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Infrastructure Investment Protection with LiDAR

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16. Abstract

The primary goal of this research effort was to explore the wide variety of uses of LiDAR technology and to evaluate their applicability to NCDOT practices. NCDOT can use this information about LiDAR in determining how and when the technology can be used most effectively. In addition to saving time and staff resources, LiDAR provides other added values such as improved safety, increased efficiency, and greater detail. The applications detailed in this report provide NCDOT with valuable information that serves the stated goals of NCDOT through applications of LiDAR.

The research products developed as a result of this research project are included in this report which documents the following research products that will be useful for NCDOT: a literature review of LiDAR state of the practice across the nation, concise one-page summaries of a variety of transportation and non-transportation applications, summaries of LiDAR discussions with NCDOT units, and survey results from state transportation agencies about their specific use of LiDAR.

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EXECUTIVE SUMMARY

The primary goal of this research effort was to explore the wide variety of uses of LiDAR technology and to evaluate their applicability to NCDOT practices. NCDOT can use this information in determining how and when LiDAR can be used most effectively. In addition to saving time and staff resources, LiDAR provides other added values such as improved safety, increased efficiency, and greater detail. The applications detailed in this report provide NCDOT with valuable information that serves the stated goals of NCDOT (2012) through applications of LiDAR which include:

- Make our transportation network safer through applications such as sight distance, pavement cross-slopes, rock slope assessments, airport obstruction surveys, and crash reconstruction.
- Make our transportation network move people and goods more efficiently through applications such as new transportation improvement construction projects, traffic flow estimation, and parking utilization.
- Make our infrastructure last longer through applications such as structural health analysis, geometric clearance, pavement assessment, rock slope assessments, and slope stability.
- Make our organization a place that works well by utilizing a technology that is more efficient and productive in specific applications.
- Make our organization a great place to work by utilizing a technology that protects employees by minimizing exposure to dangerous traffic conditions and other hazardous settings.

The results of this research project are included in this report which documents the following research products that will be useful for NCDOT: a literature review of LiDAR state of the practice across the nation and around the world, concise one-page summaries of a variety of transportation applications, summaries of LiDAR discussions with NCDOT units, and survey results from state transportation agencies about their specific uses of LiDAR.

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1. INTRODUCTION

1.1. Problem Definition and Need

Light Detection and Ranging (LiDAR) is becoming increasingly popular across the United States, and state transportation agencies are adopting practical use of the technology for transportation related applications. This is quite evident by the growing number of agencies acquiring LiDAR scanners and contracting LiDAR services. The primary factors behind this trend are that (1) surveyors, engineers, and technicians are becoming more educated and increasingly open to LiDAR and its applications, and (2) LiDAR is often more cost-effective than traditional surveying technologies. In addition to economics, LiDAR provides other added values such as improved safety, increased efficiency, and greater detail.

As the technology continues to improve and become more affordable, state agencies have implemented and applied LiDAR's capabilities to various transportation improvement projects. Thus, the work of this research seeks to identify the most promising transportation applications of LiDAR and provide guidance to engineers and surveyors on how and when to utilize LiDAR.

1.2. Research Objectives

In order to achieve the goal of this research effort, a list of objectives has been outlined below:

1. Compile a literature review on the current state of practice of LiDAR technology and implementation.
2. Develop one-page summaries on the use of LiDAR for specific transportation applications.
3. Work with NCDOT units to obtain information on experience with LiDAR and document the Department's processes of LiDAR deployment and utilization.
4. Survey all state transportation agencies in an effort to complement the literature reviewed with the intent of identifying how other agencies and their contractors are using LiDAR.

2. BACKGROUND

2.1. LiDAR Technology

LiDAR integrates lasers, sensors, Global Positioning Systems (GPS), and Inertial Navigation Systems (INS) as a range-based imaging tool. A LiDAR scanner measures the distance to an object or surface by calculating the time delay between the initial transmission of individual laser pulses and the returning detection of reflected signals, which is similar to radar or sonar technology (Fekete 2012, WISDOT 2010). A scanner calculates the return times for lasers emitted, or time-of-flight, to identify the surrounding environment relative to its own position. Each laser pulse that strikes a surface and returns has a corresponding XYZ coordinate registered into a digital three-dimensional space. The conglomeration of points within a digital space makes up what is known as a point cloud. A point cloud can be made up of millions of points, and is dependent on scanner settings for the density of laser emissions and the distance to a scanned surface.

Alternatively, phase-based scanners calculate distances by means of phase-offset technology. This technology sends out a constant laser pulse to measure the intensity of laser emissions. An amplitude modulated continuous wave laser is sent out; as the beam comes in contact with a surface, a shift in the signal is detected and registered as a point in space. The intensity is dependent on the reflectivity of the surface on which each laser strikes. Generally, closer surfaces with lighter colors induce higher reflectivity than darker surfaces farther away. Compared to time-of-flight sensors, phase-based systems are capable of obtaining more point measurements in a second. However, phase-based scanners are generally utilized for indoor or short range applications; whereas, time-of-flight scanners are rated at much longer ranges. The longer range capabilities make time-of-flight systems more applicable for transportation applications.

2.2. Types of LiDAR and Collection Capabilities

LiDAR has been commercially available since the 1990s, and the technology is continually undergoing rapid development in surface and object sensing as well as data processing. For example, within 10 years, scanner measurement rates have increased from 100,000 points per second to 500,000 or more with sensor speeds increasing from 50 Hz to 200 Hz. The total system cost has remained about the same, and purchasers or users can expect higher performance with lower costs as time continues to advance the technology. Therefore, rather than address the capabilities of current systems, it would be more beneficial to define the principals pertaining to useful, high quality LiDAR implementation.

Generally, there are three LiDAR application types that include (1) the fixed-terrestrial system in which the scanner is mounted on a stationary surveying tripod, (2) the mobile-terrestrial system that mounts onto ground vehicles, trains, and boats, and (3) the airborne system which scans from airplanes and helicopters. Each platform varies in application, time requirement, cost, and accuracy.

Fixed-Terrestrial LiDAR

Fixed-Terrestrial LiDAR, a static form of high density scanning, uses a laser and rotating mirror to rapidly scan and image surfaces, as seen in Exhibit 1. Fixed LiDAR refers to tripod-based measurements, rather than measurements taken from an aerial or ground vehicle, and therefore does not require a global positioning system (GPS) or inertial navigation system (INS) for direct georeferencing. Since it is stationary, fixed LiDAR is typically able to achieve the highest accuracy of the three types. Generally, fixed-terrestrial LiDAR relies on targeted points. Therefore, to increase accuracy, targets can be established on known benchmarks for additional geodetic control and registration. When modeling an individual object, the relative orientation between multiple scans is sufficient for a high level of precision. If the object needs to be placed in a superior coordinate system, then an absolute orientation by georeferencing is necessary (Pfeifer and Briese 2007). Types of LiDAR systems include (1) panoramic scanners, which rotate 360 degrees horizontally and 270 degrees vertically; (2) single axis scanners, which rotate 360 degrees horizontally and have fixed 50-60 degrees field of view vertically; and (3) camera scanners, which scan at set fields of view and have limited angular ranges (Shuckman 2011). Static systems can also be classified by operational range; however, the closer the range, the more accurate the data. Typical LiDAR systems used for high density scanning are medium range, which operates at distances of 150 to 250 meters, achieving millimeter accuracies.

Exhibit 1. A fixed-terrestrial LiDAR scanner (www.Terra.ch)

Mobile-Terrestrial LiDAR

Mobile-terrestrial LiDAR systems, or kinematic high density scanning, are more accurate than those of airborne LiDAR systems (Shuckman 2011). The typical mobile LiDAR setup is integrated on a ground vehicle, as seen in Exhibit 2. The combination of on-board GPS and INS devices provide georeferencing, and are especially important for the absolute accuracy of the system. The system can be safely mounted on the exterior of a vehicle to collect data at highway speeds with the flow of traffic. In addition to the increased efficiency of data collection, benefits also include minimization of lane closures, traffic disruptions, and safety hazards. Mobile scanners are effective for highway corridor surveys when topographic and infrastructure information is needed.

Exhibit 2. A vehicle with a mobile-terrestrial LiDAR system (www.McKimCreed.com)

Airborne LiDAR

LiDAR data collection procedures differ based on the type of platform used. For Airborne LiDAR, the scanner is mounted on an aircraft and emits infrared laser beams at high frequencies, recording the times from emission to reception of each signal (Stennett 2008). LiDAR scanners can be mounted on fixed-wing or rotary-wing aircrafts, as seen in Exhibit 3. Airborne LiDAR uses longer wavelengths than terrestrial systems, and are less affected by atmospheric conditions. Airborne systems scan perpendicularly to the aircraft's flight direction in an oscillating or swathing motion to capture segments of the earth's surface. The position and orientation of the aircraft is then determined by integration of GPS and INS devices. Laser emission vectors collected between the sensors and the ground below are recorded to compute XYZ coordinates of each laser beam.

Exhibit 3. A rotary-wing aircraft with airborne LiDAR (us.Network-Mapping.com)

2.3. LiDAR Data

During a scanning cycle, thousands of beams are transmitted per second, and millions or billions of distance measurements to surfaces are generated by the end of the process (Kemeny and Turner 2008). XYZ coordinates of each reflected pulse are calculated based on the distance measured and the relative position of the scanner. After processing the range and orientation of each transmission, the geometric coordinates are positioned into a spatially coherent conglomerate of points within a three-dimensional frame of reference, known as a point cloud. A point cloud is the basis from which all information and products are processed, analyzed, and derived. Typical point cloud formats include ASCII, LAS, SVY, PTS/PTX, and other proprietary formats. ASCII, American Standard Code for Information Interchange, stores a point cloud as a basic, generic set of XYZ coordinates. The file can then be imported to software as delimited text or database files. LAS, Log ASCII Standard, is a binary file format based on standard ASCII code. The format is publicly available for the exchange of LiDAR data between vendors and customers (ASPRS 2009), and was developed to relieve the process flow issues of changing systems and using proprietary formats. Additionally, LAS file format addresses processing performance issues associated with reading and interpreting ASCII elevation data, which can be very demanding on the computing capabilities of workstations. Finally, LAS files maintain information specific to LiDAR data collection that is generally lost with other raw data formats. This gives primary users the ability to troubleshoot and debug problem datasets, and allows third-party users to conduct analysis for data integrity. SVY format, or survey file, collects data in the form of Eastings, Northings, and elevations. PTS/PTX is a commonly used proprietary extension that contains a stream of XYZ coordinates, intensity values (based on incident radiation surface reflectivity), and color-coding schemes for groups of points (Payne 2012). PTX files, much like LAS files, retain original scan data and additional registration information.

2.4. Data Processing

Once a scan has been conducted, the resulting point cloud must be cleansed and filtered before it can be used for any specific application (Fernandez et al. 2007). The steps of initially processing data include segmentation or clustering, removal of erroneous points, and thinning. Segmentation and clustering are means of organizing individual points into homogeneous groups. Grouping of points allows users to assign meanings to various entities captured in a point cloud and allows data classification to a higher degree. The removal of erroneous data serves two purposes; it removes useless information, or noise, from the dataset as well as reduces the volume of data. Thinning point clouds is an additional strategy to minimize the number of points required for analysis. For linear features and flat planes, points between continuous segments may be removed. In a similar manner, extrapolation between multiple points for curved surfaces seeks to reduce the density of point clouds.

Although the advances in scanner hardware have developed quickly in recent years, the success rates of automated classification and processing efficiency have not improved as quickly. Efforts are currently underway to develop processing software for advanced modeling and analysis of point clouds for various applications and fields.

2.5. Data Storage and Sharing

Even as computer technology continues to advance and geographic information becomes increasingly available, there remains the challenge of implementing effective data integration/exchange protocol and procedures (Quiroga et al. 2009). When considering the complexity and size of LiDAR point clouds, it is important to reduce redundancy, data collection costs, and data storage requirements. When adopting LiDAR or purchasing data, transportation agencies should utilize the technology to conform to department-wide standards and practices for digital geospatial information management.

LiDAR scans require large amounts of data storage. However, point clouds can be cleaned and processed to reduce files to much more manageable sizes. The digital storage space required for LiDAR scans and products will ultimately depend on what information is needed and to what degree of accuracy is sufficient.

2.6. Processing Software

Although, LiDAR can effectively reduce the time and labor required for data collection, the analysis and extraction of useful information may be cumbersome and complicated. Post-processing LiDAR data consists of multiple aspects including georeferencing point clouds to a superior coordinate system, filtering erroneous points and outliers, and identifying and classifying objects and surfaces to produce final deliverables (Yen et al. 2011). These deliverables include, but are not limited to, digital elevation models, contour maps, orthorectified aerial imagery, three-dimensional visualizations, base maps, and cross-sectional CADD drawings (Terrapoint 2008). Automatic and manual processing software is essential for LiDAR productivity. There are many types of software that analyzed raw LiDAR data for different applications. Survey deliverables may include three-dimensional elevation products, two-dimensional meshes, objects, coordinate points, and linear features, while asset management deliverables provide locational, geometric, and condition information of highway assets and roadside features.

2.7. Accuracy and Error

The required accuracy of LiDAR varies depending on the specified application and configuration, be it airborne or terrestrial LiDAR. Generally, the two classifications of LiDAR acquisition are asset/mapping grade and survey/engineering grade (Yen et al. 2011). Mapping grade LiDAR is useful to collect data with adequate accuracy at lower costs for mapping and inventory purposes. In terms of accuracy, mapping grade LiDAR requires an absolute accuracy of 1 foot and relative accuracy of 0.1 foot. However, mapping grade systems often achieve higher accuracies when geodetic signals are strong and atmospheric conditions favorable. The design of survey/engineering grade LiDAR is to achieve the highest level of accuracy by integrating the most advanced GPS receivers, IMU, digital cameras, and LiDAR scanners. Transportation surveying and engineering applications that carry stringent financial and legal liabilities often require the highest accuracies. Survey/engineering grade LiDAR can easily cost two to five times more than mapping grade LiDAR.

With regards to geospatial and locational information, accuracy is defined as the degree to which a given dataset matches true or accepted values. It pertains to the quality of data and the number of errors in the horizontal and vertical coordinates produced. The Federal Geographic Data Committee produces the National Standard for Spatial Data Accuracy that uses root-mean-square error (RSME) to assess geodetic accuracy. RMSE is the square root of the average set of squared differences between collected values and known control points. Accuracy with respect to ground truth is reported at the 95 percent confidence level. Additionally, in the production or derivation of final deliverables, it is of utmost importance to define the accuracy to which a LiDAR-derived product meets. While the degrees of accuracy of individual point clouds may meet data specifications, post-processing and integration between points will introduce assumptions into the analysis and thereby reduce the final product's accuracy, or vice versa. Consequently, the accuracy for both the raw LiDAR data as well as the final derived product should be explicitly stated. For example, "airborne LiDAR data having an absolute accuracy within five feet was used to interpolate and derive two-foot contours." Finally, accuracy should be distinguished from precision, which refers to the exactness of the data being collected. That is, the level of measurement depends on how carefully data is measured and to what degree of detail. The required precision for engineering projects will vary depending on specified applications. Thus, it should be noted that high precision does not necessarily indicate high accuracy.

The American Society of Photogrammetry and Remote Sensing (ASPRS) LiDAR Committee published two papers outlining guidelines for reporting the vertical and horizontal accuracies of LiDAR data (ASPRS 2004 and 2005). Although primarily produced for airborne LiDAR data, the principles and practices are generally applicable to terrestrial LiDAR as they are based on national standards used by remote sensing and mapping practitioners, land surveyors, and GIS professionals. After LiDAR has been selected for a project, the first step is to specify the accuracy required for the application. The tendency to request the highest accuracy achievable must be reconsidered when data users recognize that lower resolution is sufficient and realize the increased costs for higher accuracy. It is important to specify the accuracy expected of all final products being delivered. Such is the case for products derived from point clouds. Derivatives may exhibit greater error and should not be expected to meet the same accuracy of LiDAR point clouds. By specifying the accuracy requirements for final products, error is kept within limits throughout production. Accordingly, stating a single required accuracy without additional clarification is not recommended.

In general, accuracy should be reported at the 95 percent confidence level tested against an independent source of higher accuracy. The accuracy of the control datum should have at least three times the accuracy of what is required to be collected. If independent sources are unavailable for testing, data producers should evaluate accuracy by alternative means and explicitly state that the data was compiled to meet a specified accuracy. When designing tests for accuracy, varying datasets should be identified and reported with separate values. Potential variables include the continuity of data, topographic variation, and ground cover variation. Anytime multiple surveying teams and acquisition systems are used to collect LiDAR data over the same project, data should be separated and tested independently. For varying topographic features, it is favorable to specify different requirements of accuracy and design tests for each. Testing of LiDAR data has found that the magnitude and distribution of errors often changes for different types of land cover. The common land cover categories include open terrain, tall weeds and crops, brush lands and low trees, forested areas, and urban areas. Vegetation and other occluding objects will limit bare earth detection. Therefore, open terrain should be separately tested from other ground cover types.

Differences or errors in accuracy are calculated by subtracting surveyed XYZ coordinates with corresponding values interpolated from known points. When analyzing errors, there are three causes to recognize: blunders, systematic errors, and random errors. Random errors are theoretically produced by irregular causes, governed by no known law, and cannot be adjusted with standard correction factors. Systematic errors follow a fixed pattern and occur during collection procedures or for specific systems. When identified, systematic errors can be accounted for before calculating final accuracies. Blunders are major differences between collected and known values. They may be identified as statistical outliers greater than two or three standard deviations of the mean. Blunders should be investigated as they may represent an error characteristic in the rest of the data. The key is to consider all types of errors and decide on how best to address them before proceeding to deliver or use any LiDAR dataset.

Due to the level of movement and relative position between the scanner and target surface, airborne LiDAR is typically the least accurate of the three platforms (Shuckman 2011). A typical airborne scan can range from 1 point per 3 to 5 meters up to several points per square meter with accuracies from 10 to 15 centimeters. Ground-based LiDAR, depending upon scanner settings and relative distances of target surfaces, can scan with accuracies from millimeters to a few centimeters. LiDAR, however, like all surveying technologies, is not perfect. The accuracy of any data point collected by LiDAR can be affected by numerous factors including: weather, scanning range, reflectivity of the target surface, and the angle at which laser emissions strike surfaces.

2.8. Benefits

LiDAR provides transportation agencies with the benefits of safety, data collection productivity, cost effectiveness, applicability, level of detail, and technology.

Safety

A key benefit of using LiDAR is its appeal to safety. By reducing lane closures and exposure to potentially hazardous environments, LiDAR improves the safety of field personnel as well as the traveling public. As a remote sensing technology, LiDAR collects data at a safe distance. Ground-based systems can accurately scan from distances of at least 150 feet, which is sufficient for many transportation applications. Airborne LiDAR completely removes data collection from the vicinity of the highway, thereby shifting the higher risks of traffic exposure to the lower risks of flight.

Data Collection Productivity

Due to the rapid scanning ability, LiDAR data collection can be completed in a fraction of the time required by traditional surveying and manual measurements. After the initial registration and set up of the scanner, LiDAR automatically collects and records measurements without user interaction. The data rich point cloud created during a LiDAR scan also has the ability to be re-mined. For future reference or use, a single scan of a roadway can provide information on multiple roadway aspects, thereby minimizing redundancy in data collection.

Cost Effectiveness

LiDAR can be very cost effective when compared with traditional surveying and photogrammetry. Although the initial cost of purchasing LiDAR equipment is expensive, the shared benefits across various business areas can help mitigate high capital investments. The options of rental and fractional ownership can further reduce the burden of expenses.

Applicability

The technology can be utilized for most areas of surveying that require the measurements of visible surfaces and unimpeded distances. LiDAR also possesses the ability to scan potentially unreachable areas with traditional surveying methods such as pipes, tunnels, and power lines.

Level of Detail

High-resolution point clouds and the sheer density of points collected is an attractive feature of LiDAR. The richness of data for the relative timeliness of field collection far exceeds that of any traditional surveying methods. Additionally, the digital images that are usually taken simultaneously with scans can be draped over point clouds for supplemental detail.

Technology

As an emerging tool, LiDAR profits from the integration of remote sensors and geomatic instruments, and will continue to improve through research and development. Unlike the more quantitative benefits described above, technological innovations and the trends toward continuous improvements are driving forces in today's world. Technology elicits better and smarter engineering decisions, and the adoption of tools like LiDAR can be instrumental in the constant improvement of transportation agencies and infrastructure serving the traveling public.

2.9. Costs

The three primary associated costs with LiDAR utilization are data collection, information technology, and data extraction costs (Yen et al. 2011). Data collection cost is composed of the investment or contracting of scanner equipment and hardware, equipment maintenance and upkeep, field crew mobilization, and vehicle collection platform. Information technology (IT) cost refers to the costs associated with data extraction software, digital storage and server infrastructure, data backup, and computing workstations required for the processing, analyzing, storing, and transferring of LiDAR data and derived products. Data extraction costs refer to the total costs required to extract useful geospatial data for various business areas utilizing LiDAR data. The cost is based on the time and number of technicians required to process raw point clouds into final deliverables. This cost varies depending on the features to be extracted, the degree of accuracy needed, and the format of the delivered product.

Primary Tasks Associated with Cost

When utilizing LiDAR, the tasks required to perform a scan and produce final deliverables must be recognized. The most basic tasks include developing a project/survey plan, establishing geodetic control, survey computations for quality assurance, field collection, point cloud creation/registration/editing, feature extraction/CADD production, quality control measures, and system acquisition (Vincent and Ecker 2010). The primary factor in the aforementioned task depends heavily on the professional or technical staff requirements of each action. The costs vary based on the scope of work, level of detail, task approach, technology employed, and location. When comparing fixed-terrestrial and mobile-terrestrial LiDAR, the time required and associated costs for static systems will be greater than that of mobile systems for larger scopes of work. Therefore, mobile LiDAR can be a better option for individual project sites requiring multiple, vehicle-accessible surveys or projects with multiple sites.

Airborne LiDAR produces significantly less detail, and is implemented for very large and/or inaccessible project areas. Along with the basic tasks previously mentioned, the utilization of fixed or rotary wing LiDAR requires the additional task of flight. Contrary to ground vehicle mobilization, aircraft operations increase the deployment costs considerably. Therefore, LiDAR service providers generally set a minimum breakeven scope of work between 20 to 40 acres for typical terrains when conducting airborne scans (Stennett and Wade-Grusky 2008). Some firms do not perform scans for projects smaller than 15 to 30 square miles, whereas others routinely conduct high volumes of small site surveys. A firm offering airborne LiDAR turnkey services, data/sensor operations training, sensor rentals, and fractional sales of equipment estimated the prices of contracted services by licensed professionals in the southwestern United States. Adhering to ASPRS Class 1 standards of 2-foot contours, the cost would be approximately

$3,500 plus $1.49 per acre for airborne LiDAR. As the scope of work increases beyond a few hundred acres, the price per acres decreases substantially. For large projects greater than 1,000 square miles, marginal acreage fees can be as low as $0.15 per unit. Much like photogrammetric surveying, dense ground cover and limited access increases the price of LiDAR deployment. If projects are smaller, LiDAR users can take advantage of lower marginal costs by pooling nearby projects. In general, airborne LiDAR is less commonly used by transportation agencies. Therefore, to avoid the costs of aircraft upkeep and operation, agencies can benefit from contracting services from dedicated airborne LiDAR providers.

Deployment and Acquisition Options

In terms of acquiring LiDAR scanners or data, the options include contracting data collection/post-processing/feature extraction, renting and operating equipment, purchasing and operating, or purchasing fractional ownership (Yen et al. 2011). In addition to the deployment options, the accuracy requirement will dictate whether to use mapping/asset or survey/engineering grade systems. In deciding on which option to pursue, the amount and frequency of LiDAR use for transportation improvement projects and asset management programs should be reviewed to determine the optimal decision. The advantages of each option are outlined below:

> *Contracting Services* – The primary advantage is that the contractor will provide and produce the equipment, personnel, and final deliverables of a project. Therefore, the transportation agency is not hampered with significant capital investment, personnel training, data processing, risk of technological obsolescence, and equipment maintenance/depreciation.
>
> *Renting and Operating* – In addition to reduced equipment obsolescence risks and maintenance costs, the agency benefits from equipment availability and project schedule flexibility.
>
> *Purchasing and Operating* – In consideration of the high initial costs of purchasing a LiDAR system, the advantage is the lower lifecycle cost compared to renting equipment. This option benefits from frequent, long-term use.
>
> *Fractional Ownership* – Fractional ownership is common when asset investment costs are economically impractical. The benefits of these plans are reduced cost of entry and risk of obsolescence. Initial equipment costs depend on the percentage of ownership and incremental fees to cover maintenance and insurance.

2.10. Considerations

In many instances, multiple business groups gather geospatial data specific to their line of work, which often covers the same locations but use various data collection methods and standards. The data collection processes generally present safety issues and an overall lack of efficiency by increasing field personnels’ exposure to traffic and hazards, requirements for multiple types of equipment, travel time and costs, and traffic delays for highway travelers. Mobile LiDAR systems were developed to collect geospatial data of highway infrastructure and roadside features at highway speeds for surveying, asset management, as-built documentation, and maintenance operations. The resultant point cloud is processed for mapping data, roadside asset feature data, and geometric measurements. Data extracted can be easily formatted and imported to accommodate various highway business areas, thereby reducing redundancy in data collection and storage. LiDAR as a tool for data acquisition shows promise in consolidating geospatial data and improving the efficiency of resource allocation.

When considering LiDAR for transportation applications, the costs, benefits, and ease of implementation should all be considered. Decisions based solely on the costs of capital investment are not recommended as other factors such as risks and economic feasibility should be taken into account. There are several challenges for any transportation agency to address that include the extensive knowledge, skills, and planning required to conduct LiDAR data collection and processing; the integration with current agency processes; the high technology costs of equipment, hardware, and software; and the consistency of workflow procedures. A major risk of LiDAR is technological obsolescence, but contracts for services, equipment rental, and partial ownership may act as means of mitigation. The key for agencies is to anticipate the utilization rate of LiDAR, and make investments based on economic feasibility. The most pertinent options for acquiring LiDAR systems, data, or LiDAR-derived products includes contracting services, renting equipment, purchasing fractional ownership, or making a full investment in LiDAR.

3. LIDAR APPLICATIONS

3.1. Transportation Applications

The following pages detail examples of LiDAR applications for the following: bridges; construction; geotechnical engineering; highway design and corridor mapping; hydraulics and hydrology; pavement; photogrammetry; safety and mobility; historic, natural, and cultural preservation; and forensic science and scene reconstruction. For each application, a brief description is discussed and organized in the order below.

Bridges

LiDAR has been the choice of many state transportation agencies to gather data on bridges for its ability to reach inaccessible areas and obtain detailed information on intricate geometric shapes. LiDAR is also non-intrusive, providing safety to drivers and work crews by allowing normal traffic flow and no lane closures in most instances. For these reasons, LiDAR has been proven useful for determining geometric clearances and monitoring bridge health. Specific examples discussed in the following pages include:

- Structural health monitoring
- Geometry and clearance measurements
- Restoration

Construction

Due to the ability to collect large amounts of surface data quickly, LiDAR has been used to collect geometric measurements and produce three-dimensional models of highway infrastructure, which can then be compared to original design plans and used for future reference, as as-built models. For preconstruction design and project estimation, LiDAR has been used for its accuracy, precision, and relative quickness for data collection. This enables transportation agencies to save time and money. Specific examples discussed in the following pages include:

- Earthwork quantity estimation
- As-built modeling and CADD reconstruction

Geotechnical Engineering

LiDAR has been used in the geotechnical field for its ability to provide accurate data of volumetric displacement of rockfaces. Due to LiDAR's high-speed, long-range scanning capabilities, surveyors are able to collect data safely without physical exposure to potentially dangerous terrain and with minimal interruptions to traffic flow. Specific examples discussed in the following pages include:

- Rock mass characterization

- Rockfall characterization
- Landslide mapping
- Tunnel construction and maintenance
- Slope stability
- Structural health monitoring
- Volumetric change

Highway Design and Corridor Mapping

Fixed-terrestrial LiDAR is useful for high-profile or complex highway design projects. Mobile ground-based and airborne LiDAR systems cover larger project areas very quickly. Scans provide quality information and representation of existing transportation infrastructure and surrounding conditions. Specific examples discussed in the following pages include:

- Design improvement
- Elevation and cross-section
- Topographic surveying

Hydraulics and Hydrology

Because of its ability to gather "bare-earth" information, LiDAR is used by organizations to create flood and inundation maps. Post-processing software has the ability to easily remove trees and other visibility obstructions from LiDAR point clouds. Specific examples discussed in the following pages include:

- Digital elevation model
- Geographic information system
- Coastal change
- Flood and inundation mapping
- High hazard dam

Pavement

LiDAR has been used to assess pavement attributes, such as road grade and cross-slope estimations. As LiDAR technology continues to advance, so does its ability to collect accurate data. Therefore, LiDAR has proven to be an invaluable source of information for pavement assessment and maintenance. Specific examples discussed in the following pages include:

- Grade estimation
- Cross-slope
- Resurface assessment
- Crack detection

Photogrammetry

Airborne LiDAR has been used to supplement photogrammetric operations and aerial photography. Point clouds provide exceptional data for deriving elevation products and producing base maps. Specific examples discussed in the following pages include:

- Airport obstruction survey
- Digital elevation model
- Geographic information system
- Transmission line survey

Safety and Mobility

LiDAR has been implemented in the transportation field for safety and mobility analyses by locating intersection sight obstructions and assessing traffic operations. Specific examples discussed in the following pages include:

- Intersection obstruction and sight distance
- Traffic flow estimation
- Parking utilization

Historic, Natural, and Cultural Preservation

LiDAR has recently been viewed as an asset in historical documentation and preservation for its ability to create detailed three-dimensional images without any destruction to the site. Specific examples discussed in the following pages include:

- Historic preservation
- Cultural preservation

Forensic Science and Scene Reconstruction

LiDAR has recently been used in the Federal Bureau of Investigation and other law enforcement agencies for its ability to take incredibly detailed images without disturbing or destroying evidence. Specific examples discussed in the following pages include:

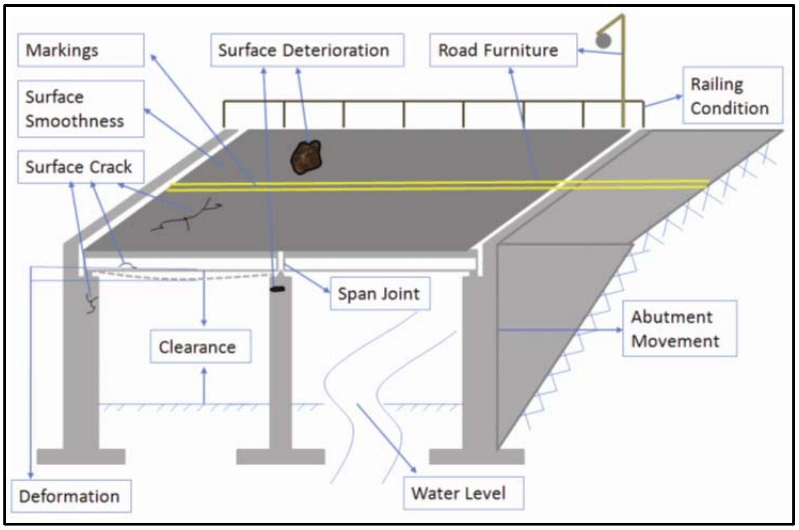
- Crash reconstruction
- Criminal investigation

LiDAR Application Case Study – Bridges

Application:	Structural Health and Geometric Clearance Measurements
Location:	North Carolina
Study Period:	2009
Equipment:	Fixed-Terrestrial LiDAR

Study Description

In a seven-volume set of reports, UNC-Charlotte developed the Integrated Remote Sensing and Visualization System (IRSV) to examine the techniques and capabilities of commercial remote sensing in bridge management and maintenance applications. Of the various techniques, LiDAR was utilized to automatically detect and quantify bridge damage, measure bridge geometry (i.e. vertical clearances), and detect structural change.



Major Findings and Limitations

- Infrared imaging and LiDAR techniques are recommended for bridge health monitoring.
- Ground-based remote sensing obtained more detailed structural information than satellite and airborne sensors.
- Structural displacement, strain, distress, surface cracking, corrosion and collision damage, and critical structural factors (i.e. bridge clearance, degree of curve, and skew distance) can be extracted directly from LiDAR point clouds.
- Using a 10 by 10 point grid with a resolution of 1 by 1 centimeter resolution, surface topologies of bridge components can be modeled to differentiate the severity and type of damages sustained by bridge decks and superstructures. Additionally, data taken over a period of time for a defective area can quantify visible damage volumes and estimate the rate of mass loss in bridge elements.
- For quality assurance (QA) of new bridge construction, LiDAR scans can confirm the displacement estimates of finite element (FE) models.
- Challenges of using remote sensing technologies include the generalized and visually-based nature of the federal bridge inspection process; the varying styles of bridge management amongst transportation agencies; the misunderstanding and inadequate experience with commercial remote sensing and spatial information capabilities; and the complexity of integrating multivariate data into a well-defined system for evaluation.

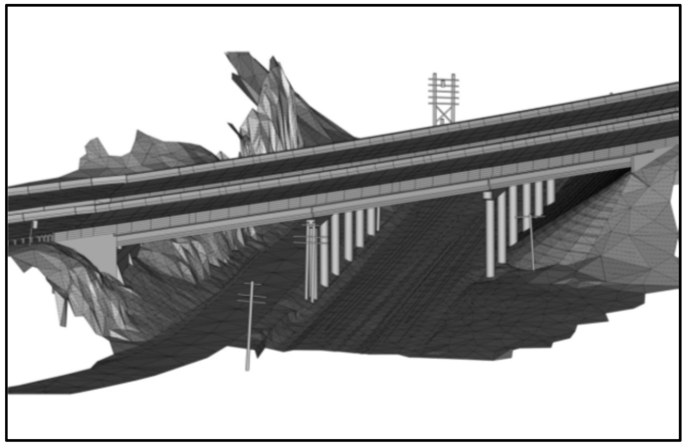
Hauser, E. and Chen, S. (2009). *Integrated Remote Sensing and Visualization (IRSV) System for Transportation Infrastructure Operations and Management*. USDOT Report Number 01221.

LiDAR Application Case Study – Bridges

Application:	Bridge Survey
Location:	Utah
Study Period:	2010
Equipment:	Fixed-Terrestrial LiDAR

Study Description

The Utah Department of Transportation contracted an engineering firm to scan a bridge to evaluate fixed LiDAR accuracy and potential uses. The Taggart Bridge on Highway 84, north of Morgan, Utah, was selected because redesign plans had been implemented to remove and replace the original 1960's deck. The main objective of this project was to evaluate LiDAR technology availability for three-dimensional bridge survey, design deliverables, and various pre-construction purposes.



LiDAR point cloud data was processed in Desk Top Survey (DTS) and CADD software to eliminate noise, such as trees, cars, and other objects. This data was then used to make three-dimensional models in AutoCAD Civil 3D, Microstation, and Cloudworx.

Major Findings and Limitations

- LiDAR data collection can be effectively used on precast deck bridge design and implemented in bridge deck removal to monitor and evaluate beam/girder rebound.
- LiDAR is proficient in measuring beam seats, deflection, camber, and splay; identifying bearing pad and plate dimensions; integrating original construction drawings with LiDAR point clouds; locating girder center lines on built structures; and assessing potential bridge subsidence, settling, and deterioration.
- In comparison with traditional surveying techniques, LiDAR was found to be significantly more cost and time effective. Traditional surveying would have taken 2 weeks and over 35,000 survey points to collect data. LiDAR required 2 days of surveying and one day of post processing with over 70 million data points with accuracies of 0.022 feet. Also, improved accuracies led to better management and engineering decisions, subsequently requiring less rework and shorter schedules. Using LiDAR also decreased safety risk of workers in the roads and was more efficient, causing no traffic delays. LiDAR saved $8,370 in man hours, 14-15 days, $1,000 in boom rental cost, and $480 in flagger cost.

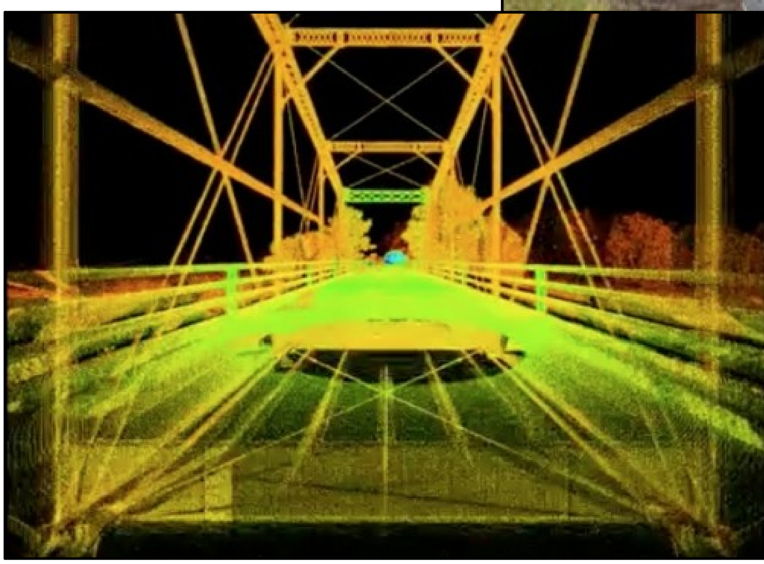
DeMann, A. (2010). *LiDAR/3D High Density Scanning (HDS) Bridge Scan. Model Project – Taggart Bridge*. UDOT Report Number UT-10.06.

LiDAR Application Case Study – Bridges

Application:	Bridge Restoration
Location:	Minnesota
Study Period:	2010
Equipment:	Fixed-Terrestrial LiDAR

Study Description

A historic, wrought iron bridge built in 1870 was selected for preservation by the Minnesota Department of Transportation. In 1937, the bridge underwent its first move to the Little Fork River. Seventy years later, in 2010, the state agency decided to relocate it to Washington County as a pedestrian and equestrian bridge.



A design firm and surveyor were contracted to take geometric measurements and determine the bridge configuration by utilizing LiDAR. The entire 162 feet bridge required nine scans over 2 days, and additional scans for each truss member removed during the disassembly process. Detailed drawings and dimensions were created from LiDAR point clouds. In the end, two floor beams, roller nest bearings, ten steel stringers, and the wooden deck were refabricated to fit joint connections. Additionally, the team used LiDAR to determine fastener patterns in order to return the bridge portals to their original clearance of 14 feet.

Major Findings and Limitations

- LiDAR is an effective method in capturing survey grade measurements and detailed configurations for older bridges undergoing relocation or preservation.
- During bridge disassembly, individual structural members can be scanned, and replacements designed based off the point clouds.

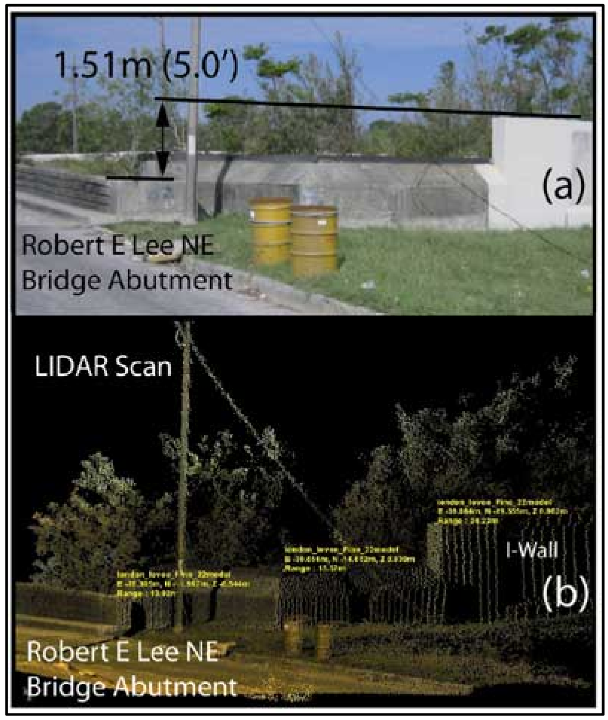
Minnesota Department of Transportation. (2010). *Silverdale Bridge – Manning Avenue (County Road 15) in Washington County*. http://www.dot.state.mn.us/historicbridges/2010and2011.html.

LiDAR Application Case Study – Bridges

Application:	Vertical and Horizontal Bridge Clearances
Location:	Washington State and California State
Study Period:	2011
Equipment:	Mobile-Terrestrial LiDAR

Study Description

The Washington Department of Transportation Bridge Preservation Office is the responsible party for collecting vertical and horizontal clearances and as-built structure information. In Washington, the absolute accuracy requirement for bridge location must be within 2 feet, whereas the relative accuracy for bridge clearances includes:



(1) Horizontal clearance of bridge columns and piers within 4 inches
(2) Vertical clearance of bridge girders within 1 inch
(3) Vertical and horizontal clearances of overhead restrictions including truss members within 1 inch and 3 inches, respectively
(4) Horizontal clearance of edge of pavement between 1.5 inches and 6 inches
(5) Vertical clearance of sign bridges within 1 foot

The current cost is estimated to be an $80,000 annual expense or $300 per structure, assuming that the agency collects bridge clearances for 270 structures per year and maintains a 10-year inspection cycle.

All measurements can be accuracy collected with a survey grade mobile LiDAR system. Cost-benefit analysis suggests contracting survey grade mobile LiDAR services for bridge clearance measurements. The advantages are that the contractor supplies the equipment, personnel, and required deliverables without burdening the state agency with training, post-processing, risks of technological obsolescence, and equipment maintenance. The final deliverable would be in the form of horizontal and vertical clearance diagrams. Based on assumed costs of information technology, data collection, and data extraction, the total cost of contracting LiDAR services was estimated to be $100 to $150 per structure.

Major Findings and Limitations

- Cost primarily depends on the number of structures and geographic separation of bridges.

Yen, K., Ravani, B., and Lasky, T. (2011). *LiDAR for Data Efficiency*. WSDOT Research Report WA-RD 778.1.

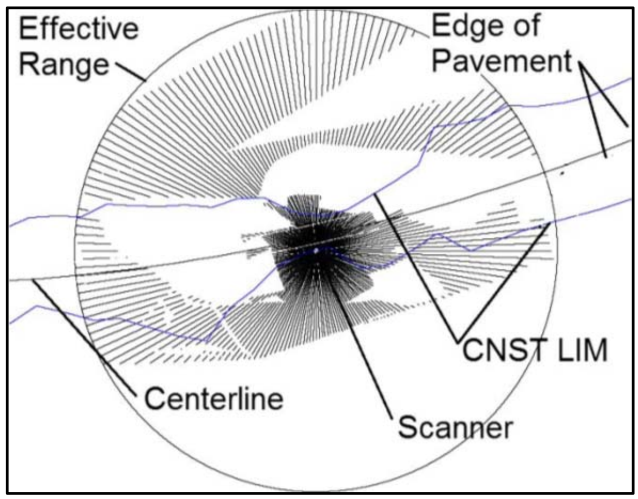
LiDAR Application Case Study – Construction

Application:	Roadway Construction – Estimating Earthwork Quantities
Location(s):	Missouri
Study Period:	2012
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Estimations of earthwork quantities for ground surface improvements are determined during construction surveys. The average end area (AEA) interpolation method of calculating areas of cut and fill are difficult to consistently apply when construction consists of nonlinear sections. LiDAR has been recognized as a viable solution to maximize productivity and leverage the shrinking number of state agency personnel.

Missouri State University developed a process for which surveying personnel and resident engineers could utilize fixed-terrestrial LiDAR to compute earthwork volumes on road construction projects without extensive training and continuous practice to maintain proficiency. The workflow includes describing the roadway horizontal alignment, planning preconstruction scans from best available terrain models, performing preconstruction scans, planning post-construction scans from digital terrain models, performing post-construction scans, and processing point clouds to calculate earthwork quantities.



Major Findings and Limitations

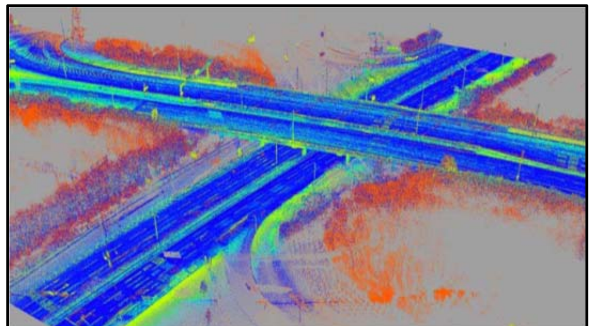
- Formalized plans of scan locations are crucial for utilizing LiDAR for construction surveys.
- Efficient data collection can be developed for both the scanning ability to set up over known points or set up without being over a known point but having three or more resection points (known reference points).
- Automated algorithms should be used to model bare ground surfaces, but processing software should allow for user interaction to verify terrain depiction and remove erroneous points.
- To facilitate understanding, scan data must be converted to state plane coordinates and then to station and offset coordinates based on horizontal roadway alignment.

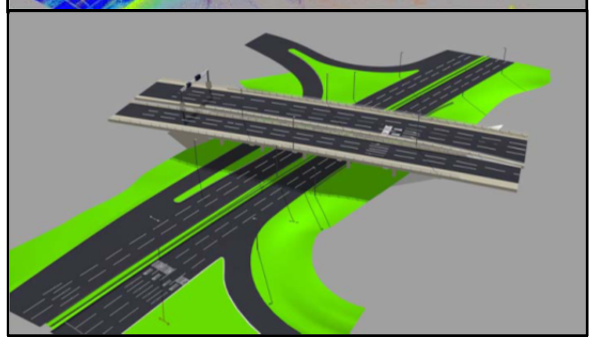
Slattery, K., Slattery, D., and Peterson, J. (2012). *Road Construction Earthwork Volume Calculation using Three-Dimensional Laser Scanning*. Journal of Surveying Engineering, Volume 138, Issue 2. American Society of Civil Engineers. Pages 96-99.

LiDAR Application Case Study – Construction

Application:	As-built Models and CADD Reconstruction
Location(s):	Athens, Greece; Korinthos, Greece; Leicester, England
Study Period:	2005
Equipment:	Mobile-Terrestrial LiDAR

Study Description





Mobile LiDAR was developed to survey large areas that would be impractical to scan with fixed systems but required accuracy and resolution exceeding those of airborne scanners. An engineering firm collaborated with a LiDAR vendor to develop a mobile mapping system to survey the transportation environment at high speeds. The primary goals were to survey highway corridors and reconstruct accurate three-dimensional models for visualization and as-built purposes. In two survey areas in Greece and England, the team used mobile LiDAR data to produce CADD reconstructions of highway infrastructure and adjacent features. Both field tests demonstrated how mobile scanners can be used to safely conduct corridor surveys at highway speeds while providing accurate data for as-built modeling.

Major Findings and Limitations

- LiDAR point clouds can be processed and archived in as-built models, which could be used as future references for the construction of new connecting roadways and the preservation of existing infrastructure.
- If GPS is interrupted from lack of signal coverage, position and orientation solution technology can correct system location with the distance measurement indicator.

Zampa, F., Conforti, D. (2009). *Lynx Mobile Mapper: The New Survey Technology*. Proceedings from ASPRS 2009 Annual Conference. March 9-13, 2009. Baltimore, MD.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Geotechnical - Rock Slope Mapping and Assessment
Location(s):	Continental United States
Study Period:	2008
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Research for USDOT was conducted to assess the geotechnical applications of fixed-terrestrial LiDAR. It was concluded that LiDAR could be utilized for rock discontinuity orientation, roughness, length, spacing, and block size, and could be extracted from the point cloud data using processing software. It was also concluded that LiDAR could be used to detect fracture orientation errors of less than one degree if at least three surveyed targets are used. It was proven to be safe, cost effective, and easy to learn. Additionally, previously scanned rock slopes could be scanned again to detect rock movement. By overlaying point clouds, the volumetric differential could be examined in order to assess rockfall, slope weathering, and volumetric change.

Major Findings and Limitations

- Generally, the distance from the scanner to the target slope should be at least the height of the slope.
- Generally, the scanner horizontal view should be 50 degrees.
- Scanning a rock face at various angles is not necessary unless the conditions are complex or high risk; if taking multiple scans, a 20 percent overlap between scans is sufficient.
- Point cloud spacing greater than 5 cm are not recommended for any geotechnical applications.
- Always take high-resolution digital images to accompany each point cloud.

Kemeny, John and Turner, Keith (2008). *Ground-Based LiDAR: Rock Slope Mapping and Assessment*. Report Number FHWA-CFL/TD-08-006. Federal Highway Administration. United States Department of Transportation.

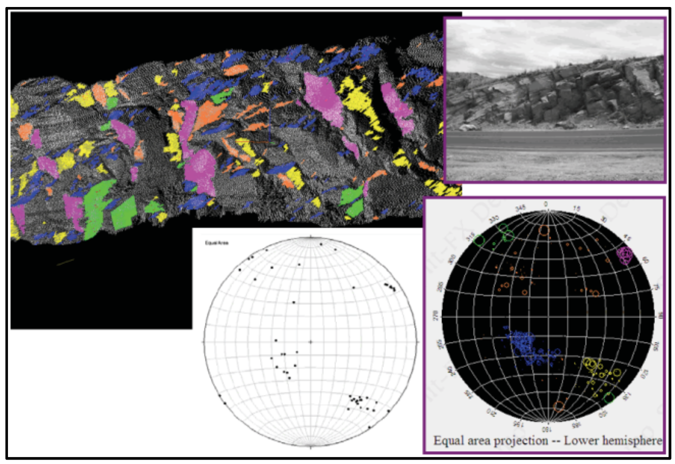
LiDAR Application Case Study – Geotechnical Engineering

Application:	Rock Mass Characterization – Discontinuity Orientation
Location(s):	United States
Study Period:	2008
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Rock mass characterization is the process of obtaining data for rock slope stability, and is currently collected manually on highway slopes and rock outcrops. Presently, LiDAR can obtain rock mass information regarding discontinuity orientation, length, spacing, roughness, and block size. The steps to identifying discontinuity orientation are (1) scan a field site of interest, produce a point cloud, and register the data to a terrestrial coordinate system; (2) create a triangulated surface mesh from the point cloud data and remove erroneous data; and (3) most importantly, delineate fracture patches from the digital surface mesh and find groups of adjacent triangles that satisfy a flatness criterion. Criterion parameters may be defined and patches can be manually adjusted. To illustrate, a patch must contain five triangles and the adjacent triangles must not deviate more than 10 degrees of orientation. Furthermore, LiDAR processing software can plot patches as single points of average orientations to a stereonet as well as allow integration between the stereonet and the point cloud.

In Tucson, Arizona, researchers compared traditional, manually-collected scanline mapping with LiDAR generated results. Most of the time saved was during data collection; it required 45 minutes of LiDAR setup and scanning as opposed to 4 hours by traditional collection. The results showed a high degree of correlation between the two methods.



Major Findings and Limitations

- Delineating joint sets from stereonet data is complex and interpretation often requires additional field work; LiDAR software allows the user to go back and forth between the stereonet and the point cloud to determine the delineation of important fractures and fracture sets.
- When compared to manual scanline mapping, LiDAR significantly reduces the collection time of rock slope characterization and generates more fracture poles.
- The shapes of the fracture sets are represented with high definition when using LiDAR data.
- When utilizing LiDAR, fracture surface scanning depends on the laser resolution, the size of the fracture, and the orientation of the fracture.

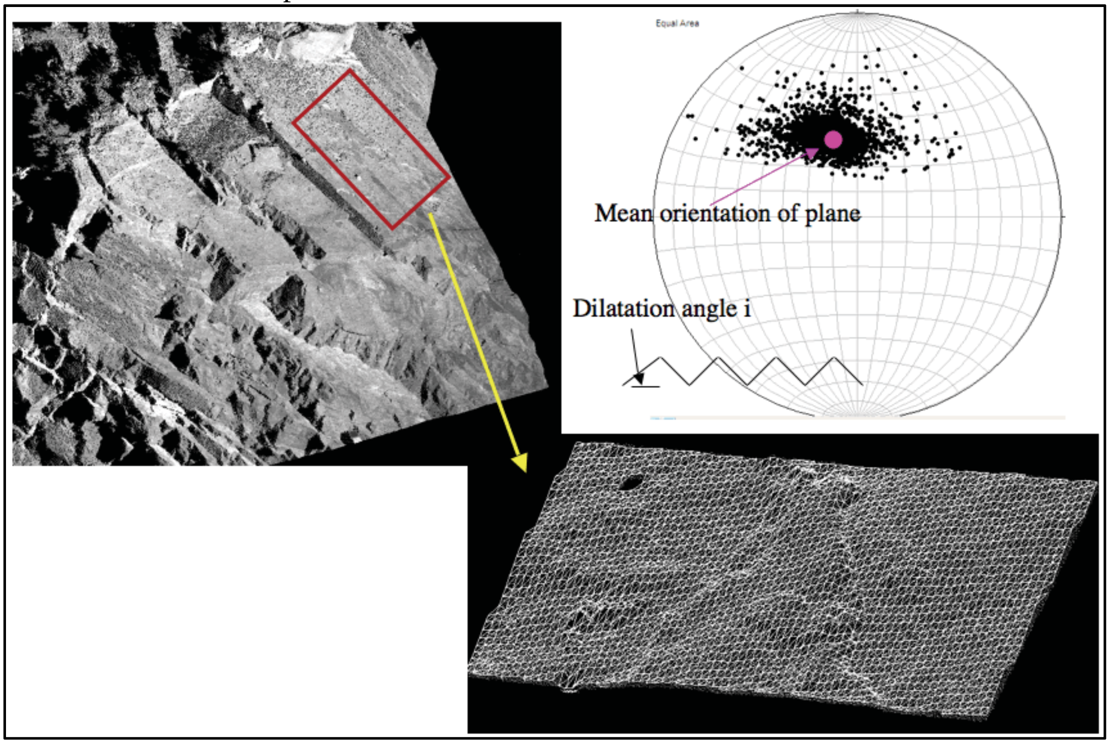
Kemeny, John and Turner, Keith (2008). *Ground-Based LiDAR: Rock Slope Mapping and Assessment*. Report Number FHWA-CFL/TD-08-006. Federal Highway Administration. United States Department of Transportation.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Rock Mass Characterization – Discontinuity Roughness
Location(s):	United States
Study Period:	2008
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Rock mass characterization is the process of obtaining data for rock slope stability, and is currently collected manually on highway slopes and rock outcrops. There are two methods to extract discontinuity roughness from LiDAR data. The first requires the triangulated mesh mapping of a point cloud and plotting triangle orientations onto a stereonet. The scatter about the mean orientation of a facture provides the dilatation angle, which directly relates to the additional friction angle due to roughness. Scale-dependent roughness can be determined by varying the size of the triangles. The second method obtains roughness measurements by making cross-sections through a fracture at different angles; the roughness profiles are calculated from the triangulated surface. Using the two-dimensional roughness profiles, published methods for extracting fracture roughness can then be implemented. Currently, the first method of plotting a point cloud to a stereonet is preferred.



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Major Findings and Limitations

- When varying triangle size to determine scale-dependent roughness, the triangle size must be greater than the scanner error so to eliminate or minimize measurement error.

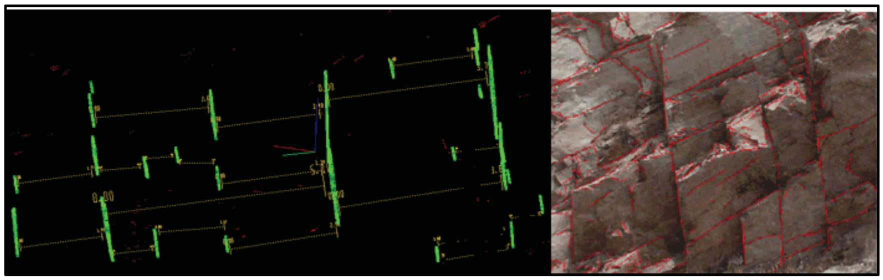
Kemeny, John and Turner, Keith (2008). *Ground-Based LiDAR: Rock Slope Mapping and Assessment*. Report Number FHWA-CFL/TD-08-006. Federal Highway Administration. United States Department of Transportation.

LiDAR Application Case Study – Geotechnical Engineering

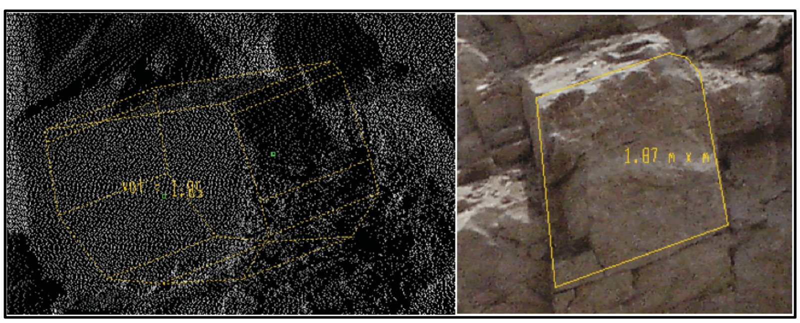
Application:	Rock Mass Characterization – Fracture Length and Spacing and Block Size
Location(s):	United States
Study Period:	2008
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Rock mass characterization is the process of obtaining data for rock slope stability, and is currently collected manually on highway slopes and rock outcrops. Fracture length and fracture spacing can be measured from LiDAR point clouds or digital images. In two-dimensional images, fracture spacing is known as "apparent" spacing and must be corrected with the true average orientation of joint sets; whereas, in three-dimensional models such as point clouds with draped digital images, the true spacing can be taken directly by measuring perpendicular to the average strike of the fracture set.



Parameters of block size are dependent on the interaction of all joint sets in a fracture network. Similarly to fracture length and spacing, block sizes can be extracted from either two or three dimensions. When using digital images, the block surface area is measured and converted into a volume by estimating the depth of the rock block in the third dimension. Accordingly, volume measurements can be directly taken from three dimensional point clouds produced by LiDAR.



Major Findings and Limitations

- For fracture length and spacing measurements, automatic trace delineation software is not recommended for the following reasons: (1) statistical parameters for assigning fractures to joint sets will require hand editing; (2) automatic algorithms will never do a perfect job with images as complex as rock outcrops; and (3) delineating fractures manually is fairly straightforward and does not take very long.
- For block delineation and distribution of block volumes, rock bridges must be identified. Hand-editing tools are recommended for the identification of rock bridges.

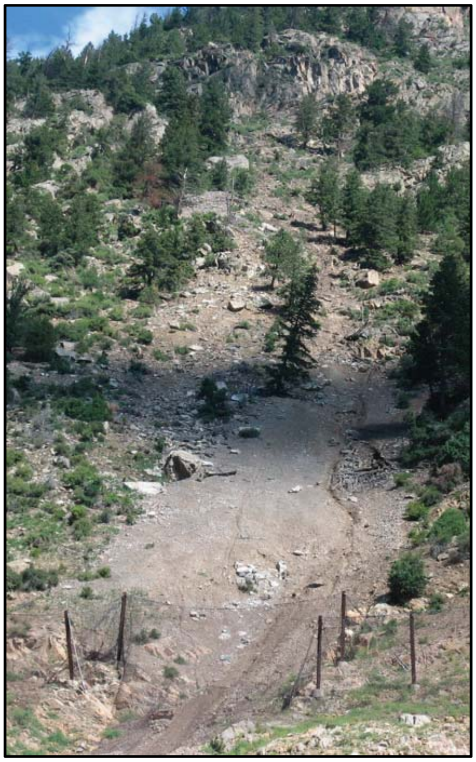
Kemeny, John and Turner, Keith (2008). *Ground-Based LiDAR: Rock Slope Mapping and Assessment*. Report Number FHWA-CFL/TD-08-006. Federal Highway Administration. United States Department of Transportation.

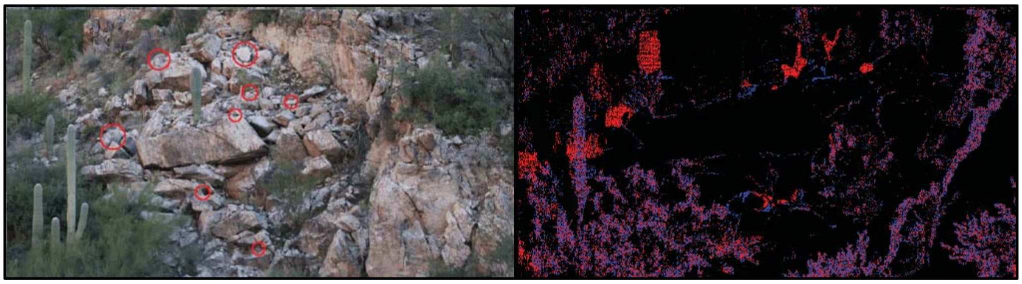
LiDAR Application Case Study – Geotechnical Engineering

Application:	Rockfall Characterization – Source Areas, Rockfall Chutes, and Occurrence
Location(s):	United States
Study Period:	2008
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Rockfall characterization is the process of locating rockfall source areas, modeling rockfall chutes, and monitoring rockfall occurrences. By using LiDAR data to characterize rock masses, rockfall sources can be located to determine risks of rockfall or slope instability. Additionally, repeated scans over time could potentially be used to monitor the weathering of a rock slope. In cases where a rock block dislodges from its source area, the block generally travels along a developed path or chute. Topographic profiles of rockfall chutes can be created using LiDAR cross-sections, which in turn can assist in the design of rockfall fences or ditches. Generally, as a rock block dislodges, it generally does not travel to its final resting place; the travel process is time-dependent and may occur incrementally. Taking LiDAR scans of the same rock slope at intervals over time is a viable method of rockfall monitoring. Change detection in point cloud software can track rock block movement, the size of moving blocks, and the total accumulated rockfall (i.e. rockfall rate). Along with the design of safety measures, rockfall monitoring can assist with fence and ditch maintenance which depends on the rockfall rate.





Major Findings and Limitations

- When monitoring change, point cloud processing software subtracts two point clouds to produce a "difference cloud," the relative difference can locate movement and quantify rockfall volume. The two point clouds must be aligned accurately.

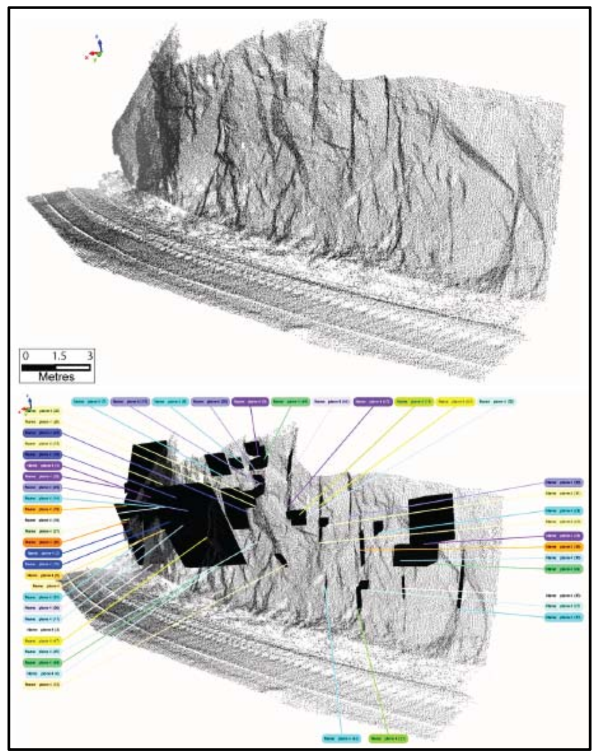
Kemeny, John and Turner, Keith (2008). *Ground-Based LiDAR: Rock Slope Mapping and Assessment*. Report Number FHWA-CFL/TD-08-006. Federal Highway Administration. United States Department of Transportation.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Geotechnical - Rockfall Hazard Analysis
Location(s):	Ottawa and Northern Ontario
Study Period:	2008
Equipment:	Mobile-Terrestrial and Fixed-Terrestrial LiDAR

Study Description

Lato et al. identified potential rockfall locations along a railroad by using a mobile LiDAR system. Mobile LiDAR was chosen as the method of surveying for its ability to measure slope height, angle, and profile without physically climbing the rock face. A Terrapoint TITAN scanner was mounted on a high-rail truck (i.e. a truck with track wheels) to collect data along a 20 kilometer stretch of railway. Collection time was five hours. The point cloud was collected at 40,000 points per second with global and local accuracies of 15 and 3 centimeters, respectively. The file size was 15 gigabytes.



To improve the accuracy of the mobile LiDAR data, a fixed-terrestrial scan was completed using a Leica HDS 6000 LiDAR system. Both mobile and fixed LiDAR data were processed in PolyWorks software. The fusion of the mobile and fixed scans was used to accurately monitor changes in volumes on the rock face. After manually removing rocks between scans, results concluded that both mobile and fixed LiDAR can detect small volumetric rock changes (less than 15 centimeters), which is valuable for monitoring progressive failure on railway side slopes. This study led to other possible applications of LiDAR such as rockfall modeling.

Major Findings and Limitations

- Mobile LiDAR demonstrates significant advantages over fixed LiDAR including coverage, acquisition rate, dynamic collection, and corridor operation integration.
- As the cost of LiDAR decreases and the technology improves over time, LiDAR integration into active rail usage may be realized. Trains equipped with scanners could potentially produce real-time differential models and hazard maps to characterize rock mass and rockfall areas along rail lines.

Lato, M. Hutchinson, J., Miederichs, M. Ball, D., Harrap, R. (2009). *Engineering monitoring of rock fall hazards along transportation corridors: using mobile terrestrial LiDAR*. Natural Hazards and Earth System Sciences. June 23, 2009.

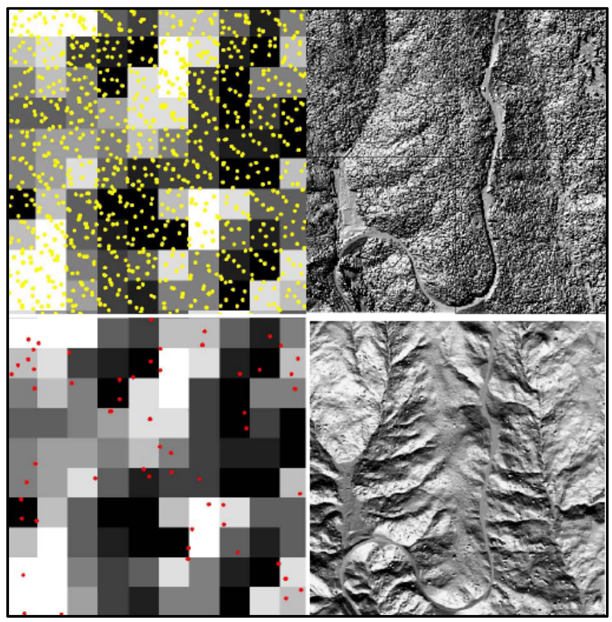
LiDAR Application Case Study – Geotechnical Engineering

Application:	Landslide Mapping
Location(s):	California
Study Period:	2003
Equipment:	Airborne LiDAR

Study Description

Mapping heavily forested, mountainous terrain for rockfalls requires substantial field effort. The distinct features of landslides must be identified and characterized through aerial photography, topographic maps, and field reconnaissance. In heavily forested terrain, aerial photos and topographic maps capture the tops of trees and use an assumed tree height to approximate ground elevations. Additional effort is required on the ground or a less accurate map is produced due to the ineffectiveness of conventional reconnaissance techniques.

Caltrans' GeoResearch Group worked with the Department of Conservation to conduct airborne LiDAR scans in 2006, mapping landslides along two heavily forested highway corridors in Humboldt and Del Norte Counties. The advantage of LiDAR was that it effectively mapped the true ground surface (i.e. last returns or "bare earth") in heavily forested areas. LiDAR data was first processed in ASCII format. This data was then processed using ArcView Spatial Analyst to generate DEMs, which were also processed in ArcView to produce shaded relief maps. Theses maps provided a bare land view, removing any vegetation that would obscure the ground view. From the shaded relief maps, slope maps were created, which were then combined with aerial photographs to prepare landslide maps.



Major Findings and Limitations

- LiDAR surveys should be used in conjunction with traditional interpretation of aerial photogrammetry and field surveys to prepare landslide maps.
- Field reconnaissance is necessary in verifying LiDAR data with actual features on the ground.

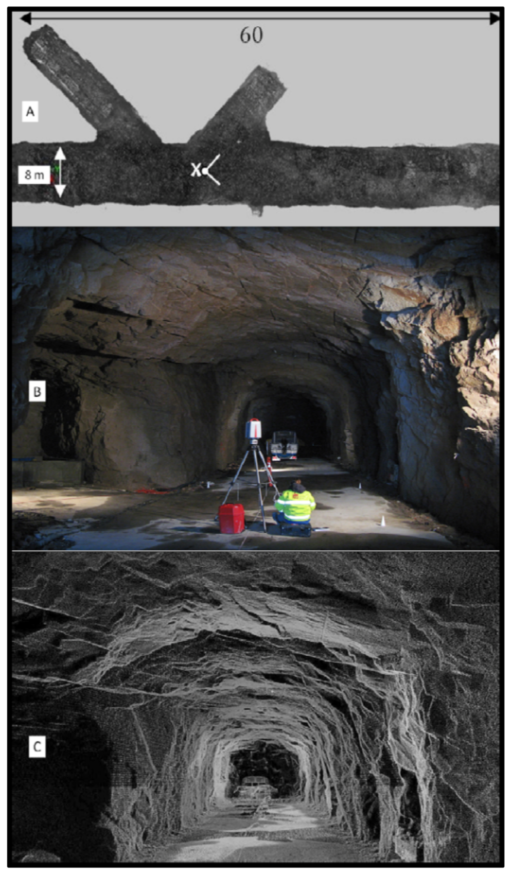
The GeoResearch Group (2003). *LiDAR Technology Provides an Advanced Tool for Landslide Mapping*. Caltrans. California.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Drill and Blast Tunnels
Location(s):	Ontario, Canada
Study Period:	2010
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Fekete proposed LiDAR as a tool for geotechnical assessment in drill and blast tunnels. The team suggested that a terrestrial fixed LiDAR could be set up relatively quickly and integrated into geotechnical evaluation without interrupting the excavation cycle. The operational applications included data extraction of tunnel geometry and installed support, which were processed for liner geometry, shotcrete thickness, overbreak analysis, verification of supports, scaling assessment, and leakage zone evaluation. Furthermore, geomechanical information extracted from LiDAR data was used for modeling elements in rock mass characterization; attributes included joint orientation and position, discrete discontinuity of rock faces, joint set spacing and large-scale joint surface characterization. Applications can be useful to construction contractors, on-site engineers, geotechnical engineers, and geologists.



Major Findings and Limitations

- With a traditional tripod setup, a complete scan for geotechnical evaluation can be conducted relatively quickly without having to suspend construction operations.
- LiDAR can be used to document final rock or liner geometry for monitoring purposes; by scanning a tunnel section at intervals over a period of time, tunnel deformation can be tracked and quantitatively compared.
- Geotechnical applications including shotcrete thickness calculations, as-built bolt density, and overbreak analysis can be implemented without significant processing.
- Geotechnical assessment methods originally developed for photogrammetry can be integrated into processing LiDAR data.

Fekete, S. (2010). *Geotechnical Application of LiDAR for Geomechanical Characterization in Drill and Blast Tunnels and Representative 3-Deimensional Discontinuum Modeling*. Department of Geological Sciences and Geological Engineering. Queen's University. Ontario, Canada.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Slope Stability of Erosion Control Devices
Location(s):	Oregon
Study Period:	2012
Equipment:	Fixed-Terrestrial LiDAR

Study Description

On project sites, straw wattles are common erosion control devices used to filter sediment from storm water run-off. During an Oregon highway realignment project, several surficial slope failures occurred on steep slopes (1.5H:1V) bracketed by straw wattles. A research team used fixed-terrestrial LiDAR to monitor and assess the effects of straw wattle placement on surficial slope stability. A three-dimensional point cloud was created and used to verify the proper horizontal installment of straw wattles along slope contours. Additionally, LiDAR point clouds were used to determine fill slope inclination angles; measure embankment slope heights; observe straw wattle contour elevations and spacing; measure failure depths and verify that failures were surficial; and establish baseline models of the slopes. Scans documented deformations that were generally less than 2 feet deep. Resulting LiDAR measurements, laboratory testing, and slope stability modeling concluded that fill slopes were constructed in accordance with design and that straw wattles had very minor effects on slope stability.

Major Findings and Limitations

- LiDAR point clouds can be used to identify localized areas of sagging on fill slopes in order to assess the mounding of water.

Olsen, M., Rikli, A., and Sillars, D. (2012). *Investigation of Straw Wattle Influence on Surficial Slope Stability*. Proceedings from TRB 91st Annual Meeting. Transportation Research Board. Washington, DC.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Structural Health Monitoring
Location(s):	Oslo, Norway
Study Period:	2011
Equipment:	Fixed-Terrestrial LiDAR Scanner (Phase-based)

Study Description

In 2011, the Norwegian Geotechnical Institute (NGI) investigated the structural status of a large number of buildings within the commercial district of Olso, Norway that built their foundations on black shale. When exposed to air and moisture, black shale can react in a volatile manner, exerting stress in buildings that can cause wall cracking and settlement. Investigators used LiDAR to document the condition of the structures and to design potential solutions.

LiDAR enabled the Norwegian Geotechnical Institute to effectively investigate characteristics of ground heave with minimal disturbance. NGI used a phase-based Far Photon 120 scanner, which collects faster at shorter ranges than time-of-flight scanners. It scanned at a rate of a million points per second, with an absolute accuracy of 5 millimeters at 25 meters. Post-processing was conducted using PolyWorks.

LiDAR was used to aid NGI in the determination of building stability with two main analyses: deformation and temporal modeling. Deformation analysis, NGI's primary analysis, included scanning load bearing walls at multiple angles, compiling the data into a single surface model, and comparing the model to a planar surface to see any deformations. Temporal analysis consisted of taking multiple LiDAR scans at different times to determine if the wall was continually deforming or if it had stabilized. If the region was continually deforming, they could calculate the rate and magnitude of deformation.

Major Findings and Limitations

- The two main analyses for building stability are deformation and temporal monitoring.
- Deformation is identified by zones in which walls and ceilings do not conform to a planar surface, while temporal monitoring refers to the time-dependent rate and magnitude of deformation or stabilization.

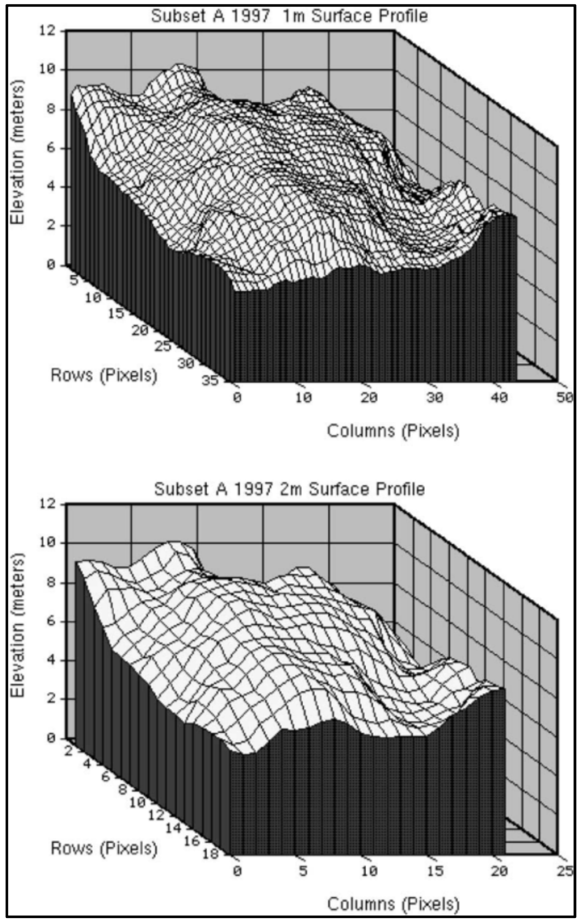
Lato, M. and Endre, E. (2011). *Investigating the applicability of LiDAR in the Detection of Ground Heave and Settlements in Building Foundation Stressed by Reactive Black Shale*. Proceedings from the 2011 Pan-Am CGS Geotechnical Conference. Toronto, Ontario. Canada.

LiDAR Application Case Study – Geotechnical Engineering

Application:	Volumetric Change of Dunes
Location(s):	Cape Hatteras, NC
Study Period:	2002
Equipment:	Airborne LiDAR

Study Description

Airborne LiDAR data was collected by the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the US Geological Survey on two site locations in Cape Hatteras, NC in 1997 to determine optimal resolution settings to detect volumetric changes. Both sites were 100 by 200 meters and were located north of Oregon Inlet on the Outer Banks of North Carolina. Data obtained in a raw ASCII format were processed into a GIS database. The grid tools in ArcGIS were applied to produce a gridded representation of the data, and ArcView was used for a portion of the analysis. It was determined that a resolution of one to two meters provided the most reliable representation of the dunes to measure volumetric changes.



Major Findings and Limitations

- With the use of spatial statistics, airborne LiDAR data can provide better understanding of coastal dune systems and characterize the structural complexity of dunes.
- When defining the required resolution, the optimum for volumetric change analysis occurs below the threshold of maximum variability.
- Due to the efficiency of data collection, LiDAR can provide more frequent data than the temporal scale of a one-year period.

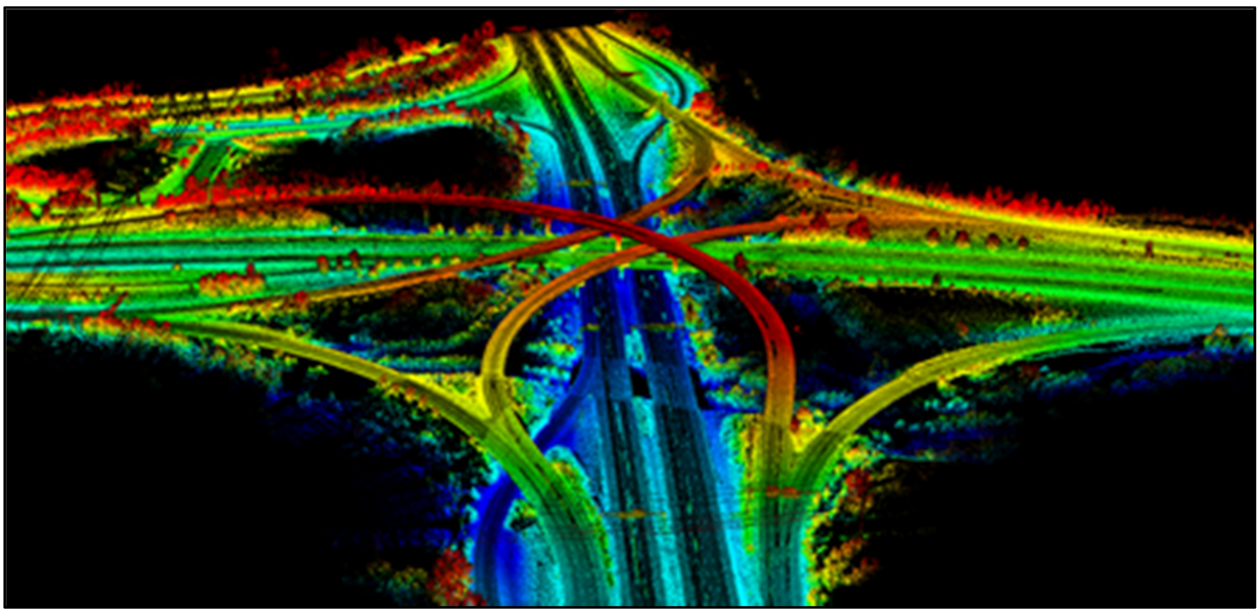
Woolard, J. and Colby, J. (2002). *Spatial Characterization, Resolution, and Volumetric Change of Coastal Dunes Using Airborne LiDAR: Cape Hatteras, North Carolina*. Geomorphology 48, 269-287. Elsevier. New York, NY.

LiDAR Application Case Study – Highway Design and Corridor Mapping

Application:	Highway Design Improvements
Location(s):	North Carolina
Study Period:	2008
Equipment:	Mobile LiDAR

Study Description

In 2008, McKim & Creed, a leading regional survey and engineering firm in North Carolina, was contracted by the North Carolina Department of Transportation in 2009 to safely survey five sections of busy and intricate interstate highways. McKim & Creed worked with Terrapoint to use the TITAN mobile system to collect a section of interstate near Raleigh, NC. The 5 projects around North Carolina were completed in 9 days, a task that normally would have taken over 50 days. McKim & Creed processed LiDAR data into design drawing deliverables for NCDOT. These drawings were then used by NCDOT to design highway improvements.



Major Findings and Limitations

- When compared to traditional surveying results, mobile LiDAR met or exceeded survey and engineering specifications.
- Five major sections of interstate highways were scanned within 9 days, as opposed to the 50+ days fixed-terrestrial LiDAR would have required.

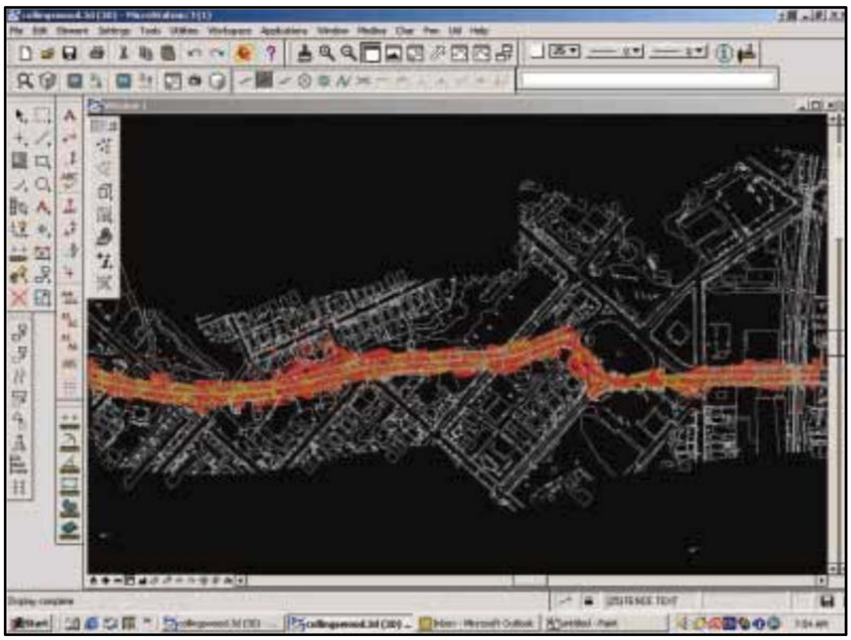
Mabey, Samantha (2009). *McKim & Creed Deploy TITAN for mobile LiDAR Scanning of Five Major Sections of North Carolina DOT Highways.* Ambercore. Houston, Texas.

LiDAR Application Case Study – Highway Design and Corridor Mapping

Application:	Highway Elevations and Cross-sections
Location(s):	New Jersey
Study Period:	2002
Equipment:	Fixed-Terrestrial LiDAR

Study Description

Medina Consultants was contracted in 2002 by the New Jersey Department of Transportation (NJDOT) to provide accurate cross-sections and digital terrain models of an existing six-lane roadway. NJDOT was tasked with replacing a traffic circle at a heavy traffic interstate at state routes 30 and 130, along approximately 6,500 feet of road. Medina Consultants used Cyrax 2500, a fixed-terrestrial system, to collect data at 150-foot intervals along each side of the roadway. 46 scans were taken at ranges between 160 and 170 feet with a minimum point density of 305 per square inch, and yielded relative accuracies within 0.25 inches. It took 15 days using multiple processing software to analyze data. By only taking 5 nights (7pm - 6am) and 4 workers, the team cut field labor costs in half and saved $24,000 in road closure fees. The scans provided more cross-sections at closer intervals, accurate three-dimensional elevations, and other valuable information.



Major Findings and Limitations

- The NJDOT saved money in road closure fees and cut field labor costs by contracting LiDAR for highway surveying.
- LiDAR scans provided accurate elevation data to derive digital terrain models and produce topographic maps.
- The high detail provided more cross-sections at closer intervals, three-dimensional elevations, and additional locational information for future use.
- Off-road setup and scanning reduced safety hazards to field personnel and avoided having to halt traffic operations.

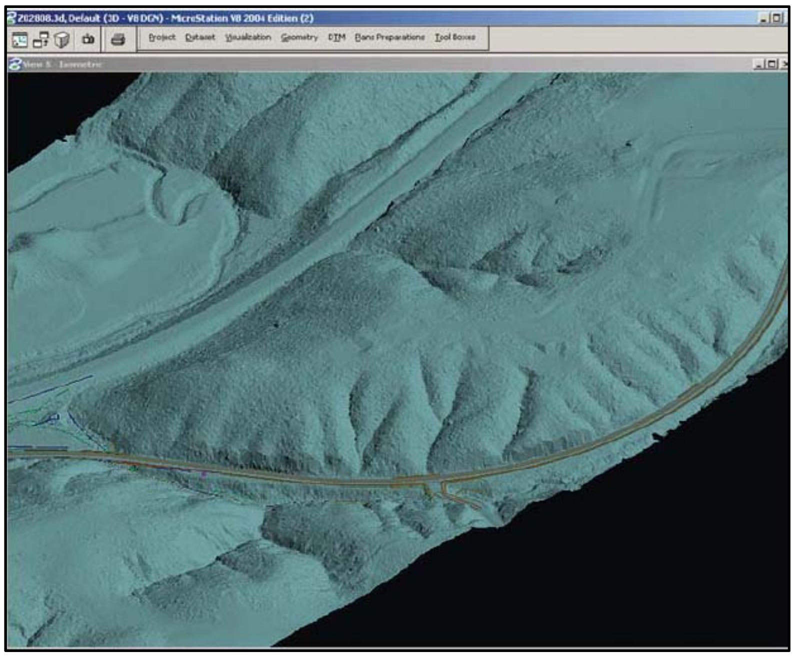
Moscetti, K. and Vespremi, L. (2002). *High-Definition Survey Provide Accurate DTM and Cross Sections of Busy Highway*. High Definition Survey. Medina Consultants.

LiDAR Application Case Study – Highway Design and Corridor Mapping

Application:	Topographic Route Survey
Location(s):	Illinois
Study Period:	2009
Equipment:	Airborne and Terrestrial LiDAR

Study Description

In 2009, the Illinois DOT contracted Sanborn to survey a mile of US Highway 20 as a pilot project for topographic route surveying. Culverts on the site needed replacement and the center line of US Highway 20 East was to be relocated adjacent to US Highway 20 West. This highway presented hazardous conditions with a rock bluff on the north side of the project and a steep slope on the south side. Sanborn used ground-based fixed and mobile LiDAR to conduct the topographic survey; the absolute accuracies were within 0.02 and 0.10 feet, respectively. The scans and derived information were produced to meet survey standards and specifications required by the state agency. The LiDAR data collected was combined with past information from traditional surveys, available airborne LiDAR, and photogrammetry to extract roadway assets, survey features, and three-dimensional images. The end product was delivered in formats compatible with Microstation and Geopak.



Major Findings and Limitations

- LiDAR can be supplemented with traditional survey for items limited by sight, establishing controls, and quality control.
- For LiDAR-derived contour maps, the removal of erroneous, non-terrain points and use of specific key points rather than all available points can reduce the size of a point cloud to 10 or 25 percent of the origin dataset.
- Non-terrain points can be used to locate topographic features but should be filtered before producing bare earth surfaces.

Peterson, J. (2009). *Survey from Sanborn Terrestrial and Aerial LiDAR*. Case Study for Illinois Department of Transportation (IDOT). The Sanborn Map Company, Inc. St. Louis, Missouri.

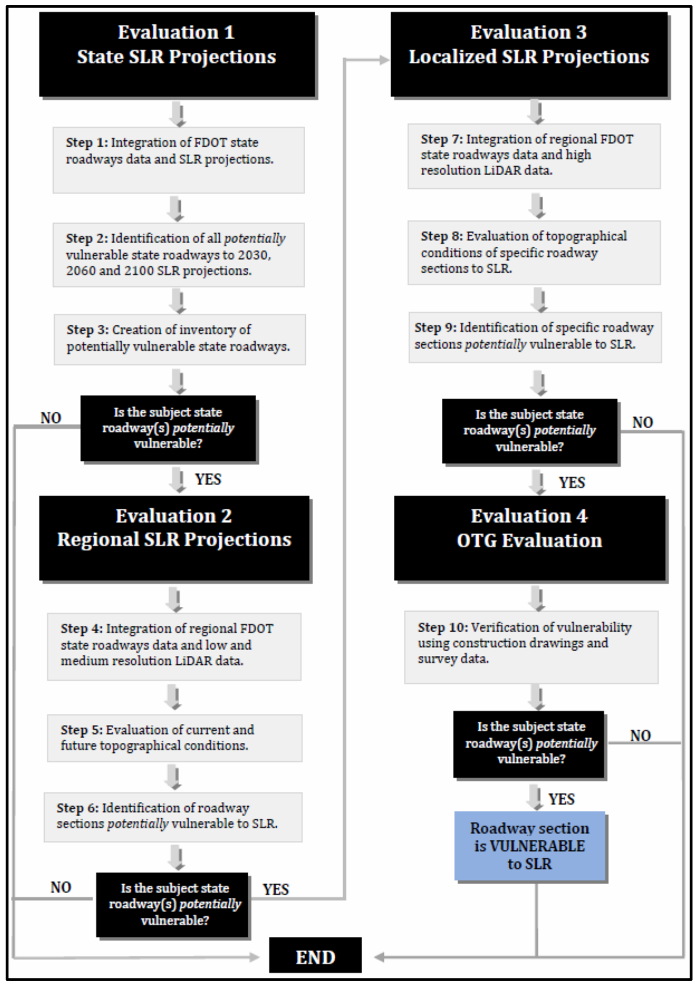
LiDAR Application Case Study – Hydraulics and Hydrology

Application:	Digital Elevation Model and Geographic Information System
Location(s):	Los Angeles and Long Beach, CA
Study Period:	2011
Equipment:	Airborne LiDAR

Study Description

In coastal regions, critical transportation infrastructure is vulnerable to sea level rise (SLR). Flooding can weaken the base of roadways and the structural integrity of transportation facilities. Additionally, infrastructure not physically damaged by flooding may experience traffic operation and management issues through secondary impacts. A team of researchers at Florida Atlantic University developed a methodology using ArcGIS to integrate LiDAR, topographic, and on-the-ground data to project SLR and evaluate the vulnerability of transportation infrastructure.

In Florida, LiDAR information is collected by Florida Division of Emergency Management and processed by supporting agencies and educational institutions. High resolution LiDAR data having a vertical accuracy within seven inches was used for analysis. Raw LAS format data translated from geographically referenced XYZ coordinates in ASCII format was used because the compatibility with ArcGIS. With GIS software, the team conducted evaluation of topographical conditions of specific roadways to identify sections potentially vulnerable to sea level rise.



Major Findings and Limitations

- Vertical accuracy of LiDAR data is a critical concern as large vertical contours are not useful for analyzing sea level rise or flooding incidents. Low and medium resolution LiDAR having vertical accuracies greater than 1 meter are not useful for climate change modeling.

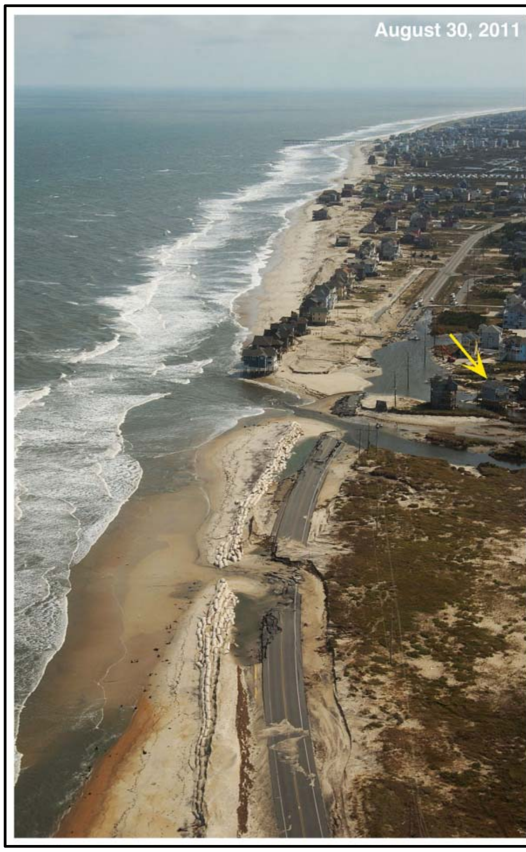
Berry, L. and Arockiasamy, M. (2012). *Development of a Methodology for the Assessment of Sea Level Rise Impacts on Florida's Transportation Modes and Infrastructure*. FDOT Contract BDK79 977-01 Final Report. Florida Department of Transportation. Tallahassee, FL.

LiDAR Application Case Study – Hydraulics and Hydrology

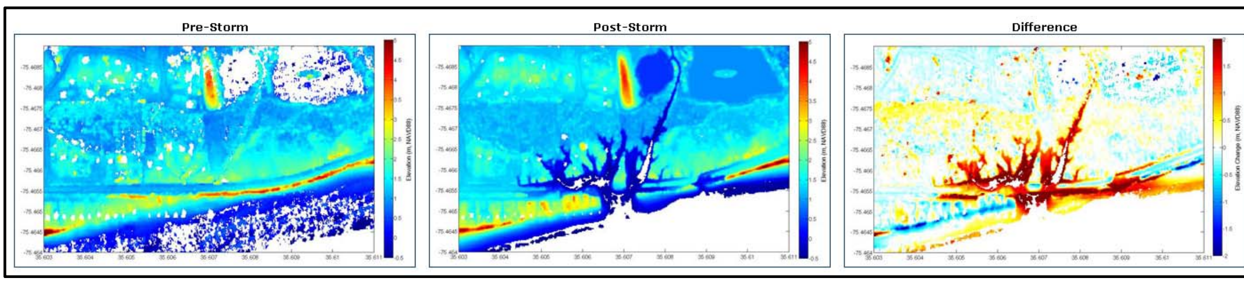
Application:	Coastal Change from Hurricanes and Storms
Location(s):	Outer Banks, NC
Study Period:	2011
Equipment:	Airborne LiDAR

Study Description

The landfall of Hurricane Irene brought elevated water levels, tidal waves, and currents that led to major beach erosion and island breaching on the Outer Banks of North Carolina. As a result, sections of NC Highway 12 were severed at 2 locations. A storm-impact scale developed by the United States Geological Survey was used to compare hurricane-induced water levels with known coastal topography to define four coastal change regimes. A post-storm assessment of Hurricane Irene was carried out to determine the occurrences of collision, overwash, or inundation regimes based on erosion and deposition patterns. The assessment examined storm surge water levels and LiDAR-derived dune and berm elevations.



A post-storm LiDAR survey was completed on August 28, 2011 and compared to a LiDAR scan performed in 2009. By overlaying a pre-storm and post-storm scans, researchers could quantify coastal change and characterize the nature, magnitude, and spatial variability of Hurricane Irene.



Major Findings and Limitations

- From point cloud image differences, a meter of vertical erosion was found at beaches that were breached.

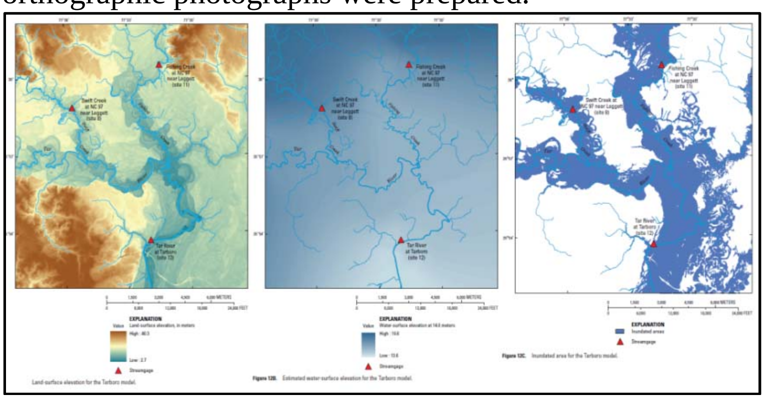
United States Geological Survey (2011). *Hurricane Irene – Pre-storm 3D LiDAR Topography: Outer Banks, NC*. Coastal Change Hazards: Hurricanes and Extreme Storms. St. Petersburg Coastal Marine Science Center. www.USGS.gov.

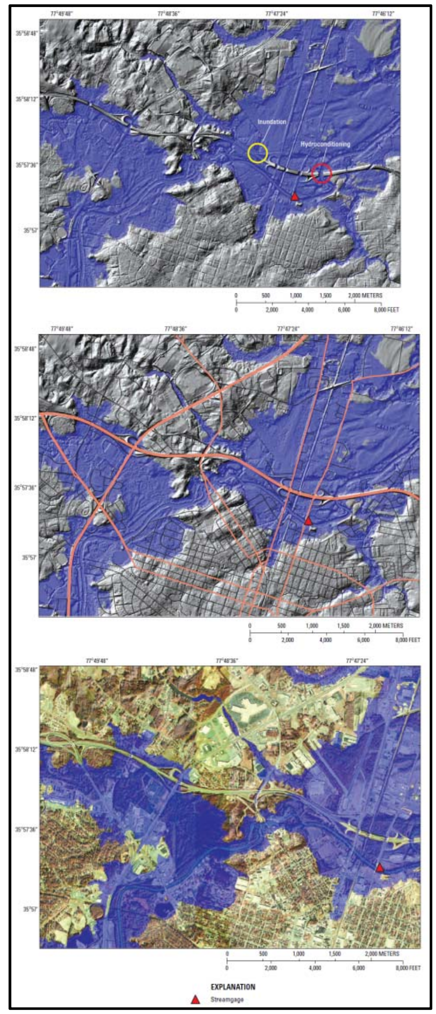
LiDAR Application Case Study – Hydraulics and Hydrology

Application:	Flood Mapping and Inundation Maps
Location(s):	Tar-Pamlico River Basin, NC
Study Period:	2007
Equipment:	Airborne LiDAR

Study Description

At selected sites in North Carolina's Tar-Pamlico River basin, airborne LiDAR data was utilized to produce flood-inundation maps. The data was collected by the North Carolina Floodplain Mapping Program between January and March of 2001. The raw point data was processed to remove LiDAR returns from ground-impeding objects such as trees, buildings, and structures. Then, the filtered bare-earth LiDAR points were used to produce digital elevation models with 1.5 by 1.5 meter cells. The Hydraulic Engineering Center-River Analysis System, developed by the US Army Corps of Engineers, was used for hydraulic modeling. ArcGIS algorithms were developed to use DEMs, road information, and stream networks to automatically locate road and stream intersections, identify low elevations points, define buffer areas, create segments to connect low points, and model flow paths. Inundation maps showing transportation networks and orthographic photographs were prepared.





Major Findings and Limitations

- Bathymetric and topographic data derived from LiDAR data can be used to develop inundation models.
- Terrain elevation is the dominant influence on locating the edges of inundated area; detailed LiDAR elevation data combined with low-resolution one-dimensional hydraulic modeling provides a good representation of the edges.

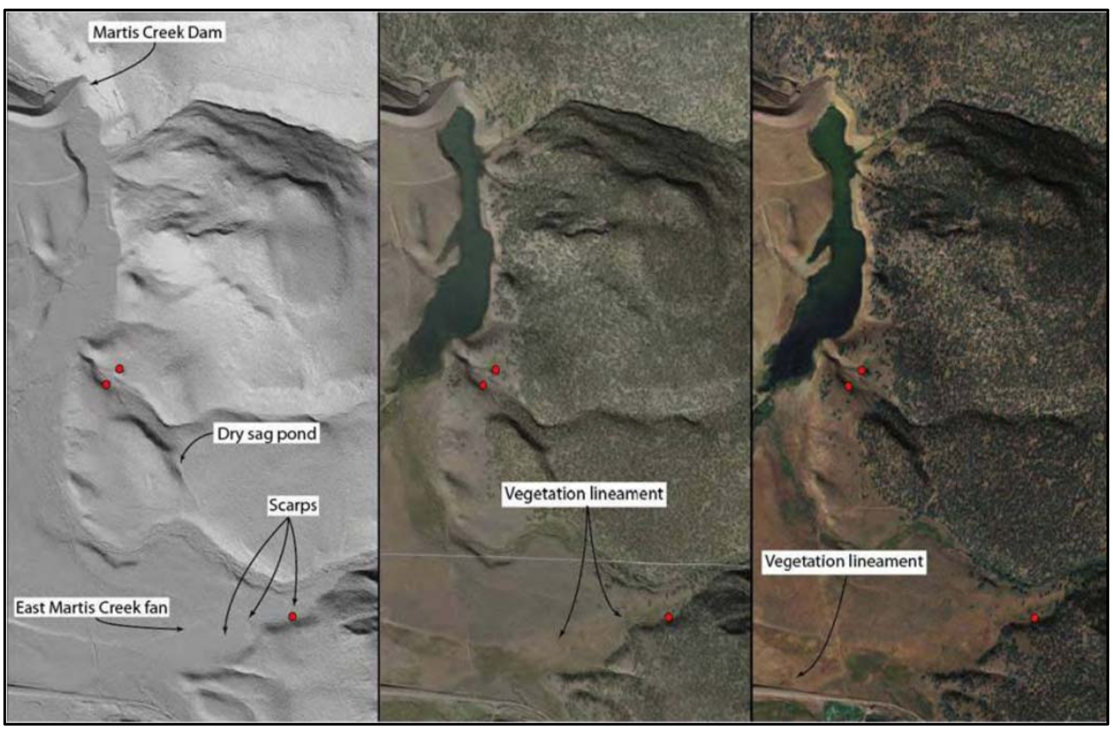
Bales, J., Wagner, C., Tighe, K., and Silvia Terziotti (2007). *LiDAR-Derived Flood-Inundation Maps for Real-Time Flood-Mapping Applications, Tar River Basin, North Carolina*. Scientific Investigations Report 2007-5032. North Carolina Floodplain Mapping Program. US Department of the Interior. US Geological Survey. Reston, VA.

LiDAR Application Case Study – Hydraulics and Hydrology

Application:	Tectonic Geomorphology Assessment
Location(s):	Lake Tahoe, California
Study Period:	2009
Equipment:	Airborne LiDAR

Study Description

California engineers used airborne LiDAR to assess Martis Creek Dam in 2009. Martis Creek Dam, located in the Truckee Basin north of Lake Tahoe in California, is one of the US Army Corps of Engineers' highest risk dams in the United States. Engineers used LiDAR data to examine tectonic geomorphology around the dam. By using one-mile tiles of LiDAR data with imagery and geomorphology, two sites were identified for paleoseismic trenching to determine if a fault line existed. At investigation sites, trenches were found to have a sharp contrast in vegetation and appeared to have a well defined scarp (a notable displacement of land surface by movement along faults) from the airborne LiDAR data. The features at the sites revealed a fault did exist, and the subsequent discovery of the Polaris Fault. This discovery has led to re-evaluation of new hazards for the Martis Creek Dam.



Major Findings and Limitations

- Comparison and combination of photogrammetric imagery and LiDAR data provides detailed interpretation of vegetation, topographic features, and geomorphology.

Hunter, L., Rose, S., Hilton, B., McCormick, W., and Crampton, T. (2009). Use of Hi-resolution LiDAR in Discovering the Polaris Fault, Martis Creek Dam, Truckee, California. Collaborative Management of Integrated Watersheds. Unite States Society on Dams. Denver, CO.

LiDAR Application Case Study – Hydraulics and Hydrology

Application:	High Hazard Potential Dams
Location(s):	North Carolina
Study Period:	2011
Equipment:	Airborne LiDAR

Study Description

In North Carolina, Emergency Action Plans (EAPs) for high hazard potential dams are being developed to integrate high-definition airborne LiDAR data. The detail and content of inundation mapping depends on the characteristics of hazardous areas. For commercial and residential areas, along with houses and buildings, maps generally show county, state, and national roads that are at risk to flooding. Airborne LiDAR is being used to reduce the time needed for field surveys as well as provide highly accurate data for producing inundation maps. LiDAR, in combination with field survey and hydraulic/hydrologic modeling software, is used to predict key points of flooding by interpolating between elevation features.

Major Findings and Limitations

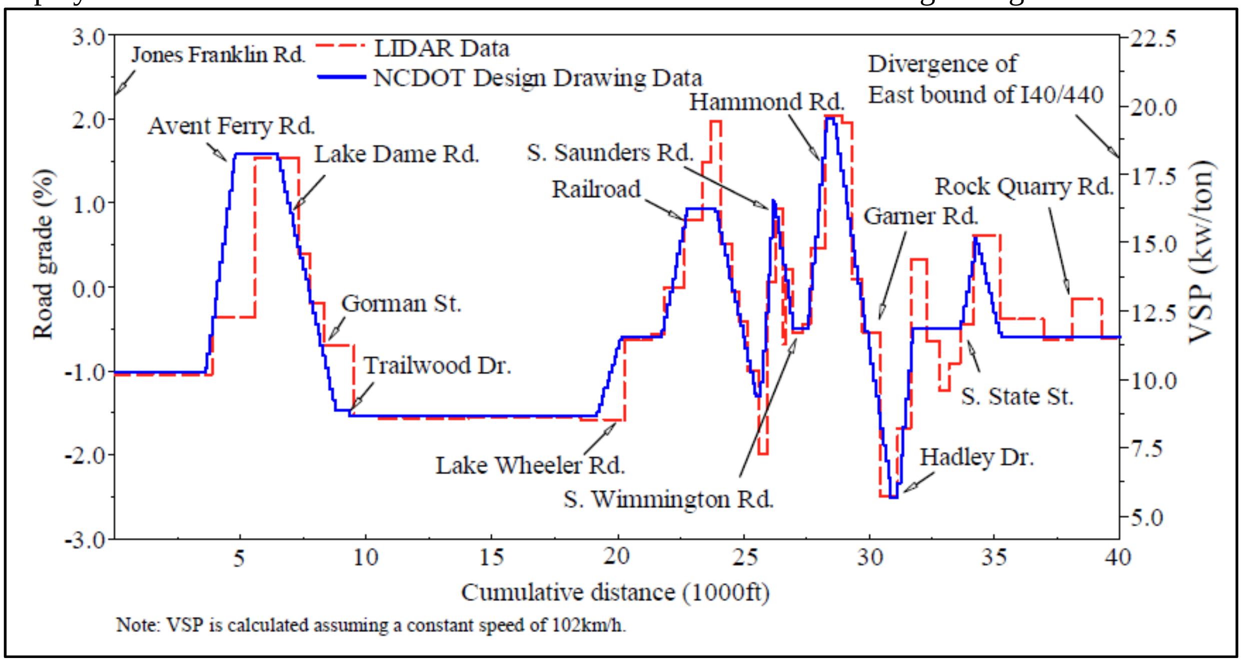
- High-resolution LiDAR provide detailed information that can be used for dam breach analyses and inundation mapping.
- The combination of LiDAR, field survey, and Hydrologic Engineering Centers River Analysis System (HEC-RAS) software/GeoRAS GIS extension is effective in modeling hazardous areas of potentially risky dams.

North Carolina Dam Safety Program (2011). *New Inundation Mapping Technology Helps EAP Development*. North Carolina Emergency Action Planning. DamSafetyAction.org.

Application:	Pavement Grade Estimations
Location(s):	North Carolina
Study Period:	2005
Equipment:	Airborne LiDAR

Study Description

Zhang and Frey conducted a study to determine if LiDAR was a viable way to estimate road-grade for vehicle specific power (VSP). VSP is calculated based on vehicle speed, acceleration, and road grade to estimate engine power demand. Using airborne LiDAR, a scan was conducted for selected segments of I-40 and I-540 in Raleigh. Estimated road grade was then compared with NCDOT design drawing data, and most of the roadway segments showed less than a 5 percent difference. A comparison graph of LiDAR data and NCDOT design drawing data is displayed below. Results concluded that LiDAR is reliable for estimating road grade.



Major Findings and Limitations

- A Geographic Information System (GIS) macro can be developed to buffer LiDAR points along roadways and calculate distances along road centerlines.
- When compared with traditional surveying methods, airborne LiDAR can provide better accuracy, denser nominal point spacing, lower costs, and ease of use when collecting elevation data.

Zhang, K. and Frey, C. (2005). *Road Grade Estimation for On-Road Vehicle Emissions Modeling Using LiDAR Data*. North Carolina State University, Department of Civil, Construction, and Environmental Engineering. Raleigh, NC.

LiDAR Application Case Study – Pavement

Application:	Pavement Cross-Slopes
Location(s):	Florida
Study Period:	2011
Equipment:	Riegl VMX-250 Mobile LiDAR

Study Description

EarthEye LLC worked with Riegl USA to scan a 9-mile stretch of I-95 for the Florida Department of Transportation (FDOT). Once LiDAR data had been collected by using a Riegl VMS-250 mobile scanner, Earth Eye generated cross-slopes at incremental distances and then exported them out as three-dimensional vectors. These vectors were then symbolized based on their cross-slope percentages and exported as a KML file (used with Google Earth and Google Maps). The KML files made it easy to visually identify problem areas and subsequent design solutions. The use of reliable LiDAR data enabled paving contractors to submit accurate proposals, which allowed FDOT to decrease project change orders and overrun costs.

Major Findings and Limitations

- Mobile LiDAR can quickly and easily be used to collect cross-slope information which can in turn generate pavement resurfacing plans.
- Accurate and relevant data of as-built pavement conditions can reduce the cost of over-engineering resurfacing or re-design pavement projects.

Amadori, Jason (2011). *Mobile LiDAR and Cross-Slope Analysis*. Jason Amadori's LIDAR GIS Blog. September 14, 2011. URL: http://jasonamadori.com /2011/04/27/mobile-lidar-and-cross-slope-analysis/.

LiDAR Application Case Study – Pavement

Application:	Pavement Resurfacing Assessment
Location(s):	Florida
Study Period:	2011
Equipment:	Riegl VMX-250 Mobile LiDAR

Study Description

EarthEye conducted mobile LiDAR scans of the Southern Connector in Orange and Osceola counties for Florida's Turnpike Enterprise (FTE) in 2009. FTE needed accurate information for milling, resurfacing, and design upgrades. Since the Southern Connector is a high-speed, congested, four-lane divided highway, traditional surveying techniques could not be implemented due to lane-closure policies and safety factors. EarthEye used the Riegl VMX-250 scanner, which collected 6.2 miles of divided highway and ramp pavement in 2 hours. The point cloud data was then used to create cross-sections of the highway for every 25-foot interval using EarthView software. Tools in EarthView were then able to measure cross-slope and profile, as seen below. Post-processing and delivery took a total of three days, and FTE later used EarthView software from EarthEye to evaluate safety-related issues such as: guardrail height, sign post offsets, light poll offsets, sign height, and roadside slopes.

Major Findings and Limitations

- Accurate data for roadway resurfacing can be collected at highway speed with two passes, one in each travel direction, using mobile LiDAR.

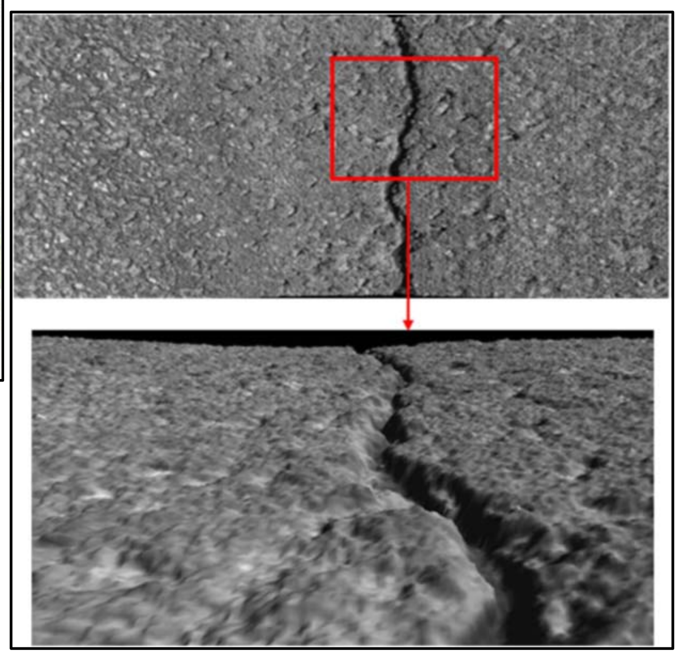
Amadori, Jason (2011). *Mobile LiDAR and Cross-Slope Analysis*. Jason Amadori's LIDAR GIS Blog. September 14, 2011. URL: http://jasonamadori.com /2011/04/27/mobile-lidar-and-cross-slope-analysis.

LiDAR Application Case Study – Pavement

Application:	Pavement Crack Detection
Location(s):	Georgia
Study Period:	2012
Equipment:	Mobile three-dimensional data acquisition system

Study Description

Ambient lighting and low intensity contrast conditions pose a challenge for two-dimensional imaging systems used for automated pavement distress detection and classification. A study conducted for the USDOT Research Innovative Technology Administration program suggested using three-dimensional laser technology to detect cracks under various lighting and intensity contrast conditions. The technology utilizes two high-performance laser profiling units that employ similar technology found in LiDAR to produce detailed three-dimensional images of the pavement being scanned. The system is mounted onto a vehicle.



Results from a controlled laboratory test and an actual field test of Georgia roadways demonstrated the abilities to effectively detect cracks two millimeters or wider; achieve consistent results throughout different lighting conditions; and detect cracks with low intensity contrast.

Major Findings and Limitations

- Mobile three-dimensional imaging systems are effective under ambient lighting and low intensity contrast conditions for automated crack detection and classification.
- Scanner tilt angle, transverse profile spacing, and sampling frequency potentially affect the crack detection capability of automated laser profiling units.

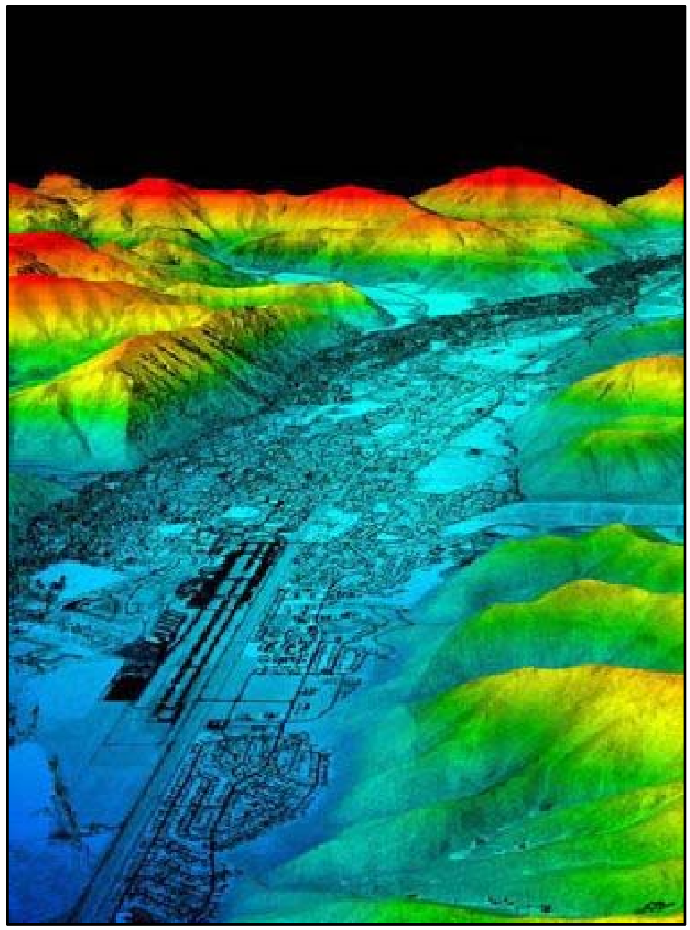
Tsai, Y. and Li, F. (2012). *Critical Assessment of Detecting Asphalt Pavement Cracks under Different Lighting and Low Intensity Contrast Conditions using Emerging 3D Laser Technology*. Journal of Transportation Engineering. American Society of Civil Engineers.

LiDAR Application Case Study – Photogrammetry

Application:	Aviation – Airport Obstruction Surveys
Location(s):	North America
Study Period:	2011
Equipment:	Airborne LiDAR

Study Description

Uddin et al. discussed the current practices in utilizing airborne LiDAR to conduct airport obstruction surveys. The research team reviewed the requirements of obstruction surveys as well as the federal standard related to airspace analysis and the airport. LiDAR survey specifications were highlighted to reflect the current capabilities of LiDAR equipment and processes, and were recommended for pilot implementation and for establishing vendor qualifications.



Major Findings and Limitations

- When compared to traditional photogrammetry-based obstruction surveys, LiDAR data analysis used to generate potential obstruction features has been successfully completed by commercial survey companies for several airport surveys at competitive costs.
- Obstructions detected by LiDAR data can be seamlessly integrated into electronic airport layout plans as GIS shape files.
- LiDAR data may be reanalyzed to generate accurate elevation models, contours for engineering design, and planimetrics for GIS mapping.

Uddin, W., Gutelius, B., Parrish, C. (2011). *Airborne Laser Survey Specification and Quality Management Protocols for Airport Obstruction Surveys*. Transportation Research Record 2214. Journal of the Transportation Research Board.

LiDAR Application Case Study – Photogrammetry

Application:	Digital Elevation Model and Geographic Information System
Location(s):	Los Angeles and Long Beach, CA
Study Period:	2011
Equipment:	Airborne LiDAR

Study Description

A research project conducted for the METRANS Transportation Center in Southern California sought to obtain, process, and develop digital elevation models (DEMs) of the Los Angeles-Long Beach Port Complex by using airborne LiDAR. Elevation data derived from LiDAR point clouds were used in the METRANS Geographic Information System. The typical procedure for developing LiDAR data derived DEMs is to use vertical elevation points from three-dimensional point clouds and interpolate between them to create a gridded surface model. The factors affecting the accuracy of DEMs derived from LiDAR data included the post-processing interpolation algorithm and the grid cell resolution. The researchers wanted to evaluate and compare the accuracy and time efficiency of various combinations of interpolation methods and grid cell resolutions. Therefore, Inverse Distance Weighted (IDW), spline, and Kriging interpolation techniques with 0.25, 0.5, 1.0, and 2.0 meters squared cell resolutions were selected for comparison.

Interpolation	Cell Size	Average RMSE	Interpolation Time (Hrs.Min)	RMSE Rank	Time Rank
IDW	0.25	0.555	123.17	1	11
IDW	0.5	0.862	18.27	3	9
IDW	1	1.078	2.33	5	4
IDW	2	1.084	0.22	6	1
Kriging	0.25	2.878	162.30	9	12
Kriging	0.5	3.127	20.18	12	10
Kriging	1	2.945	12.35	10	8
Kriging	2	3.107	9.01	11	7
Spline	0.25	0.592	7.07	2	6
Spline	0.5	0.921	4.15	4	5
Spline	1	1.253	2.08	7	3
Spline	2	1.754	1.05	8	2

An airborne LiDAR vender was contracted to scan and collect data over a 100 square kilometer area. The scans were taken in 2005 and 2006 at 3000 feet above the port complex. There were approximately 121 million points and 57 gigabytes in size. Research concluded the Inverse Distance Weighted interpolation technique with grid cells of 0.25 meter resolution produced the most accurate DEMs, but took the most significant amount of time for processing. Whereas, the best compromise between time and accuracy was found with the spline method at 0.25 meter resolution. The table shows the RSME values and the processing time for each combination of interpolation technique and resolution

Major Findings and Limitations

- When considering DEMs derived from LiDAR data, interpolation accuracy, interpolation time and the accuracy of features extrapolated from the derived surfaces must be prioritized in order to select the most valuable interpolation method and grid cell resolution.
- LiDAR data are expensive, but freely available DEMs derived from LiDAR are available from the USGS.

Wechsler, S. P. (2011) *Development of a LiDAR Derived Digital Elevation Model (DEM) as Input to a METRANS Geographic Information System*. Department of Geography, College of Liberal Arts. California State University. Long Beach, CA.

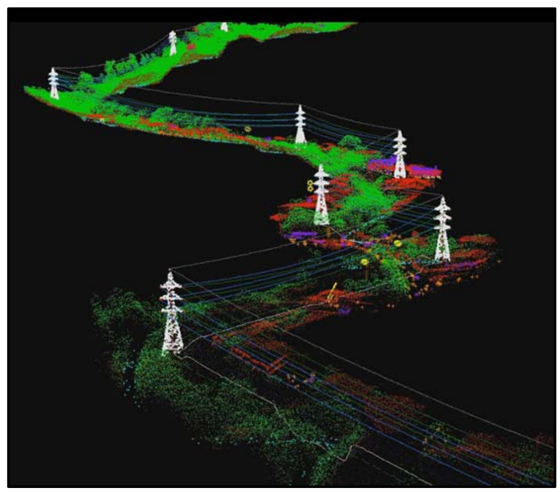
LiDAR Application Case Study – Photogrammetry

Application:	Electric Transmission Line Surveys
Location(s):	North America
Study Period:	2005
Equipment:	Airborne LiDAR

Study Description

Airborne LiDAR is a proven technology for producing accurate elevation and as-built models of transmission lines. During a scan, the ground below the transmission line, the position of towers and poles, the wire and wire sag, and the incursions within the right of way can be collected. Currently there are no other efficient ways of accurately measuring the actual height of transmission lines above the ground. Generally, for mapping transmission lines, the absolute accuracy is within 6 inches and the relative within 3 inches. Along with a point cloud, digital images are simultaneously captured to provide information of the conditions within the right of way.

Superseding data collection, quality control processing should be carried out to ensure completeness and integrity of scan coverage. If data does not meet specifications, the survey crew should isolate problems and re-fly areas if necessary. For post-processing, the combination of scans and digital images can be characterized into three separate files: ground elevation/surface files, vegetation files, and conductor files. The files can be used individually or combined for measurements and analysis of elevations, locations, and change in wire sag.



Major Findings and Limitations

- Individual digital photographs are registered with its center point having a GPS coordinate. Sets of photographs can be rectified in a mosaic by locating images into a superior UTM coordinate system.
- With the use of LiDAR, engineering designs and placement of towers or poles can be done within the office.
- Associated costs generally depend on the straightness of power line paths. Major power lines with relatively few bends cost less, because the aircraft or helicopter pilot may fly faster with fewer navigational changes.

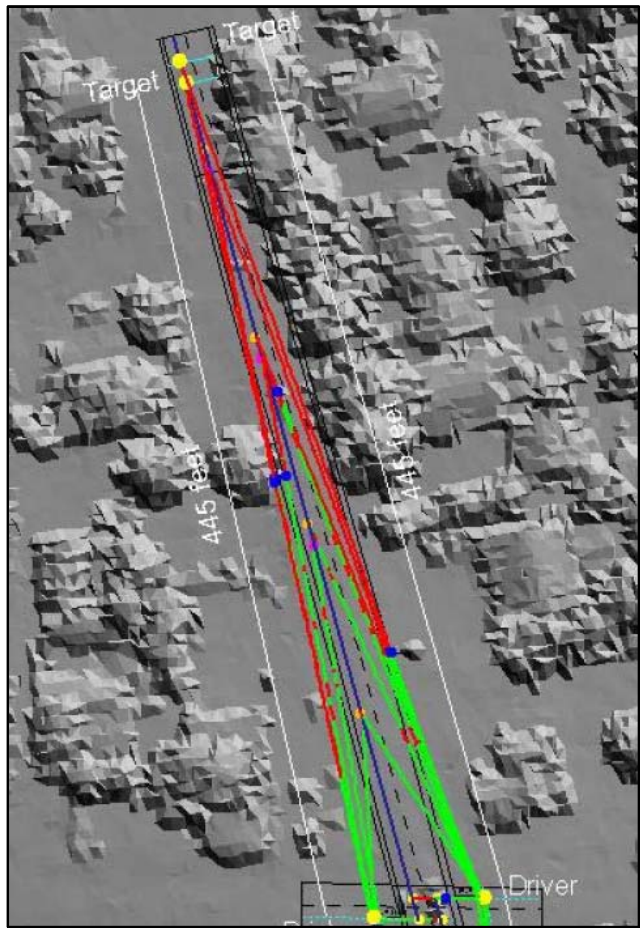
Mangold, R. (2005). *Airborne LiDAR Surveys Electric Transmission Lines*. Spatial Resources. Centennial, CO.

LiDAR Application Case Study – Safety and Mobility

Application:	Intersection Obstructions and Sight Distances – Line-of-Sight
Location:	Iowa
Study Period:	2001 - 2003
Equipment:	Airborne LiDAR

Study Description

Khattak and Gopalakrishna conducted a study to test the reliability of LiDAR and identify potential sight distance problems for drivers. Intersection sight triangles are critical to safe intersection navigation. Iowa DOT conducted scans of the northern section of Iowa Highway 1. The research approach consisted of combining crash data, LiDAR data, and area orthographic photographs into Geographic Information System (GIS). Then a line-of-sight analysis was conducted using sight triangles as described in the AASHTO Green Book and compared the findings with a field validation. By inputting the observer location and height, target location and height, a GIS macro calculated if the observer had a clear line of sight to the target and if not, identified the locations of the obstructions. By using GIS, 66 potential sight distance obstructions were revealed, and 62 of those 66 (89.9%) were confirmed by field validation. Four of those 66 were not confirmed by field validation (5.8%). Three (4.4%) potential sight distance obstructions were discovered in the video analyses that were not detected by the line-of-sight analysis. The project cost $30,000 in labor, $3,000 in computer and camera equipment, $1,200 in software, and $35,000 in LiDAR data collection.



Major Findings and Limitations

- LiDAR was concluded to be effective in determining line-of-sight obstructions.
- Potential and actual obstructions can be correctly identified by line-of-sight analysis.
- LiDAR data quality may directly affect the analysis of intersection sight triangles.

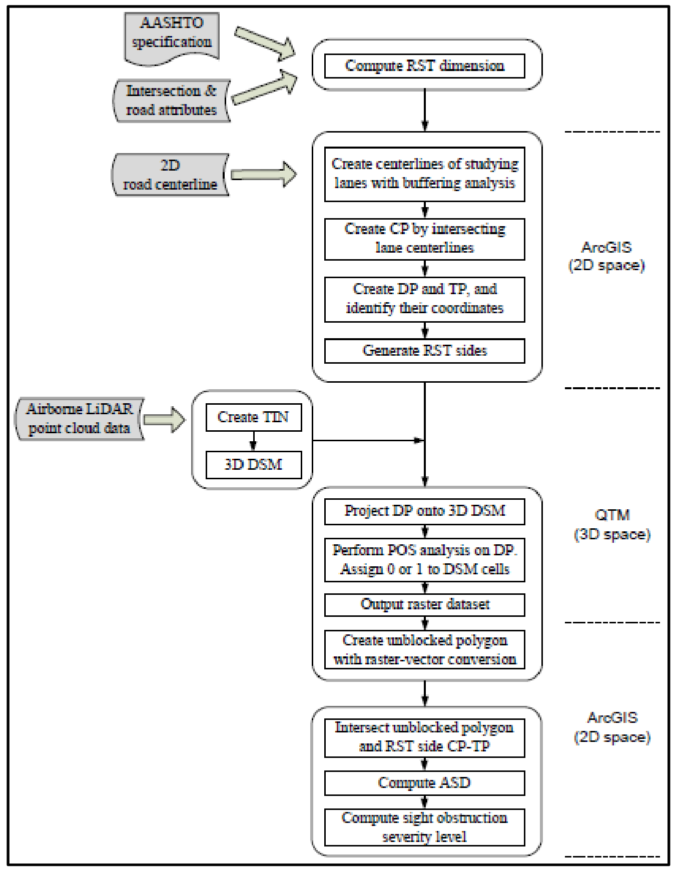
Khattak, A. and Gopalakrishna, M. (2003). *Remote Sensing (LIDAR) for Management of Highway Assets for Safety*. Mid-America Transportation Consortium. Department of Civil Engineering, University of Nebraska-Lincoln.

LiDAR Application Case Study – Safety and Mobility

Application:	Intersection Obstructions and Sight Distances – Plane-of-Sight
Location:	Savannah, Georgia
Study Period:	2008 - 2010
Equipment:	Airborne LiDAR

Study Description

The identification of obstructions and assessment of adequate sight distances are crucial for the safety evaluation at roadway intersections. Researchers assessed the feasibility of using LiDAR to locate intersection obstructions and quantify sight distances at nine right-angle, non-signalized intersections in downtown Savannah.



The methodology was as follows: (1) determine the required sight triangle at each intersection based on roadway geometry, intersection features, and AASHTO specifications; (2) plot sight triangles into a two-dimensional GIS coordinate system and locate driver decision points; (3) generate a digital surface model using three-dimensional LiDAR coordinates; (4) perform plane-of-sight (POS) analysis at each decision point defined in step 2; (5) identify sight obstructions and quantify the severity of inadequate sight distances.

Test results obtained by the aforementioned methodology correctly identified 92 percent of sight obstructions at the 9 intersections examined.

Major Findings and Limitations

- Compared to the 64 percent accuracy of obstructions identified by a 100-foot line-of-sight assessment, plane-of-sight analysis was substantially more effective.
- Terrestrial LiDAR scanners can supplement airborne LiDAR to locate objects under cover of trees, shrubs, and other impediments.
- Complex or skewed intersections require additional analysis and assumptions.

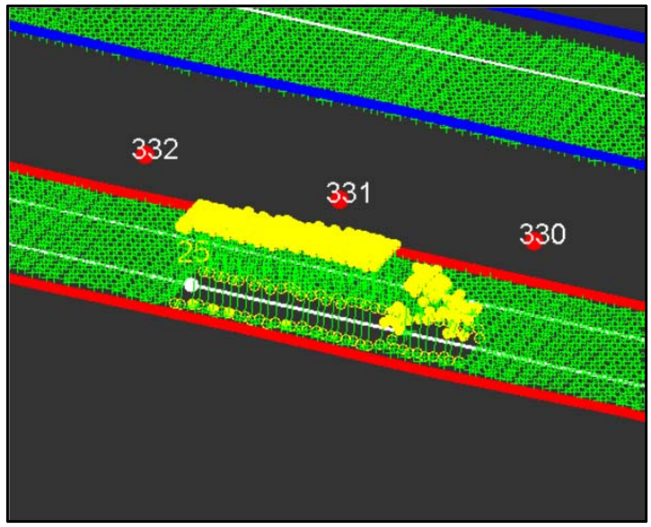
Tsai, Y., Yang Q., Wu, Y. (2011*). Identifying and Quantifying Intersection Obstruction and Its Severity Using LiDAR Technology and GIS Spatial Analysis*. Proceedings from the TRB 2011 Annual Meeting. Transportation Research Board. Washington, DC.

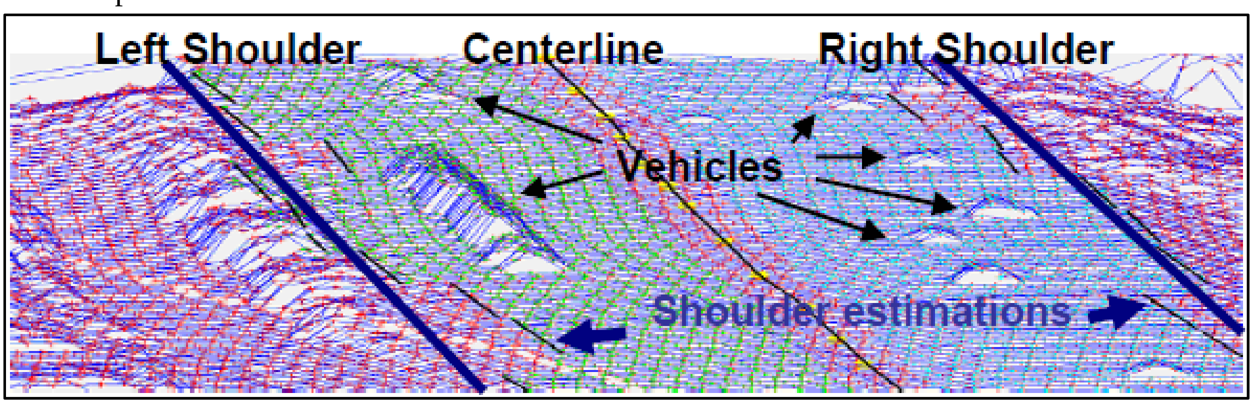
LiDAR Application Case Study – Safety and Mobility

Application:	Traffic Flow Estimation
Location(s):	Columbus, OH
Study Period:	2005
Equipment:	Airborne LiDAR

Study Description

Ohio Department of Transportation in 2005 took advantage of airborne LiDAR's ability to preserve the geometric shape of a moving object for traffic flow estimation. Airborne LiDAR was used to collect data over transportation corridors for vehicle counts, vehicle classification, velocity per vehicle category, and intersection movement patterns. Ohio DOT later developed the L-FLOW program that is able to input LiDAR data files and output information. L-FLOW is able to extract vehicles from LiDAR data, group them into main vehicle categories, estimate velocity, and output a list of extracted vehicles. From experimental results, the L-FLOW algorithm was able to successfully achieve vehicle extraction and classification 85 to 99 percent of the time.





Major Findings and Limitations

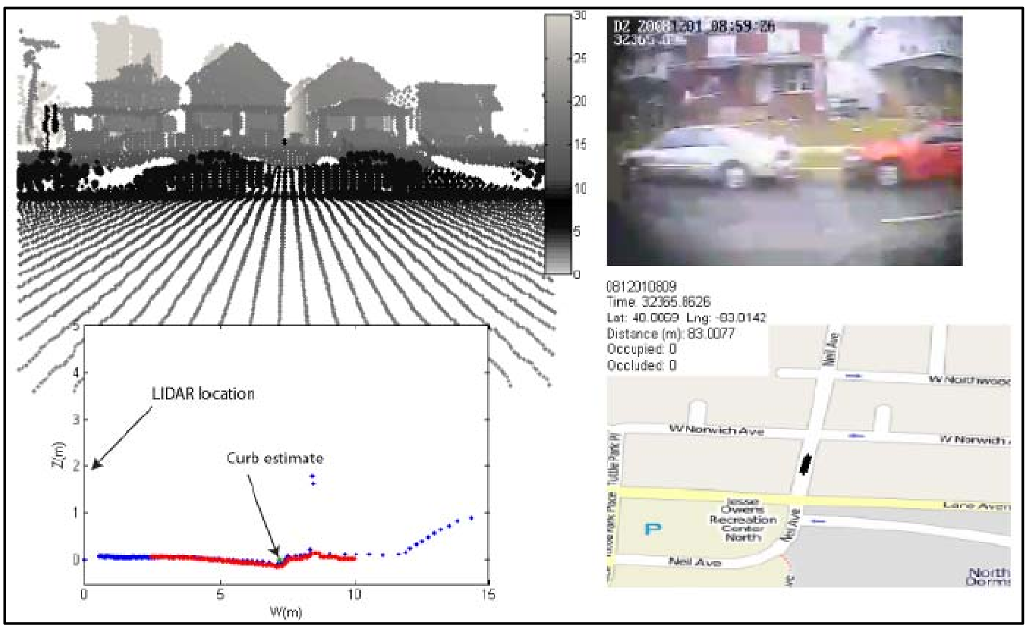
- Automated vehicle extraction and classification algorithm can be developed for data collected by airborne LiDAR; aerial photography can be supplemented to remove most sources of ambiguity during processing.

Moafipoor, S., Toth, C., Grejner-Brzezinska, D. (2005). *Traffic Flow Estimate from LiDAR DATA: Operational Experiences*. Proceedings from Pecora 16 "Global Priorities in Land Remote Sensing." October 23-27, 2005. Sioux Falls, SD.

Application:	Parking Utilization Surveys
Location(s):	Columbus, OH
Study Period:	2012
Equipment:	Mobile Terrestrial LiDAR

Study Description

Parking surveys provide transportation planners with information regarding the parking needs and trends of motorists. By recognizing over-utilized areas, planners can adjust parking policies and plan future parking supply accordingly. A team of researchers in Ohio investigated the potential of automatically collecting parking utilization data along arterial roads using mobile LiDAR. Point clouds were processed to estimate the curb location, identify the presence of objects in the road, and determine which objects were parked vehicles. The primary goals of automated parking detection were to reduce the labor of parking surveys, provide measures that are generally cost prohibitive, and provide parking information in real time. A test to automatically monitor parking utilization in parallel parking areas yielded results nearly identical to ground truth with an error rate of 1 among 340 vehicles.



Major Findings and Limitations

- To reduce data collection costs, the host vehicles for mobile LiDAR scanners can be transit buses and other municipal vehicles conducting daily duties.
- LiDAR offers potential to collect park vehicle information, such as vehicle classification and parking duration, with minimal effort.

Thornton, D., Coifman, B., and Redmill, K. (2012). *Automating Parking Studies using LiDAR Sensors – A Proof of Concept*. Paper number 12-2886. Proceedings from TRB 2012 Annual Meeting. Transportation Research Board. Washington, DC.

LiDAR Application Case Study – Historic, Natural, and Cultural Preservation

Application:	Historic Preservation of Petroglyphs
Location(s):	California
Study Period:	2008
Equipment:	Fixed-Terrestrial LiDAR

Study Description

The Cultural Resource Branch of the California Department of Transportation (Caltrans) used LiDAR to scan a large number of petroglyphs, also known as rock engravings. In coordination with the Caltrans District 11 Surveys Division, they used a Leica ScanStation 2 to survey these archaeological sites. Each control station was mapped using a GPS Pathfinder Pro Network. Along with the Leica scanner, a fish-eye camera took 360-degree photos. For every one day of surveying, there were three days of post-processing. The point-cloud data was processed in GIS/CADD to create a DSM, which can be incorporated into a Google Earth movie view through Quicktime. The final product used all data, LiDAR scans and photographs, in Google Earth SketchUp software. This data was then archived in the National Archives with the National Register Nomination Form. LiDAR was effectively implemented to produce three-dimensional images of cultural and historical preservation sites.

Major Findings and Limitations

- Technological advances have allowed Caltrans to utilize the departmental survey instruments for cultural resource mapping; the tools evolved from the Brunton compass to photogrammetry to laser transits, GPS, and GIS to LiDAR three-dimensional mapping.
- Engineers, surveyors, and archeologist should consult cultural heritage groups before making any decisions.

Dominici, D. (2008). *Caltrans' Future: LiDAR, Three-Dimensional Mapping*. District 11, Caltrans. San Diego, CA.

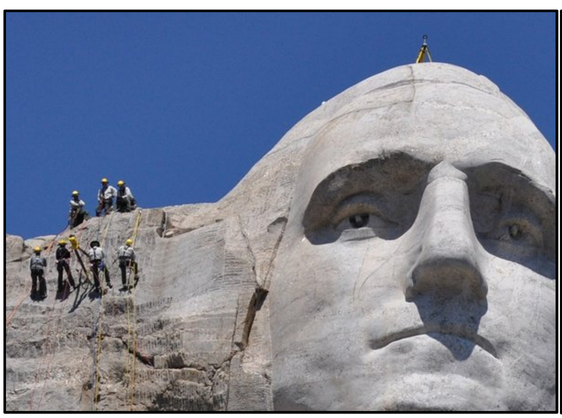
LiDAR Application Case Study – Historic, Natural, and Cultural Preservation

Application:	Cultural Preservation of Significant Sites
Location(s):	Worldwide Cultural Heritage Sites
Study Period:	Present
Equipment:	Fixed-Terrestrial LiDAR

Study Description

CyArk initially began its CyArk 500 Challenge in 2011. CyArk's founder, Orindan Ben Kacyra, was a key player in the development of Cyrax, the first portable LiDAR scanner. After marketing the product and selling it to Leica Geosystems, Kacyra now uses LiDAR for archiving historical sites. Dubbed the CyArk 500 Challenge, CyArk aims to document 500 sites all over the world over a 5-year period. Some of these sites include Pompeii, Egyptian pyramids, and the Taj Mahal.

Before the CyArk 500 Challenge in May of 2010, CyArk worked with Scotland and Glasgow School of Art to scan Mount Rushmore, their first international project. CyArk, also in coordination with the Centre for Digital Documentation and Visualization, collected 93 scans that consisted of over 1.3 billion points with a resolution of 4 millimeters. The file format for data point storage was subsequently over 100 gigabytes. CyArk then processed this data to create two-dimensional CADD drawings of the park and use imagery to track rock movement. These LiDAR points were superimposed with digital photos for animations and prototype models of Mount Rushmore.



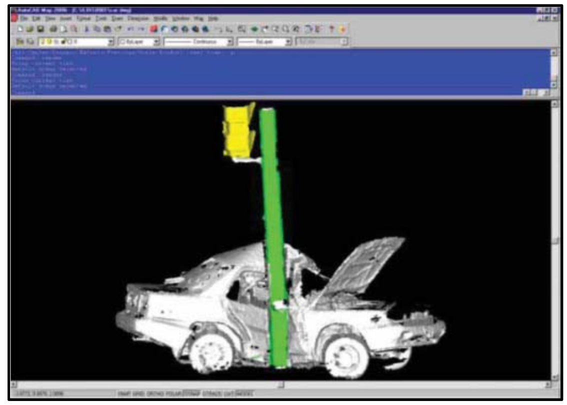

Major Findings and Limitations

- LiDAR can be used to digitally preserve cultural heritage sites through collecting, archiving, and virtually providing access to significant locations.
- Researchers and Archeologist can perform work without physically being at sites.

Kacyra, B. (2011). *CyArk500 – 3D Documentation of 500 Important Cultural Heritage Sites*. CyArk and Partners. Oakland, CA.

LiDAR Application Case Study – Forensic Science and Scene Reconstruction

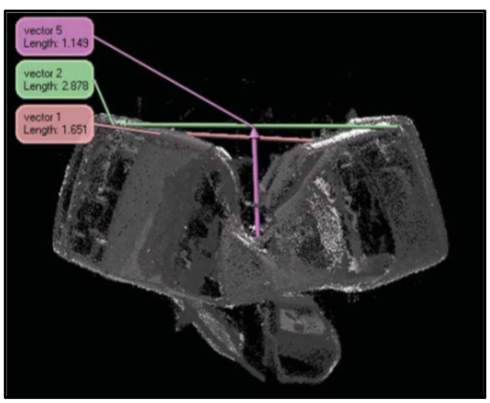
Application:	Forensic Survey – Crash Reconstruction
Location(s):	Toronto, Canada
Study Period:	2002
Equipment:	Fixed-Terrestrial LiDAR



Study Description

When a vehicle crash occurs, law enforcement and transportation agencies must accurately document and identify the crash environment in which the incident took place. Physical elements include skid marks, road configuration, pavement/ shoulder conditions, and roadside features are inventoried for assessment. Fixed-terrestrial LiDAR provide a fast and accurate method for three-dimensional data collection. LiDAR can be utilized by investigators to conduct crash reconstruction.

In September of 2002, the Toronto Police contracted a third-party surveying company to deploy Optech's ILRIS-3D static scanner for a crash scene investigation. The crash under examination involved a single vehicle colliding into a traffic signal mast at a busy intersection. Toronto Police required a three-dimensional image of the scene for reconstruction and forensic analysis. The LiDAR vendor surveyed the scene by taking five scans of the vehicle and collateral conditions. The total on-site survey of 3,506,402 points took approximately 1 hour and allowed for timely re-opening of the intersection. With post-processing software, the skid marks and point of impact were analyzed. Using vector placement and various measurement techniques, the crash dynamics were modeled. The CADD model was generated from the point cloud and delivered to the Toronto Police for evaluation, documentation, and presentation in a court of law.



Major Findings and Limitations

- LiDAR's capability to survey sub-centimeter accuracies at long-range distances provides investigators with a substantial amount of three-dimensional data for crash reconstruction.
- LiDAR scanners are rated to operate in inclement weather.
- LiDAR scanners integrate active sensors so that time of day and ambient lighting do not affect the quality of models.

Optech Incorporated (2006). *Forensic Survey: Accident Reconstruction*. Field Notes. Vaughan, ON. URL: www.optech.ca.

LiDAR Application Case Study – Forensics Science and Scene Reconstruction

Application:	Helicopter Crash Reconstruction
Location(s):	Baden-Wurttemberg, Germany
Study Period:	2011
Equipment:	Fixed-Terrestrial LiDAR (Phase-based)

Study Description

In Germany, the Criminal Investigation Department investigated a helicopter accident. In addition to human observation, the department used fixed-terrestrial scanner to model the scene of the crash. Along with the helicopter, the scans captured the surrounding topography and environment. LiDAR accurately captured the entire accident scene and proved to be a critical step in recreating the crash and determining the sequence of events that led to the incident. A total of 6 scans with more than 50 million points were brought into processing software. The software's primary function was to digitize models of physical objects.

During the processing of data, removal of outliers, reduction in noise, and filling in of holes was first conducted. The second step required the alignment, merging, and registering of multiple point clouds to create a polygon mesh. Finally, the polygon model was modified, edited, and cleaned to produce a digital replica of the damaged helicopter and surrounding terrain. The measurements and model provided information to assess the extent of damage sustained by the helicopter and the collision course. The police determined the crash to be a result of pilot error.

Major Findings and Limitations

- LiDAR facilitates investigations and quickly models complicated objects for the incorporation into animations, scene sketches, and reports.
- Point cloud and model viewing software allows crash scenes to be viewed from various angles that typically cannot be accomplished on-site.

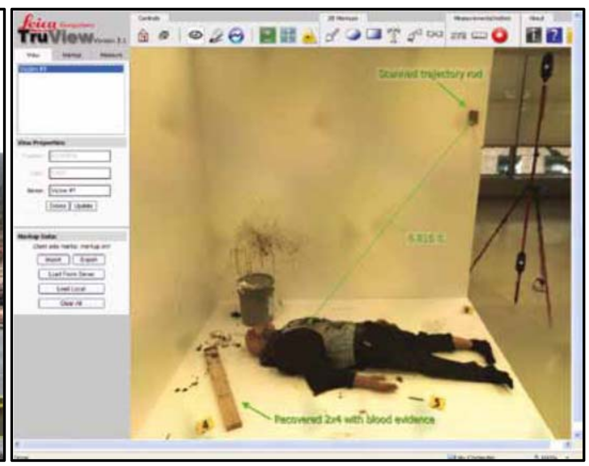
Cramblitt, B. and Grissim, T. (2010). *3D Scanning: Visualizing Scenes in Another Dimension.* Evidence Technology Magazine, Volume 8, Number 5. Kansas City, MO.

LiDAR Application Case Study – Forensic Science and Scene Reconstruction

Application:	High-profile Criminal Investigations
Location(s):	Austin, Texas
Study Period:	2009 and 2010
Equipment:	Fixed-Terrestrial LiDAR

Study Description

The Killeen Police Department's criminal investigation division (CID) utilized their LiDAR scanner to forensically map two high-profile crime scenes in Texas: the Fort Hood shooting and the suicide plane crash into the Austin field office of the Internal Revenue Service. In 2009, the CID forensic team used a Leica three-dimensional scanner to survey the Fort Hood crime scene which consisted of a row of six buildings and parking lots on either side of the buildings. The scan data was imported into CADD software to generate a crime scene representation. In 2010, Investigators used LiDAR after an airplane crashed into the Austin Internal Revenue Service building. A pilot, who was dissatisfied with the IRS, crashed his small plane into the large government building, resulting in an explosion which caused massive amounts of debris that defied the capabilities of a simple tape measure. LiDAR was successfully used quickly and accurately to depict the crime scene.



Major Findings and Limitations

- A typical homicide scene requires seven to eight hours to manually collect and process evidence on-site; utilizing LiDAR can reduce the process to less than three hours.
- LiDAR reduces the time required for crime scene documentation as well as produce high-quality, detailed information for criminal investigation professionals.
- LiDAR scanners can be acquired with asset forfeiture funds.

Cramblitt, B. and Grissim, T. (2010). *3D Scanning: Visualizing Scenes in Another Dimension*. Evidence Technology Magazine, Volume 8, Number 5. Kansas City, MO.

4. UNIT SURVEY RESPONSE

The research team met with multiple North Carolina Department of Transportation units and groups to present potential LiDAR applications and to receive feedback regarding experience and/or interest in technology implementation. Through suggestions from the Steering and Implementation Committee, the following teams were selected to be interviewed: CADD Services, Construction Unit, Geotechnical Engineering Unit, Hydraulics Unit, Pavement Management Unit, Photogrammetry Unit, Roadway Design Unit, Structures Management Unit, State Road Management Unit, Traffic Management Unit, Traffic Safety Unit, and Visualization Enterprises. Per discussions with each group, researchers found that the units could be defined by their roles of collecting, processing, and extracting locational data as service providers or using processed data for design, management, and analysis as end users. Of the aforementioned teams, Location and Surveys Unit, CADD Services, and Photogrammetry Unit can generally be recognized as service providers, while the remainder are described as end users. The interviews have been outlined below.

CADD Services

The CADD support group within the Information Technology department provides basic computer training services and technology management to the various NCDOT units. The primary issue discussed was the usability and availability of LiDAR data to end users. Due to the complex nature and overwhelming storage requirement of point clouds, raw LiDAR data must be processed and filtered down tremendously before it is made available on a central server. More manageable point clouds can be integrated in CADD software to be viewed by designers. Along with point clouds, three-dimensional elevation models derived from raw LiDAR data and other sources are gaining popularity over two-dimensional raster.

Construction Unit

In discussions with the Construction Unit, the primary applications presented as most promising were geometric measurements for quantity estimation and Quality Assurance (QA) and Quality Control (QC) and as-built models for infrastructure management. The Unit expressed interest in using geometric measurements for checking superelevations on newly constructed roadways, resolving quantity disputes of unclassified excavation during construction processes, and confirming adequate clearances within the construction area. Furthermore, a reoccurring issue is locating subsurface or submerged utilities. However, as a non-penetrating technology, LiDAR cannot be accurately used to detect objects underground or underwater.

The Construction Unit has never directly utilized LiDAR equipment or raw point clouds. However, when in need of geometric and geographic data, the Unit generally requests information from the Location and Surveys Unit and the Photogrammetry Unit. The service providing units will, in turn, determine the most effective and economical technique for collecting required data, and at times LiDAR or a combination of LiDAR and other techniques is utilized.

Geotechnical Engineering Unit

The applications presented to the Geotechnical Engineering Unit were rock slope mapping and stability assessment, construction quantity estimations, and structural health monitoring.

Although primarily an end user of LiDAR data, the Geotechnical Engineering Unit has experience with LiDAR through data collected by the Location and Surveys Unit, as well as third party vendors. The Eastern Regional Office uses LiDAR to monitor structural movement of buildings. NCDOT is currently conducting a bridge replacement project in downtown Elizabeth City waterfront. A creek runs beneath a building adjacent to the roadway and many areas along the roadway and sidewalk have large voids. Piles are being driven into the ground to stabilize the roadway, and many building owners are concerned that potential damage may ensue with the construction process. NCDOT's Geotechnical Engineering Unit, in collaboration with the Structure Design Unit, are developing a plan of action to stabilize the pile-supported roadway slabs while maintaining the stability of the surrounding structures. LiDAR is currently being used to carefully monitor building settlement to minimize building damage.

The Western Regional Office has worked with Location and Surveys Unit to estimate the amount of rock from a large rockfall along I-40 in the Pigeon River Gorge. As the rock mass was too large to be captured alone with a fixed-terrestrial LiDAR system, the investigators supplemented the scans with depth measurements taken by the Photogrammetry Unit using aerial photography. More recently, the Western Regional Office contracted a third party vendor to collect point clouds of rock faces along various mountainous highway segments. The scans are used for monitoring slope stability with the possibility of more complex analysis, including rock mass characterization. Finally, a specific application regarding structural health monitor is detecting change in mechanically stabilized earth (MSE) walls. Both the Structures Management and the Geotechnical Engineering Units expressed concerns in older MSE walls. Many of the walls built more than fifty years ago are undocumented and contain backfill material that often does not meet current standards.

Hydraulics Unit

For runoff and drainage modeling and assessments, the Hydraulics Unit generates its own contour maps based on triangulated irregular networks (TINs) and digital terrain models (DTMs) provided by the Photogrammetry Unit. TINs and DTMs are directly integrated into the CADD software. The products that the Photogrammetry Unit provide are created from data obtained by a combination of aerial photography and NCFMP airborne LiDAR. Furthermore, at the microscopic level, the Hydraulics Unit uses ground-based LiDAR to assess issues of pavement dishing and hydroplaning hazards.

Pavement Management Unit

The Pavement Management Unit currently implements a mobile scanning system that is dedicated for Pavement Condition Surveys (PCS). The mobile acquisition system produces high-definition three-dimensional images of the road's surface to assess distress. The system integrates a laser illuminated camera with sensors much like the technology found in LiDAR.

Photogrammetry Unit

In 1999, Hurricane Floyd brought torrential rainfall and flooding that devastated North Carolina. As a result, the Federal Emergency Management Agency (FEMA) designated North Carolina the first Cooperating Technical State (CTS). The NC Floodplain Mapping Program (NCFMP) contracted airborne LiDAR collection of the entire state over a three-phase cycle in 2001, 2003, and 2005. The Photogrammetry Unit updates NCFMP LiDAR mass point elevation data by integrating current aerial photography to produce digital elevation data. The elevation data is used for functional and preliminary design. As a service provider, the Unit delivers TINs and DTMs to end users.

Roadway Design Unit

Terrain feature extraction, asset and utility inventory, and construction QA/QC were presented as the most useful LiDAR applications for corridor mapping and highway design. The Roadway Design Unit is solely an end user of LiDAR derived products. In particular, the Unit found high definition data produced by LiDAR to be most applicable for designing highway corridors with steep slopes, locating utilities and existing buildings for design clearances, and producing as-built models. Finally, the design platform within CADD is progressing from two-dimensional planimetric CADD files to three-dimensional DTMs derived from point clouds.

Structures Management Unit

The primary LiDAR application for bridges is the measurement of horizontal and vertical clearances. Solely an end user, the Unit requests clearance measurements directly from the Location and Surveys Unit without any direct involvement in the process in which geometry is collected. Depending on the requirements, the Location and Surveys Unit decides on the optimal measuring technique.

In addition to obtaining bridge geometry, the Structures Management Unit was interested in the ability to produce as-built models and detect structural movement of transportation infrastructure through the use of LiDAR.

State Road Management Unit

Asset and utilities inventory, condition assessments, and sight obstruction analysis were presented as the most useful LiDAR applications for the management of the highway and roadside features. Although LiDAR has the ability to capture highly detailed surveys of highway corridors relatively quickly, the State Road Management Unit does not require the level of accuracy and amount of detail produced by point clouds.

Traffic Safety Unit

The Traffic Safety Unit requests and utilizes high-definition surveying primarily for wet crash locations suspected of hydroplaning hazards. The locations are investigated when pavement readings have acceptable friction numbers and no apparent surface issues can be easily identified. LiDAR point clouds are delivered directly to the Division Design and Construct office or the District office for analysis with hydraulic modeling tools. LiDAR provides topographic representations of the pavement being scanned so that traffic safety engineers can assess low spots and pavement panning, inadequate superelevation, and drainage from driveways entering the travel way. When using LiDAR data, a common issue is inconsistency with the format and lack of a well-defined findings summary.

In the meeting with the Traffic Safety Unit, the North Carolina Highway Patrol’s Reconstruction Unit was present to discuss crash reconstruction technology. LiDAR was presented as a valid method for collecting highway crash data and reproducing three-dimensional models of vehicle collision scenes.

Visualization Enterprises

Although primarily a service provider, Visualization Enterprises is an end user of digital surface and digital terrain models. The group found LiDAR data to be very effective in locating existing structures and measuring infrastructure geometry for the production of visualizations.

5. NATIONWIDE SURVEY RESPONSE

In addition to contacting specific business areas within the North Carolina Department of Transportation, key contacts from the 49 state transportation agencies were contacted in regards to the utilization of LiDAR systems or data. Out of the 49 agencies surveyed through email, 36 responded. The responses were as follows: 19 of 36 agencies conduct or contract airborne LiDAR scanning and processing, 15 of 36 utilize mobile-terrestrial LiDAR, and 19 of 36 implement fixed-terrestrial LiDAR. The following sections detail key findings from the nationwide survey respondents.

Licensures Requirements

Responses from state agencies resulted in a varying degrees for licensed Professional Land Surveyor (P.L.S.) requirements. Some agencies do not require a P.L.S. for any stage of work, while others required a P.L.S. for oversight and data collection. Additionally, a P.L.S. may not be required for in-house work, but may be required of third-party contractors. As LiDAR continues to develop and become more available, there will be trends to establish individual state or national standards and requirements for the collection and usage of LiDAR data.

In addition to the survey conducted for this report, authors of Professional Surveyor Magazine surveyed every state board of registrars to inquiry about the governing and regulatory environment of LiDAR activities (Stennett and Wade-Grusky 2008). Although practices varied by state and specific applications, one or more states regulate LiDAR usage under state licensure laws for (1) the operation and collection of LiDAR sensors and data, (2) the computation of collected LiDAR data, (3) the setup of geodetic control points with GPS receivers, and/or (4) the measurement of ground elevations with GPS receivers to validate LiDAR data. Stennett and Wade-Grusky concluded that it is preferable to ensure coordination and oversight with a P.L.S. on all LiDAR projects.

Utilization

In the utilization of airborne LiDAR, state agencies use data in conjunction with or to supplement aerial photogrammetry. Primarily, airborne LiDAR is used over large project areas that required moderately accurate elevation data for the production of TINs, DSMs, DEMs, and contour maps. Additionally, LiDAR users analyze data for base mapping, feature extraction, transportation corridor planning, preliminary engineering and estimation, and hydraulic/hydrologic modeling. Mobile systems are used by transportation agencies for maintenance and design purposes. In the maintenance work, usage includes the inventorying of highway assets and roadside features as well as the inspection of bridge clearances. Pavement condition and roadway geometry are assessed for design, construction, and rehabilitation. Generally, agencies found fixed-terrestrial LiDAR to be effective in surveying areas with high traffic or limited access. Due to the high absolute accuracy of stationary systems, state engineers use fixed LiDAR for bridge and structural monitoring, pavement grade and slope safety assessment, and rockfall analysis.

Data Processing, Sharing, and Storage

In general, most data collected is processed with software provided by LiDAR vendors and manufacturers. For further analysis, data is integrated into CADD software. Because of the complexity and large storage requirements of LiDAR data, raw point clouds are rarely shared within agencies; instead, CADD drawings, TINs, and DEMs derived from LiDAR data are provided to end users. These products are stored on servers, FTP sites, or DVDs.

Overall Consensus

LiDAR systems have been beneficial in the safety of field personnel and the traveling public. The technology reduces personnel exposure to high traffic, the need to access hazardous locations, and lane closures, which all contribute to the safety of workers and travelers. If implemented in the right setting, LiDAR can be more economical and efficient than traditional surveys. Improved mobility, data accuracy, and survey detail are additional benefits.

LiDAR, although extremely accurate and effective, is not a complete substitute for traditional surveying methods. LiDAR scans create large data files, which many computer storage systems are not equipped to handle. In addition to the sheer size, the complexity of point clouds only adds to the challenge. There is a lack of sufficient, automated software to remove erroneous data, such as trees and other vegetation. Manual extraction is tedious and must be done by a trained technician, thereby being a costly investment and requiring lengthy analysis time. As a relatively new technology, the steep learning curve for correct interpretation of LiDAR data induces staff reluctance to adopting its use. Furthermore, ongoing developments in hardware and software pose obsolescent risks in investing in LiDAR. Like all other surveying methods and technology, LiDAR is never perfectly accurate. To produce the most accurate data possible, traditional methods must be implemented to establish proper surveying controls and satisfy measures of quality assurance and control. Lastly, the high costs of initially setting up or contracting LiDAR makes the technology economically infeasible for many transportation agencies.

The consensus on LiDAR is that it is an exceptional tool for transportation related projects but the data and products derived must be checked and verified under all circumstances. Prior to data collection, careful planning and attention must be paid to how and where scanning should be taken. For quality assurance, fixed-terrestrial LiDAR accuracy is highly dependent on the use of control points and targets. The calibration and satellite signal availability of INS and GPS are essential to accurate measurements of mobile and airborne systems. After data collection, quality control measures should be taken to validate all data before any release and use of the collected information. Finally, end users and purchasers of LiDAR data must clearly define specifications and accuracy requirements when requesting data from in-house surveyors or third-party contractors.

6. CONCLUSIONS

6.1. Findings

LiDAR Platforms

LiDAR is a remote sensing technology that integrates multiple sensors to produce three-dimensional models in the form of point clouds for the collection of geometric and geographic information. The types of LiDAR primarily include three platforms, a static ground-based unit, a mobile-terrestrial configuration, and an airborne system. Each platform varies in costs, accuracy, and data collection time, and may be implemented for a variety of different applications. In Exhibit 4, a radar chart compares the three platforms for their applicability, cost effectiveness, data collection productivity, ease of use, level of detail, post-processing efficiency, and safety. A 5-point rating scale has been applied for the platforms' performance in each aspect; a value of 5 represents the highest rating, a value of 3 represents the medium, while a value of 1 represents the lowest. The center point of the chart solely represents the graphical origin and is denoted with a value of 0. This comparison chart is based on the general utilization of LiDAR for all transportation and traffic related applications. The performance categories and relative platform ratings are defined and discussed in further detail. When addressing specific applications, each platform's ratings may vary depending on a given project's scope of work. This chart or modifications of it may be used to aid decision-making processes of deploying LiDAR.

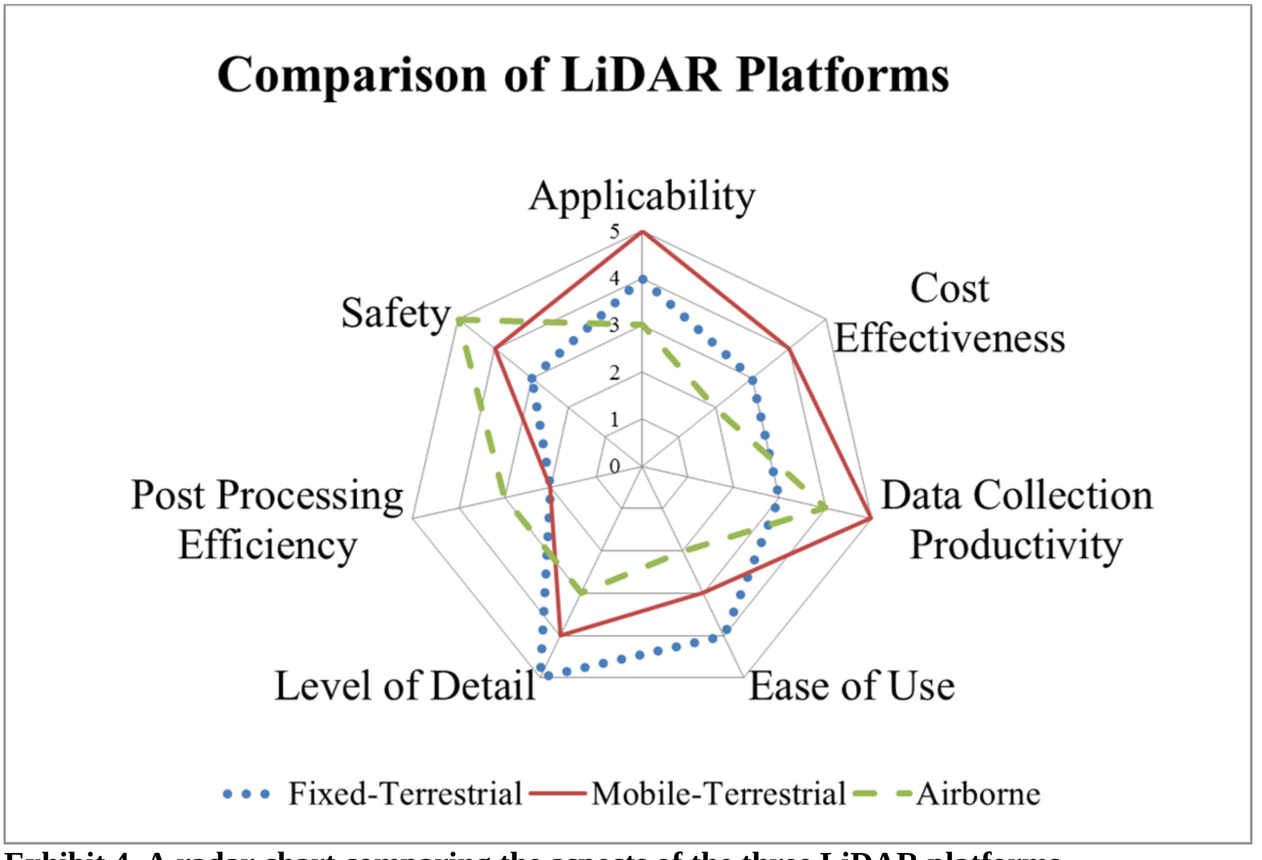


Exhibit 4. A radar chart comparing the aspects of the three LiDAR platforms

Applicability was determined by the number of useful applications each platform has in transportation related projects. While more of the case studies in Section 3 present examples of fixed-terrestrial LiDAR utilization, future trends towards the implementation of mobile-terrestrial systems are apparent. These trends are primarily due to the advancements in scanner technology; mobile-terrestrial systems have benefited significantly in the ability to capture survey/engineering grade data while traveling at highway speeds. Therefore, mobile systems can produce highly accurate point clouds while covering large project sites that would otherwise be inefficient and costly of stationary setups. Although airborne LiDAR can be used in areas inaccessible by foot or ground vehicle, it received a medium rating because of its limited photogrammetric/aerial capabilities and reduced accuracy.

Cost Effectiveness relates to the competitiveness of implementing one system over another. Fixed-terrestrial and airborne systems were rated medium and lower scores, respectively. While fixed-terrestrial systems produce high detail, the scanner is limited to the effective range relative to its setup location. Therefore, as the required number of setups increases, so too does the cost. Airborne systems tend to have the lowest frequency of deployment, thus the high costs of owning/renting, storing, maintaining, and operating fixed wing or rotary wing aircrafts reduce the overall cost effectiveness. Associated costs of a ground vehicle are relatively inexpensive when compared to the investment in scanner and sensor equipment. Although mobile-terrestrial LiDAR's hardware acquisition costs may be significantly higher than that of fixed-terrestrial scanners, the long-term cost effectiveness and ability to survey from site to site without additional setups give it a higher rating.

Data Collection Productivity of mobile and airborne LiDAR is higher than that of fixed due to their capability of covering much more ground in a single scan. Mobile-terrestrial LiDAR received the highest rating for rapid rates of data collection and high degrees of accuracy; it collects at highway speeds and produces detailed point clouds that can be used for both asset and survey grade applications. While mobile and airborne platforms integrate GPS and INS that simultaneously track the location and position of a moving scanner, fixed-terrestrial systems generally require an additional setup of controls similar to that of traditional surveys conducted with the Total Station.

Ease of Use is based on the tasks of operating each type of LiDAR. Compared to other survey and geodetic tools, LiDAR is fairly complex as proper operation requires proficient understanding of the technology. After initially registering a fixed-terrestrial scanner, a trained technician needs only to activate the scan cycle; thus, fixed-terrestrial LiDAR is given a higher rating. In addition to scanner operation, mobile-terrestrial and airborne LiDAR requires knowledge of GPS and INS devices. The multi-sensor systems must be calibrated to account for the relative locations of each sensor. Airborne LiDAR received the lower rating of the three due to an additional requirement of needing a professional pilot to fly an aircraft.

Level of Detail varies for each of the platforms. Fixed-terrestrial LiDAR was the highest rated for its capability in producing data with the greatest absolute accuracy and relative precision. While mobile-terrestrial systems collect less accurate absolute accuracies, they still can be used for survey grade data collection. Airborne LiDAR is more commonly used for asset grade surveys to produce base maps and elevation/surface models. Therefore, it received a medium rating.

Post Processing Efficiency is relatively low for terrestrial scanners. Where LiDAR has a distinct advantage in data collection productivity, it loses in post-processing efficiency. The sheer amount of data and detail captured with LiDAR scanners makes analysis very time consuming. Less stringent accuracy requirements and limited applications of airborne LiDAR reduce the complexity of processing useful data.

Safety relates to the reduction of potential hazards to field personnel and the traveling public during transportation-related data collection, and it is the key advantage of LiDAR over other surveying methods. Although fixed-terrestrial LiDAR requires field personnel to be exposed along the travel way, the speed and range of data collection reduce the overall exposure to dangerous traffic/environmental conditions. Mobile-terrestrial and airborne LiDAR allow operators to survey at highway speed or completely away from highway, thus, receiving higher and highest ratings, respectively.

Transportation Applications

All across the world, transportation agencies are increasingly acquiring scanners and/or contracting services from the private sector. Compared with other surveying methods, LiDAR produces relatively high degrees of accuracy when measuring visible geometries and locating geographic positions. LiDAR's high accuracy capability allows engineers, surveyors, scientists, and technicians to utilize the technology for transportation infrastructure and traffic operation projects. Furthermore, LiDAR collects millions of digital coordinate points in a single scan. The ability for simultaneous data collection reduces the time required by field crews to take measurements while creating rich datasets of the targeted objects and surrounding environment. The speed of data collection reduces labor costs and, most importantly, limits field personnel's exposure to potentially hazardous traffic and/or environmental conditions. Coupled with the ability to collect precise measurements, LiDAR is effectively utilized for complex or high profile transportation projects that require the greatest level of detail and information. Exhibit 5 displays a matrix of which platforms are most useful for specific transportation applications by business areas. LiDAR data and services have been used successfully by a number of transportation agencies for the following applications:

Bridges: structural monitoring, geometric measurements, bridge clearance, and restorations
Construction: earthwork estimations, as-built modeling, and base mapping
Geotechnical engineering: Rock mass and rockfall analyses, slope stability assessments, and volumetric change monitoring
Highway design and corridor mapping: surface transportation improvements, elevation and cross-section measurements, and topographic surveys
Hydraulics and hydrology: coastal change detecting, flood mapping and inundation maps, and hazardous dam assessments
Pavement: roadway geometry measurements, resurfacing assessments, and crack detection
Photogrammetry: airport obstruction surveys, topographic and elevation products, and utility and obstruction mapping
Traffic safety/mobility: sight distance, traffic flow estimates, and parking utilization
Historic, natural, and cultural preservation: significant site preservations
Forensic science/scene reconstruction: crash reconstructions and criminal investigations

Applications	Optimal LiDAR Platform	Structures Management/ Maintenance	Construction	Geotechnical Engineering	Highway Design	Hydraulics	Pavement Management/ Maintenance	Safety and Mobility
		Primary Business Areas						
Airport Obstruction Survey	Airborne	X						
As-built/ CADD Modeling	Fixed-Terrestrial, Mobile-Terrestrial	X	X	X	X			
Base Mapping	Mobile-Terrestrial, Airborne	X			X			
Clearance Measurement	Fixed-Terrestrial, Mobile-Terrestrial	X	X	X	X			X
Corridor Mapping/ Highway Planning	Mobile-Terrestrial, Airborne				X			
Coastal Change	Airborne					X		
Crash Reconstruction	Fixed-Terrestrial							X
Crime Scene Investigation	Fixed-Terrestrial							X
Digital Elevation/ Surface Modeling	Fixed-Terrestrial, Mobile-Terrestrial, Airborne			X	X			
Floodplain and Inundation Mapping	Airborne				X	X		
Foundation Assessment	Fixed-Terrestrial, Mobile-Terrestrial	X		X				
High-definition Hydraulic Modeling	Fixed-Terrestrial, Mobile-Terrestrial					X	X	X
Hydrologic Stream Modeling	Mobile-Terrestrial, Airborne					X		
Intersection Obstruction	Fixed-Terrestrial, Mobile-Terrestrial, Airborne				X			X
Pavement Grade and Cross-slope	Fixed-Terrestrial, Mobile-Terrestrial		X		X		X	X
Quantity Estimation	Fixed-Terrestrial, Mobile-Terrestrial, Airborne		X	X	X			
Rock and Slope Characterization	Fixed-Terrestrial, Mobile-Terrestrial			X				X
Site Preservation	Fixed-Terrestrial	X	X					
Structural Health Monitoring	Fixed-Terrestrial, Mobile-Terrestrial	X		X				
Survey Grade Geometric Measurement	Fixed-Terrestrial, Mobile-Terrestrial	X	X	X	X		X	
Traffic Operation	Mobile-Terrestrial, Airborne							X
Utility Survey	Fixed-Terrestrial, Mobile-Terrestrial, Airborne		X		X			
Volumetric Change Detection	Fixed-Terrestrial, Mobile-Terrestrial	X		X				

Legend: ***Fixed-Terrestrial*** ***Mobile-Terrestrial*** ***Airborne***

Exhibit 5. LiDAR platform utilization by applications and business areas

6.2. Considerations

When considering the acquisition of LiDAR systems and/or contracted services, a transportation agency should take into account the type of system best suited for the agency's needs (i.e. fixed-terrestrial, mobile-terrestrial, or airborne), the agency's capital and funding availability; their human resources and organizational structure; the capacity of the agency's information technology infrastructure; and the inherent limitations and risks of technological investments. In deciding which system best suits a particular transportation agency, the business areas within the agency and their goals and responsibilities should be reviewed. Fixed, mobile, and airborne LiDAR should be utilized when appropriate; the applications and examples outlined in this report can provide guidance in platform selection and support their implementation. Furthermore, the system chosen must be assessed to ensure that the data and products derived will meet specifications defined by the governing standards and regulations. If the agency finds that the system in consideration produces excessive amounts of detail and more than sufficient accuracy, they may decide that their current methods suffice and that the cost of LiDAR acquisition exceeds the benefits. Consequently, it is most important to first consider the traditional surveying methods.

To compare LiDAR with traditional surveying methods, performance measures should first be established for various aspects. Much like the comparison of LiDAR platforms in the previous section, aspects for evaluating advantages and disadvantages of utilizing one tool over another may include cost, delivery time, safety, and data quality (Vincent and Ecker 2010). LiDAR may have many potential benefits over conventional methods, but often these benefits may not be fully realized or easily quantified. Thus, the comparison chart in the previous section can be modified to address and determine the optimal tool to be deployed for a given project. To illustrate, an example is provided. Richard Vincent and Michael Ecker conducted an evaluation of LiDAR for the Missouri Department of Transportation (MoDOT) by comparing the three LiDAR platforms with traditional methods for roadway design utilization. A mapping company was hired to collect data using all types of LiDAR on a seven-mile stretch of MoDOT highway. The project site had all field control survey and aerial photography data already collected prior to comparison. The evaluation found that conventional aerial mapping along with airborne LiDAR provided the shortest potential schedule for collecting mapping data because of the speed of collection. Mobile-terrestrial LiDAR came in third; followed by traditional survey design and fixed-terrestrial LiDAR, respectively. For cost, conventional aerial mapping and airborne LiDAR were the most effective followed by the aforementioned order. LiDAR benefited primarily from safety enhancements and data quality, but was at a disadvantage for data processing and management. In Exhibit 6, a radar chart has been developed to visually illustrate the evaluation of the 5 methods used in the study. Although LiDAR was not the most promising tool for this specific roadway design application, the technology should still be considered for its cost effectiveness and potential benefits over its entire lifecycle deployment. Although, seemingly expensive, the costs are driven down when considering the continually decreasing costs of advanced technologies maturing over time and the cost reduction of limiting field collection redundancy and project change orders attributed to rich, high-quality datasets.

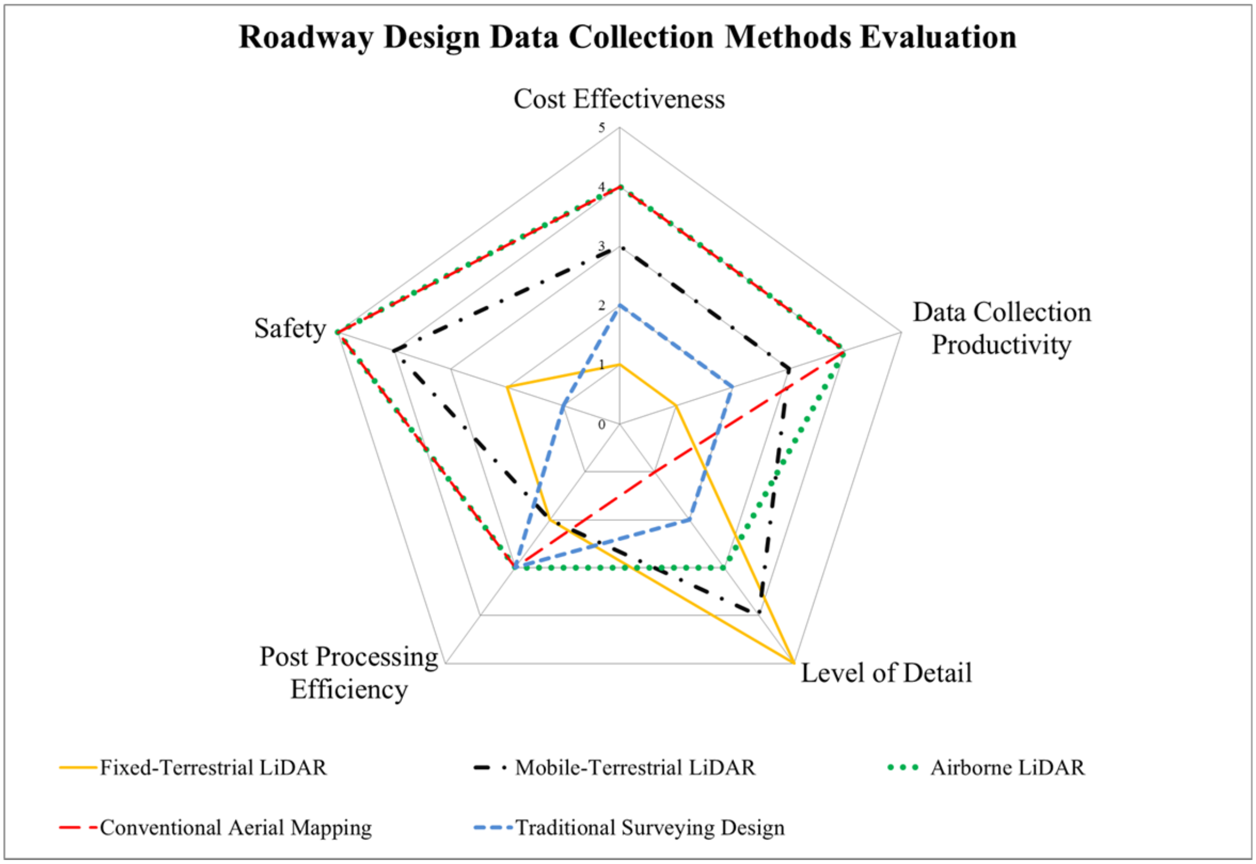


Exhibit 6. Evaluation of various data collection tools for roadway design applications

Although LiDAR costs continue to become more affordable as the technology matures, the initial purchase and setup of LiDAR systems can be a costly investment. Along with the expenses of scanners, sensors, and vehicle equipment, the adopting agency also will be required to make investments on personnel training, workstation upgrades, software purchases, and information technology infrastructure. Therefore, when assessing the total budget for LiDAR acquisition, the interested party should evaluate their current capabilities and assets, and take into account any additional investments required for a fully functional LiDAR system. In terms of personnel, does the agency have technologically proficient personnel whom are readily available and willing to learn the processes of collecting and analyzing LiDAR data? If not, will funding be sufficient to hire dedicated staff or contract services? These are only a couple of basic questions the agency should understand with regards to the acquisition of LiDAR.

At the business specific level, the agency and its individual units must identify the applications most pertinent to their areas of expertise, and determine whether the work is to be conducted by a service providing group or a particular end using unit. While most end users of LiDAR data and derived products will never need to conduct point cloud analyses, other units requiring more complex analyses may be better suited for internally processing data. Although it would be most cost-effective to concentrate resources in an individual group, the complexity of various LiDAR applications may make it infeasible. Thus, optimizing resource allocation and staff utilization must be planned and understood, accordingly.

Once LiDAR related tasks have been outlined and assigned to specific groups and staff, workstation upgrades will most likely be required as the computer graphics and computing power are relatively demanding for LiDAR. The three driving factors are the level of detail required, the type of computing tasks conducted, and the computing requirements of the software implemented. Generally, the final products derived from LiDAR have been simplified to be accessible and manageable by basic workstation machine. Therefore, the agency can minimize the costs of workstation upgrades and software purchases by contracting services or purchasing final products. If the agency decides to collect and process raw LiDAR data in-house, the cost of investing in workstations and software will be dependent on the type of application utilized as well as the accuracy, precision, and size of the information required. Most LiDAR scanner manufacturers design software and provide supplementary support for their systems. Thus, selecting equipment and software that matches an agency's implementation goals will optimize the investment of LiDAR acquisition. Consequently, LiDAR investments come with the risk of obsolescence, as technology is constantly improved and replaced.

Remote sensing/surveying technology and equipment, as with the case of LiDAR, continually evolve over time and are replaced by other tools and instruments. Surveying has experienced significant innovations, from the early methods of triangulation stations, geodetic levels, transits, theodolites, steel measuring tapes, and Gunter's Chain to the development of Electronic Distance Measuring Instruments (EDMI), integrated Total Stations, and automatic levels, and most recently, to GPS, INS, and three-dimensional LiDAR scanners. The agency acquiring LiDAR must accept the risk of the technology becoming obsolete, and in today's technologic driven world this could happen at a faster rate than in the past. Hence, LiDAR acquisition through derived products, contracted services, or equipment rental rather than a complete purchase of equipment, information technology infrastructure, and supporting software will leverage the inherent risks. Any party interested in LiDAR investments should determine the feasibility of acquisition, the capability of integrating the technology into departmental practices, as well as the frequency and lifecycle duration of utilization. The aforementioned considerations and an understanding of LiDAR's limitations are crucial in deciding how and when to acquire LiDAR technology and/or data.

6.3. Recommendations for NCDOT

Currently, NCDOT owns and operates a fixed-terrestrial panoramic scanner. The High Definition Scanning Group, based in Raleigh at the Location and Surveys (L&S) Unit's central office, conducts surveys across the state. In general, most applications have been internally conducted within the Unit. Based on the needs and requirements of other business areas, the Unit decides whether or not the project warrants the deployment of LiDAR. If so, the High Definition Scanning Group will mobilize the scanner to the selected site, scan and produce a point cloud, and process it at the office. Although the processed point cloud is stored on a central server and accessible through L&S, the final product delivered to the end user is usually a geometric dataset or set of CADD drawings. This practice has worked well within the Department and is consistent with its current information technology and transfer procedures. NCDOT should continue to operate under this organizational structure, in which L&S carries out the collection, analysis, and final production of LiDAR data for requesting business areas. This process will reduce data redundancy and ensure quality control in the sharing of information.

For more complex analyses, L&S may not be able to provide quantitative conclusions or qualitative engineering judgment on more specialized projects warranting LiDAR. In these cases, the High Definition Scanning Group can still deploy the static scanner for data collection and may carry out the initial post-processing of the raw point cloud. Segmenting and clustering groups of points, removing erroneous data, thinning the point cloud, and draping digital photography into three-dimensional space can make the scan much more manageable before beginning any business specific analysis. Other than basic point cloud viewing software, the business area or unit conducting specialized analysis should be responsible for obtaining additional processing software that may be needed. For future reference and good record keeping measures, it is recommended that all users of LiDAR data document their findings from the analyses conducted in a consistent format. Exhibit 7 provides an example of a one-page reporting form that could be completed by users deploying LiDAR and other geodetic instruments.

Original Date:
Dates Revised:

NCDOT – SUMMARY OF SURVEYING FINDINGS

All questions contained in this questionnaire are regarding the implementation of surveying for any projects that required the use and/or contracting of geometric/geographic measuring services and locational data.

Project Title:	**Project Number:**
Project Description and Location:	
Requesting Personnel & Business Area:	**Date Requested:**

GEOMETRIC/GEOGRAPHIC INFORMATION COLLECTION AND USAGE

Instrument:	☐ GPS	☐ LIDAR	☐ Other: ____________
Accuracy Requirement:	☐ Asset/Mapping Grade *(~ Absolute within 1' and relative within 0.1')*		☐ Survey/Engineering Grade *(Highest accuracy obtainable)*
Field/Survey Crew and Equipment:			
Datum/Control Information:			
Description of Locational Data			
Collection Method:			
Analysis:			
Findings:			

Actions Taken *(Based on findings)*

Date(s)	Decision(s)	Method(s)

Other Contact Information *(Departmental and/or third-party)*

Name(s)	Business(s)	Task(s)

Exhibit 7. An example of a surveying findings reporting form

LiDAR Deployment and Acquisition
NCDOT's fixed-terrestrial scanner has been implemented in multiple projects including and not limited to, geometric measurements, slope stability issues, structure and foundation monitoring, identifying pavement dishing for hydroplane hazards, and monitoring rockfall. Based on the Department's substantial experience with LiDAR, it is recommended that further exploration of the scanner's capabilities be conducted in as-built or in situ models of transportation infrastructure, construction quantity estimations, applications of geotechnical engineering, and finally cross-collaboration with law enforcement agencies.

Currently, the Department relies on the design drawings for constructed facilities information. It is not uncommon for change orders to occur during the construction process, and depending on the overseeing entity, modifications may go undocumented. Therefore, the final construction of modified projects may not necessarily be consistent with the original plans. As-built models can be very useful for quality control and referenced throughout the design life of a constructed facility. LiDAR has proven to be an exceptional tool for producing as-built models. Quantity estimations during the preliminary phases of pre-construction are often imprecise approximations. When earthwork quantities are exceedingly underestimated, a change order occurs and the Department may pay more than initially budgeted. NCDOT could deploy LiDAR for projects in which quantity estimations are deemed significantly inaccurate or for projects that require more than a specified portion of the budget devoted to earthwork. For more complex geotechnical analyses, the fixed-terrestrial scanner shows great promise in rock mass and rockfall characterization. The USDOT's "Ground-Based LiDAR Rock Slope Mapping and Assessment" report is an excellent reference that outlines the best practices in the field and for data processing when utilizing fixed-terrestrial LiDAR for specialized slope stability analyses. Finally, the last application recommended for further investigation is collaboration with the law enforcement agencies. The scanner can be deployed for crash reconstruction of major vehicle collisions on North Carolina's highways. It is suggested that NCDOT assists the NC Highway Patrol in conducting a pilot experiment in deploying LiDAR for crash scene reconstruction. Many law enforcement agencies have adopted the use of LiDAR, and a demonstration by the High Definition Scanning Group would be invaluable in helping the NC Highway Patrol decide on whether or not LiDAR could be a useful tool. In the long run, a partnership would be beneficial to both parties. LiDAR could help reduce the post-crash traffic delays, provide substantial detail for crash reconstruction, and help the Department make better decisions on highway safety improvements.

At this time, NCDOT has contracts with two firms that supply mobile-terrestrial LiDAR on an as-needed basis. The work is contracted through the Department's Private Engineering Firms (PEF) administrative office with involvement from the High Definition Scanning Group. Mobile LiDAR has been used extensively since 2008 on highways and railways, primarily in the creation of digital terrain models. Additionally, for business specific utilization, the Geotechnical Engineering Unit contracts services for slope scanning along mountainous segments of the interstate in the western region of North Carolina. Mobile scanning could prove to be an excellent return on investment for NCDOT. Mobile LiDAR's diverse applications and overall performance as described in Section 6.1 support its deployment. A system could be integrated into the existing organizational structure and goals of NCDOT. The acquisition of mobile LiDAR through purchasing or renting can potentially replace time-consuming, labor intensive, costly operations and processes for statewide inventories, bridge inspections, and roadside conditions on North Carolina's publicly owned highways.

Airborne LiDAR data was collected across the State by NCFPM in three phases; the mountain region, most recently in 2005, the piedmont in 2003 and 2001, and the coast in 2001. The North Carolina Floodplain Mapping Program manages the data. NCDOT's Photogrammetry Unit has found use in integrating LiDAR elevation data into its current processes. By combining aerial photography, LiDAR, and other geodetic data, the Unit provides elevation products to the various business areas of NCDOT. Trends towards three-dimensional design using digital elevation models as opposed to two-dimensional planimetric CADD files may warrant future utilization of more accurate LiDAR data.

7. FUTURE RESEARCH NEEDS

The literature provided in this report provides a solid framework for decision makers looking to implement LiDAR within their surveying unit. However, there is little more than anecdotal evidence to support when a specific LiDAR platform should be applied verses a traditional surveying method under various applications. Decision makers within geomatic and surveying departments who use LiDAR regularly weigh the options of which surveying method to utilize for specific projects and base decisions on performance tradeoffs. The research team recommends that future research be conducted to survey state transportation agencies for implementation of various surveying techniques under a variety of examples to provide helpful information to current and potential users during the decision making stages of a project.

Another important research area regarding the use of LiDAR would evaluate the costs and benefits of each LiDAR platform based on the needs of a specific transportation agency. For instance, an agency that surveys large areas or segments on a regular basis would likely benefit financially by operating its own mobile or airborne LiDAR system in lieu of contracting private firms at a considerable cost. However, transportation departments and other public entities regularly make decisions based on immediate costs incurred by purchasing a unit without assessing the lifecycle benefits and long-term viability. Since costs are almost always front-loaded, the potential monetary outcomes of such a purchase are rarely considered, actually decreasing the productivity of a unit by using inferior, less cost-effective methods or employing expensive contractors. A benefit-cost analysis based on solid research would help make those types of decisions and could easily be updated as equipment costs and uses change in time.

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