mapping/ip-s2).

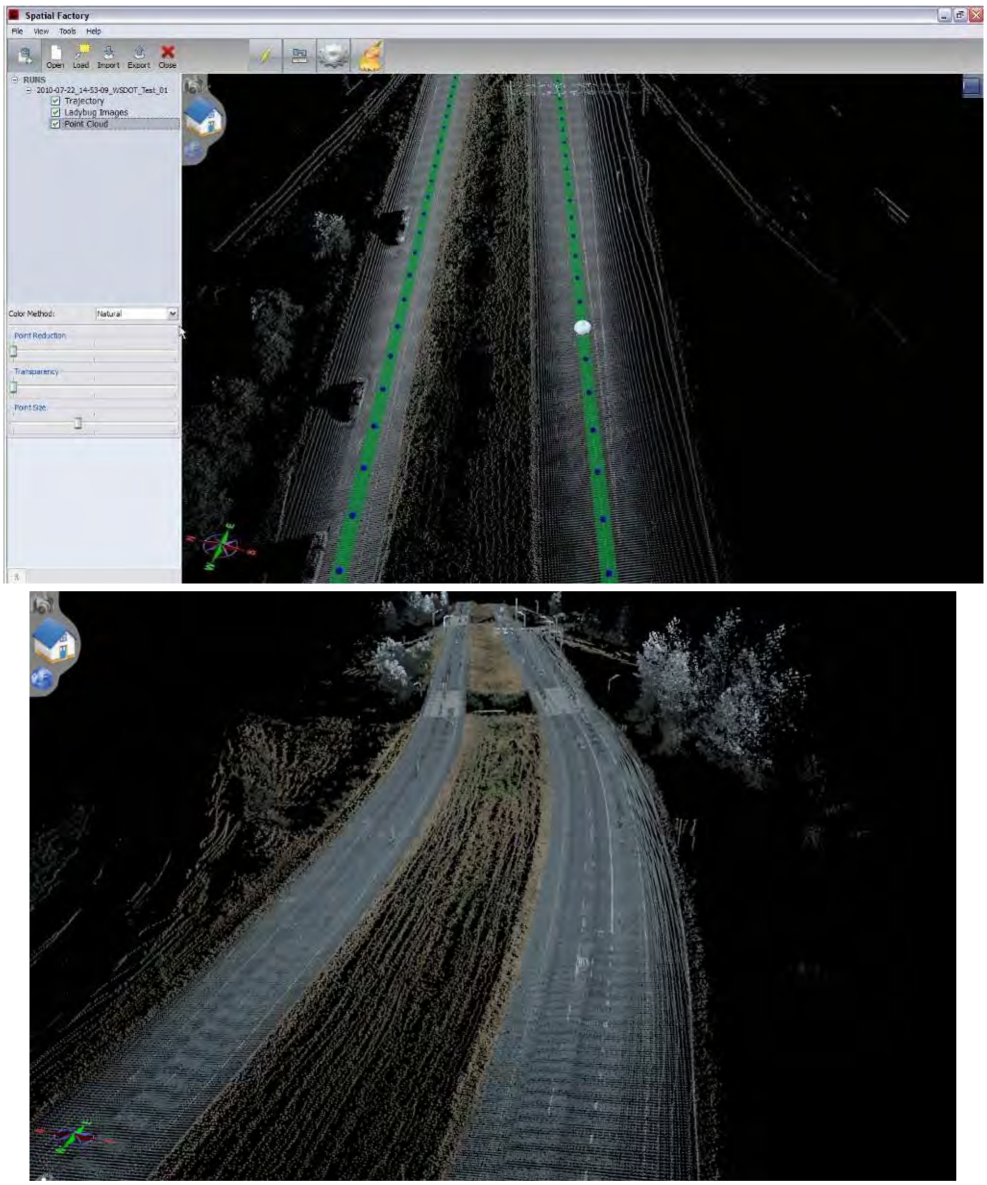

Figure A.24 Spatial Factory screen shot

Trimble MX8

GEO-3D provides georeferenced mobile mapping technologies comprised of integrated software and hardware to government entities and service providers around the world. Founded in the mid 1990's, GEO-3D was acquired by Trimble Navigation Limited in 2008. It is now part of the Trimble Geo-Spatial Group.

Trimble Geo-Spatial Group offers several mobile systems for different applications and markets. Their systems are highly-configurable, and users may choose to have up to six sensors of any combination of LiDAR scanners and cameras, as well as any available Applanix POS LV positioning system. Figure A.25 shows one of their previous generation systems, configured for GIS and asset management applications. The low-cost system employs the low-cost SICK LMS 291 and/or RIEGL LMS-Q120i LiDAR scanners and forward looking digital cameras. Photogrammetric techniques are used in conjunction with LiDAR to locate asset and assist feature extraction.

The latest Trimble MX8 is designed to be scalable with several sensor upgrade options. Users may choose any available Applanix POS LV positioning system for their MX8 system depending on the accuracy requirement of their applications. The MX8 system sensors—two VQ-250 LiDAR scanners, digital cameras, GNSS antenna, and IMU—are mounted rigidly inside a custom enclosure as shown in Figure A.26. The performance characteristics of the RIEGL VQ-250 LiDAR scanner were discussed in a previous section. The twin 360^{o} FOV VQ-250 LiDAR scanners are mounted orthogonal to each other in order to reduce shadows caused by line of sight obstruction from objects. It captures all three sides of a building facet in a single pass. If only one LiDAR scanner is used, one side of the building facet is blocked from view of the scanner by the other building facet. The MX8 has three forward looking cameras, three backward looking cameras, and one camera pointing toward the pavement. In addition, multi-spectrum cameras in ultraviolet (UV) and near infrared (NIR) spectrum are also available as an option. NIR cameras could provide better imagery in dark subway tunnels, and UV cameras could assist identifying the health of certain tree species and vegetation.

Trimble sells and provides support for their hardware and post-processing software. Their Trident 3D Analysis post-processing software is used for processing the raw GNSS/IMU and LiDAR data, feature extraction, and data visualization. Moreover, it can be used to perform elevation adjustment using external ground control points. In addition, it can also output point-cloud data in standard LAS format file for 3rd party data extraction software. The Trident 3D Analysis software is design for GIS and asset management applications. It also provides automated feature extraction routines for poles, edge, road sign, lane line, and bridge horizontal and vertical clearance. It can also create DTM/TIN Grid with automated break line detection. Figure A.27 shows the Trident 3D Analysis software user interface. More software features have been added recently. The estimated mobile system cost is between $75,000 and $700,000 depending on the system configuration. Long term rental options are also available. Further detail about the Trimble MX8 system may be found at their website (http://www.trimble.com/geospatial/Trimble-MX8.aspx?dtID=overview&).

Figure A.25: Available mobile LiDAR systems

Figure A.26: Trimble MX8 (copyright The American Surveyor Magazine© 2011)

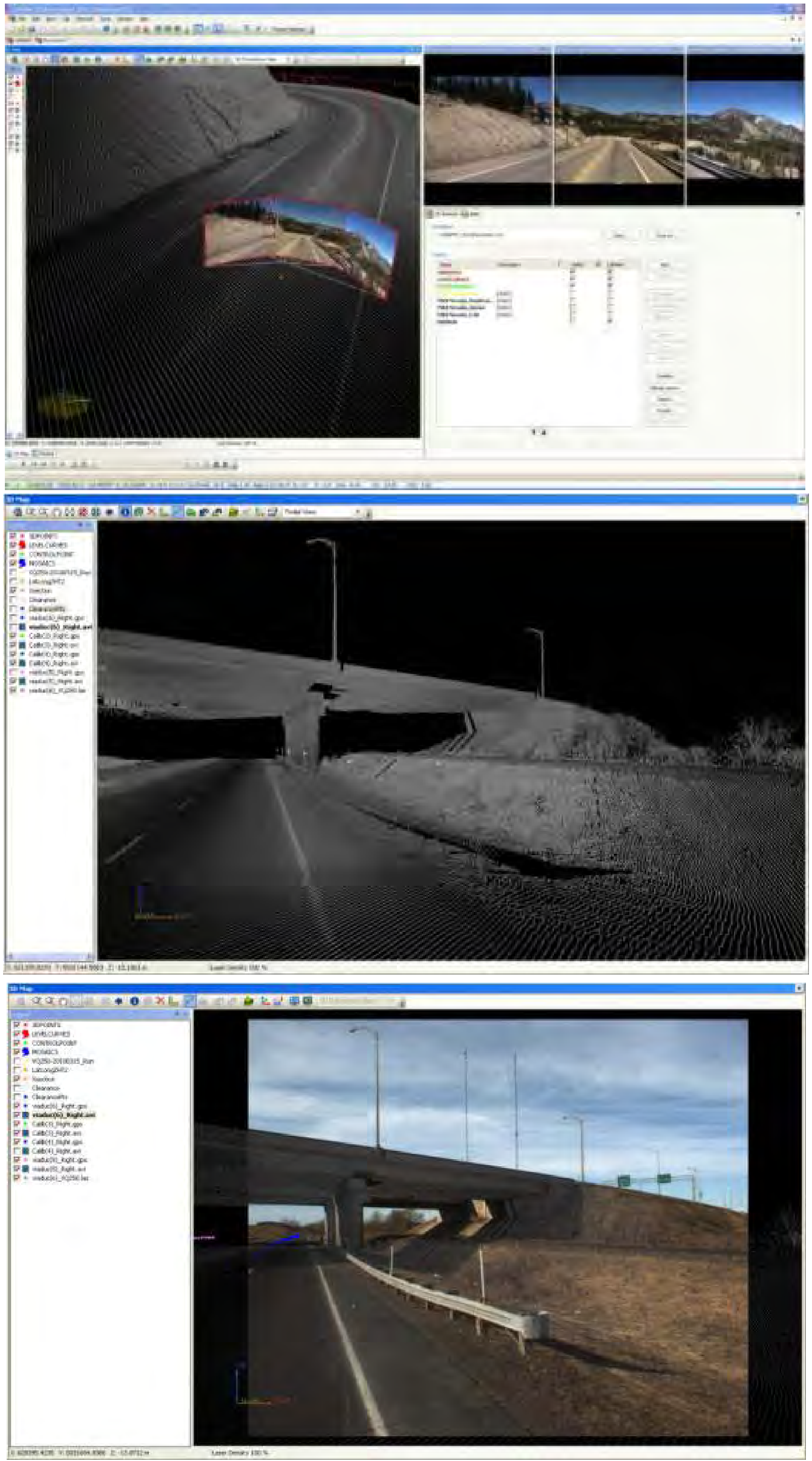

Figure A.27: Screen shot of Trident 3D Analysis software

Data Post-Processing and Feature Extraction Software

The term "data post-processing" is not well-defined in the mobile LiDAR mapping world. Depending on the context, it could mean:

1. The processing of GNSS/IMU/LiDAR raw data with GNSS base station(s) data to produce a geo-referenced point cloud. Depending of the project requirements, the point-cloud is then adjusted to local vertical datum and ground controls. This step is often required for delivering high accuracy engineering grade data. In addition, the "noise" points caused by moving vehicle traffic, unwanted vegetation, and other unwanted objects are removed.

2. The extraction of data from the point-cloud and geo-referenced images to recognize and locate objects of interest to create the required deliverables.

Generally, the office time required for data post-processing and feature extraction could be 2 to 10 times that of the field data collection time. The amount of office data post-processing time depends highly on the deliverable requirements; hence, point cloud and geo-referenced image post-processing and feature extraction software is critical in enhancing office productivity. The choice of software depends highly on the deliverable requirements. DOT survey deliverables are topographic maps, TIN mesh, contour maps, objects, points, and lines, etc. On the other hand, asset management deliverables are location, dimension, and conditions of roadside features and assets. Therefore, the user must examine their work and deliverable requirements first before selecting the appropriate software. Software evaluation was not the focus of this research project but, because the WSDOT CAE group has a lot of experience with this type of software, they can do this evaluation if and when the time comes.

The software that processes the GNSS/IMU/LiDAR raw data with GNSS base station(s) data is specific to each system, and it is only provided by the mobile LiDAR system's provider. The processing time of this operation has a relatively fixed ratio with the field data collection time. If the data is collected in an area that has limited or filtered GPS satellite signals, the processing time may increase.

Recently, the number of point-cloud processing software solutions has increased dramatically. Both the AutoDesk AutoCAD software suite and Bentley MicroStation CAD have recently upgraded to support point-cloud data. Currently, they provide a set of basic tools for visualization, dimension extraction, and CAD modeling. ESRI (a GIS company) also supplies GIS and mapping applications for point-cloud data. Other advanced 3rd party point-cloud post-processing software includes Leica Geosystems Cyclone, InnovMetric PolyWorks, GeoCue software suite, TerraSolid software suite (TerraScan, TerraModeler, TerraMatch, TerraPhoto, TerraControl, and TerraOffice), PHOCAD (www.phocad.de) PHIDIAS, Pointools, and Virtual Geomatics software suite. Software selection depends on the final deliverable requirements. Each software solution excels in a specific area. Often, several pieces of software have to be used to create the final deliverable required by customers.

Consideration on Mobile LiDAR System Selection

Selection of a mobile LiDAR system depends on the application requirements. Digital camera images are crucial in asset identification and their condition assessment. On the other hand, digital camera images are rarely collected in pavement survey applications. The system's absolute accuracy refers to the position accuracy of a point in the point-cloud in a global coordinate system. The system's relative accuracy refers to the position accuracy of a point relative to other points in close proximity. Measuring bridge vertical clearance requires high relative accuracy with lower absolute accuracy. Pavement survey requires high relative and absolute accuracy. Other key specifications of mobile system have been outlined below:

- GNSS/IMU positioning system performance specifications – Its performance is directly related to the system absolute's accuracy.

- Range Accuracy within useful range – A scanner's single-point accuracy within its useful range is directly related to the mobile LiDAR system's relative accuracy. Each application may have different relative accuracy requirements. The range accuracy may be degraded with high laser angle of incidence and poor object reflectivity.

- System LiDAR Field-of-view (FOV) and 2D LiDAR scanner mounting geometry – Most modern systems have a LiDAR FOV of 360^o to ensure all tall structures or overhead structures are captured into the point-cloud. Some systems have twin 360^o FOV 2D LiDAR scanners to reduce "shadows" caused by line-of-sight obstructions.

- Useful range of scanner – The manufacturer's datasheet typically provides only the maximum range of the scanner, i.e. the range at which the scanner can get an acceptable return signal to obtain a range measurement based on an object with high reflectivity (e.g. 80%), facing directly toward the scanner so that the laser incidence angle is near 0°. In a DOT project or practical scenario, where the object to be scanned is black-top asphalt of approximately 5% diffuse surface reflectivity with a high incidence angle, the useful range of the scanner is greatly reduced when compared to the maximum range.

- Scan rate (Hz) – This refers to the revolution rate of the LiDAR scanner mirror. Higher scan rate enable higher vehicle speeds while maintaining required point density of the resulting point-cloud. Thus, it improves operational efficiency and reduces hindrance to the moving traffic on the highway.

- Built-in digital camera – The image assists in feature recognition and sign recognition. The color images are often used to overlay / colorize the points in the point-cloud. The proper camera orientation is vital in ensuring the critical features are captured within the camera's FOV.

- Rental or partial ownership options exist to reduce the risk of technological obsolescence and entry cost.

Best Practices and Data Exchange Standard

Previous studies have been performed in the application and evaluation of mobile LiDAR systems. Their results support the laser scanner manufacturers' claims of improved productivity and safety and their system accuracy. End users and manufacturers agree that standards are needed in the following areas: best practices on the use of mobile LiDAR system on different applications, uniform result reporting, and universal data exchange formats. These standards will increase the users' confidence in the performance of their chosen systems, facilitate interoperability, and promote the overall growth of the industry. Currently, LAS is the preferred standard data exchange format for the point-cloud produced by the mobile LiDAR system. However, there is no standard for exchanging the geo-referenced digital images.

The American Society for Photogrammetry and Remote Sensing (ASPRS) is actively updating the LAS format to better address mobile LiDAR mapping application requirements. The ASPRS mobile systems committee, chaired by Dr. Craig Glennie, is working on a best practices and guidelines document, with the goal of having an initial draft prepared for ASPRS 2012. In addition, Geospatial Transportation Mapping Association (GTMA) (www.usgtma.org), chaired by Ray Mandli, was formed recently. Their aims are:

- Educate industry on what they should be looking for
- Create a standard for quantifying results
- Create some sharing of information and data between vendors
- Create a national dataset of highway data for Federal use