Airborne Laser Terrain Mapping for Expediting Highway Projects: Evaluation of Accuracy and Cost

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Abstract: A typical highway project generally takes 5 years or more from planning phase to construction stage, particularly in wooded and difficult terrain using traditional topographic terrain mapping methods. This paper presents an application of airborne laser terrain mapping technology for a 9 km (5.9 mi.) long highway project in a difficult densely wooded terrain with steep slopes and ravines. Elevation data accuracy, efficiency, and cost effectiveness were compared with the traditional aerial photogrammetry and ground based total station survey methods. The elevations of centerline and 15 different cross sections were compared with groundtruthing data from the total station survey. Using appropriate flight mission parameters, the airborne laser technology permits elevation accuracy of 0.13 m (5 in). There are less operating constraints which adversely affect the productivity of traditional methods, such as cloud and vegetation cover, time of day, and intrusion into private properties. It is recommended to combine the low-altitude airborne laser technology with centerline staking by total station survey and aerial photography. The recommended combined approach saves 33% of the budget and 35% of time.

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Introduction

According to the Rebuild America Coalition of Washington, D.C., the nation's infrastructure funding needs, including those for schools, will exceed appropriations by $400 billion; and highways and bridges share more than half of the funds needed for transportation assets and utilities (ASCE 2000). The preservation of our nation's infrastructure requires innovative technologies and sound engineering analysis for cost-effective maintenance management within limited available funding resources. The application of innovations must consider efficiency and time saving, while achieving high resolution and accuracy in an overall cost-effective product. Topographic surveys are required for all types of transportation planning, design, and construction projects. Planning and design of a typical 10-km highway project may take around 5 years or more before actual construction. Most of this period is required to conduct topographic surveys and centerline staking for horizontal alignment. Traditionally, aerial photographs are used to locate preliminary routes and aerial photogrammetry is conducted for terrain mapping and contour generation to facilitate alignment design and earthwork quantity calculations. This is followed by labor intensive ground survey and centerline staking using total station crews.

Proper use of the innovative remote sensing airborne laser terrain mapping technology or light detection and ranging (LIDAR) offers significant time saving because it is not affected by common operating constraints, which interfere with the traditional topographic methods (Al-Turk and Uddin 1999; Pereira and Janssen 1999). An airborne platform provides nonintrusive operation. From an aircraft flying a pattern over the survey area, a focused, infrared laser (eye safe at survey altitudes) is transmitted. A high-accuracy scanner sweeps the laser pulses across the flight path and collects the reflected electromagnetic radiation. By varying the aircraft altitude and speed and the scanner angle and frequency, the operator is able to program ground point spacing to fit the particular survey mission (Uddin 2003a,b).

Objectives and Scope

The overall objective is to validate utilization of the airborne LIDAR remote sensing technology to acquire economically justifiable high-resolution and accurate digital terrain modeling (DTM) data, with efficiency and significant time saving, as compared to the DTM data obtained from conventional ground surveying and photogrammetric mapping methods. Therefore, the three methods evaluated in this study are: (1) TOTAL—conventional ground total station survey method used for groundtruthing; (2) PHOTO—photogrammetry method; and (3) LIDAR—new innovative airborne LIDAR technology for digital topographic data. Detailed cost data were also collected related to the three methods and used to determine cost and time saving of using LIDAR versus conventional surveying and photogrammetry methods. The specific objectives of this study are to: (1) acquire terrain data using the three methods from the proposed highway alignment; (2) compare the topographic data and DTM from the airborne LIDAR technology with the traditional methods; (3) validate the LIDAR-derived elevations for the centerline and cross sections with the groundtruth data from the total station survey; and (4) evaluate economic feasibility of airborne LIDAR technology.

Judging the accuracy and efficiency of using LIDAR-based

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digital terrain model versus conventional field surveying and photogrammetry procedures, either singularly or jointly, in an operational environment is an important contribution of this project. Traditional aerial photogrammetric methods have worked well for open areas, but do not have the efficiency of the new innovative LIDAR sensor mapping technology for densely vegetative and wooded areas. Translating research results to acceptable operation procedures, within cost and accuracy constraints, is expected to be the decisive factor in utilizing the new LIDAR technology. If the research validates that the LIDAR is technically equivalent to other conventional survey methods for topographic mapping of transportation corridors with significant savings in time and money, then, it is expected that airborne LIDAR can be utilized effectively by most highway agencies.

Review of Terrain Mapping Technologies and LIDAR Data Accuracy Studies

Conventional topographic survey is conducted on-the-ground by one or more survey crews using total station equipment. The corridor alignment survey consists of: (1) establishing bench marks on the test site using the global positioning system (GPS) control markers in the vicinity; (2) marking centerline and staking at every 30.5 m (100 ft) for review and approval by the sponsor agency; and (3) marking and taking cross-section data every 30.5 m (100 ft) interval for up to 45.8 m (150 ft) on each side of the centerline. The success and usefulness of a good survey crew is the collection of survey data at all visible break points along the centerline and along each cross section. Actual productivity of a survey crew depends on the terrain. The ground survey work is significantly affected by the following operating constraints: (1) only daytime operation in good visibility; (2) rain and other bad weather conditions; (3) productivity loss in wooded areas due to manual clearing of shrubs and branches and other difficult terrain problems; (4) large physical obstacles (for example, the presence of an abandoned chicken ranch house on the Raleigh Bypass project, Raleigh, N.C. caused severe delays); (5) obstacles related to ravines, streams, and other inaccessible areas; (6) traffic interference on existing roadways, traffic congestion, and proximity to urban locations; and (7) physical interruptions by property owners because of the intrusive nature of field survey operation and delays due to land disputes.

Traditionally, commercial aerial photography (passive sensor) has been used to produce orthorectified photos and digital elevation models for most transportation and landuse planning and engineering studies. A recent trend is to convert analog aerial photographs by scanning into raster images, called digital orthophoto quads (DOQs). These images are resampled to fit accurately onto a ground coordinate grid with very high pixel resolution–usually 1 or 2 m; they may be used for geospatial analysis in combination with other kinds of cartographic data. Although for highway planning and design applications, we need higher spatial resolutions, most highway agencies have been acquiring their own aerial photographs for corridor planning purposes. It should be recognized that remote sensing topographic technologies are complementary to ground survey as the ground survey is still needed for staking the centerline on the ground for highway alignment projects and during the entire construction operation for quality control and quality assurance.

Airborne LIDAR Terrain Mapping and Past Studies of Elevation Data Accuracy

With the use of pulsed lasers and integrated GPS and inertial measurement unit (IMU) technology, airborne LIDAR has emerged in recent years as a competitive low-cost, efficient alternative for topographic surveys and terrain mapping projects. The wavelengths of light range from about 1 mm for the far infrared to about 10 nm for the extreme ultraviolet in the electromagnetic spectrum. LIDAR systems utilize active laser sensor measurement in the near-infrared (NIR) electromagnetic radiation and measure the laser pulse travel time from the transmitter to the target and back to the receiver. Because the speed of light in the atmosphere is known, the range can then be calculated. A constant fraction discriminator (CFD) and time interval meter are used in measuring the time of flight of the laser pulse. A single-axis, cross track scanning mirror with scan frequencies of several thousand pulses per second is used to create a swath on the ground. High-accuracy differential GPS receivers are used in the aircraft together with the aircraft avionics and several high-resolution GPS ground monuments. The airborne LIDAR technology continues to improve constantly. Currently, modern airborne LIDAR remote sensing technology operates at 33,000 Hz. Kalman filters are applied both in real time and in postprocessing to integrate the GPS and IMU data and obtain statistically optimal (with minimum mean square error) estimates of the position and attitude of the laser scanner. By varying the aircraft altitude, the aircraft speed, the scanner angle, and the scanner frequency, the operator is able to program ground point spacing and density to fit the particular survey mission. To cover dense areas, multiples flights can be combined. For high-resolution topographic data, LIDAR missions are flown at low altitudes, often around 1,000 m or lower. After the flight mission is completed, the data points already in digital format can be easily loaded in computer workstations for processing and interpretation.

A single pulse may have multiple returns; the first return may be from tree canopy or building tops, the second from undergrowth, and the last return from bare earth. By appropriate data processing, these multiple returns are used to identify and isolate vegetation cover and buildings/structures from the bare earth terrain model. Depending on the application, specific software can be used for final revision and analysis. An example of the use of specialized software is to remove vegetation to determine bare-earth ground elevations. These data are used to generate a digital elevation model (DEM). Several studies (e.g., Hodgson and Bresnahan 2004; Veneziano et al. 2002; Shrestha et al. 1999) have demonstrated that vertical accuracy or root mean square error (RMSE) of 0.15–0.40 m (or even better in ideal circumstances) on terrain and horizontal RMSE of 0.5–1.0 m are achievable with LIDAR. The accuracy will be highly dependent on mission operational parameters and the type of terrain. Most studies have used photogrammetric and/or field GPS survey data to check the accuracies of LIDAR elevation data. In this study, total station groundtruth data are used to check the elevation accuracy of both airborne LIDAR and aerial photogrammetric methods.

Raleigh Bypass Alignment Project

Project Site and Traditional Topographic Surveys

Managing funding and technical resources and the changing environment of the transportation system within Mississippi have

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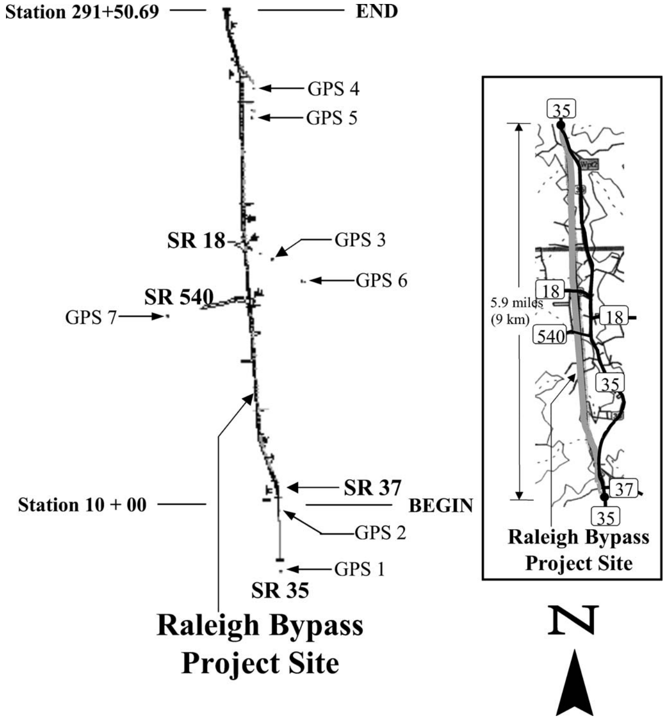

Fig. 1. Raleigh Bypass highway project location and centerline alignment established by ground control survey

crucial tasks, recognizing natural disasters and increased funding to build and/or upgrade many state maintained highways. Each new or improved transportation corridor requires detailed information about the topography of the proposed area. The Mississippi Department of Transportation (MDOT) funded the conventional surveying component to survey a section of state highway, known as SR35 Bypass of Raleigh, with a length of approximately 9 km (5.9 mi.) in Smith County, Mississippi. The MDOT's project served as a match to the NASA Stennis Space Center's funding for the airborne laser remote sensing component of the project. The bypass is necessary considering the safety concerns and inconvenience to the local residents due to heavy logging truck traffic on SR 35 passing through the city of Raleigh. The bypass site starts at the south boundary of the Raleigh, West of SR 35, crosses over intersecting SR 18, passes over private properties, an abandoned chicken farm, and several wooded areas. After some higher grounds, it connects with SR 35 again. Most of the site passes through a dense wooded area with thick vegetation cover, ravines, streams, steep slopes, and sharp changes in elevations. The project site covers an area of about 4 km^2 (1,000 acres). The general location of this SR 35 highway corridor is shown in Fig. 1.

The conventional ground-based total station surveying methods were used in coordination with the specifications set forth by MDOT in the MDOT survey manual. A conventional ground survey was conducted using traditional total station survey equipment as well as high-resolution GPS survey receivers to define points with extreme horizontal and vertical accuracy, and to determine the actual topography of the ground. The survey control points were established using several GPS markers as control points in the vicinity of the project study site. These are included in the high-accuracy reference networks (HARNs) and county base network, established by the National Geodetic Survey (NGS) and MDOT (NGS 2001; Mississippi DOT 2001). The initial estimate for the case study of the Raleigh Bypass project was 4 months from the date of start using two ground topographic survey crews; however, this initial estimated schedule prolonged due to several interruptions related to having no access to some private properties and other usual ground operating constraints. The airborne LIDAR data for this study needs to meet National Mapping Agency Standards (NMAS) for 0.3-m (1-ft) interval contour mapping (Minnesota DOT 2002). This accuracy is crucial for the planning, design, and construction phases of the highway corridor. The point spacing to be used to achieve this accuracy will necessitate submeter ground point spacing.

The aerial photogrammetric mapping portion of the project necessitates the use of a 1:4,800 scale (1 m=4.800 m) and a resolution of 0.15 m (6 in.) to meet the specifications set forth by MDOT. Generally, leaf-off periods in late fall and early spring are more suited for photogrammetry derived high-accuracy digital elevation model when trees are without leaves and there is no snow on the ground. Because of scheduling and work permission constraints, the aerial photography mission was accomplished in April 2000 over Raleigh in clear weather. This represents essentially a leaf-on period. In the field mission for Raleigh project the aircraft was flown from approximately 732 m (2,400 ft) above mean ground level. For the purpose of producing high-resolution DEM data, black and white aerial photographs were taken using a 152 mm (6 in.) focal length camera interfaced with a GPS receiver and inertial sensor technology. The aerial survey camera used Kodak Double X aerographic film 2405. This is a panchromatic negative aerial camera film with good contrast for easier interpretation from negatives, high-resolution, and wider exposure latitude. Each photo on 0.23 m × 0.23 m (9 in. × 9 in.) black and white film provided 1 km × 1 km coverage. Therefore, the aircraft made fewer flight lines. No IMU system was used because the aerotriangulation method was used in the photogrammtery process. Taking ground elevation data into consideration a forward overlap of 60% and a sideoverlap of 30% was ensured for accurate determination of features in x, y, and z coordinates during stereographic analysis. The detailed procedure is described by Uddin (2003b). Once in digital format, the orthophoto mosaic image can be viewed and printed at various scales.

Airborne LIDAR Survey Mission and Data Processing

The detailed steps used in LIDAR calibration over a building site of known topography, flight-path planning, mission parameters, ground GPS data collection, and data processing are discussed by Uddin (2003a, b) and not presented here for brevity. The airborne LIDAR mission was conducted in less than 4 h over Raleigh in clear, sunny weather in summer. Ground GPS receivers on control points were used for base control during the mission. The mission was conducted at 500 m (1,500 ft) and a pulse repetition rate of 5,000 Hz using a twin-engine Piper Aztec propeller aircraft, equipped with an ALTM 1020 laser, IMU, avionics, and a Trimble air navigational GPS receiver. Table 1 shows the specifications used in the LIDAR system. The flight path was planned to cover the study area satisfactorily including both parallel and enough cross flight lines to eliminate shadowing and allow for proper quality control. Unlike aerial photogrammetry, LIDAR missions can be flown without regard to sun angle. To minimize loss of points due to the removal of vegetation, tree, or building canopy in data processing, the total scan angle is kept narrow; however, this reduces the area covered, increasing the number of flights required. A narrow scan angle of 19° was used for this project. The aircraft was set for flying stability at 160 km (100 mi.)/h for

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Table 1. Specifications of LIDAR System Used

Specifications for Optech ALTM 1020	
Pulse energy (μJ)	60 μJ/pulse
Pulse length (ns)	20
Maximum laser rep rate (Hz)	7, 000 (5,000 Hz used in the study)
Laser average power emitted (mW)	52
Divergence (mrad)	2
Operating wavelength (nm)	1,064
Nominal survey speed (mi/h)	depends on desired point spacing; 160 km/h for Raleigh
Nominal survey altitude (m)	1,000 (500 m used for Raleigh)
Footprint at this altitude and 18° scan angle (19° used for Raleigh)	=2 × altitude × tan(0.3 mrad)
Maximum system FOV (deg)	±20° (40 full angle)
Nominal system FOV (deg)	±20° (40 full angle)
Nominal swath width (m)	Variable from 0 to 0.68 × altitude
Nominal scan rate (Hz)	Variable; depends on scan angle; e.g., 28 Hz for ±20° scan
Pulses per pixel	1
Ground pixel size (m)	See footprint size above
Nominal horizontal accuracy (m)	Better than1/2,000 × altitude (1σ)=0.25 m for Raleigh survey
Nominal vertical accuracy (m)	Better than 0.15 m (1σ)

Note: FOV=field of view.

good data collection purposes, or flying at 296 km (185 mi.)/h for transit to and from missions. Before a flight, ground-based GPS receivers were set up on known points in the survey area. Ground receivers are set so that the aircraft was within 32 km (20 mi.) from any receiver. Flight planning determines optimal LIDAR settings and aircraft parameters. The Raleigh survey was completed in about 2 hours of flight time. GPS data were collected aboard the aircraft every second using signals from 12 satellites by the ALTM operator for precise time and GPS stamping. A hand-held Husky computer was used for operation and collection of all data. The data were stored on 1 GByte tape with about 600 Mbytes used on the tape.

LIDAR scanning produces large volumes of data, which require several processing steps to produce the final DEM. The first step is to calculate the position of each returned pulse. This is a vector problem; to calculate the position of the reflecting surface, we need the starting point of the vector (the scanner position), the direction of the vector, and the length of the vector. The aircraft navigation information, along with the offset between the GPS receiver and the scanner aperture, gives the position of the scanner at the time the pulse was emitted. The direction of the laser ray is calculated from the aircraft orientation, obtained from the aircraft IMU navigation, combined with any angular offsets between the scanner chassis and the IMU, and also the angular position of the scanner for the pulse. The time of flight of the pulse gives the length of the vector from the scanner to the reflecting surface. Multiple returns for a single pulse are filtered next, to remove scatter typically caused by reflections from the vegetation canopy. For bare earth terrain modeling required for highway applications, scatter or reflections caused by buildings or trees or other tall structures must also be edited out and blank areas or missing data interpreted from the adjacent points. Scanning areas with elevated objects will result in "blank areas" or missing data, behind the objects. The terrain in the blank areas must be interpolated from the adjacent points. Fig. 2 shows the LIDAR data processing activity flow. A proprietary "vegetation

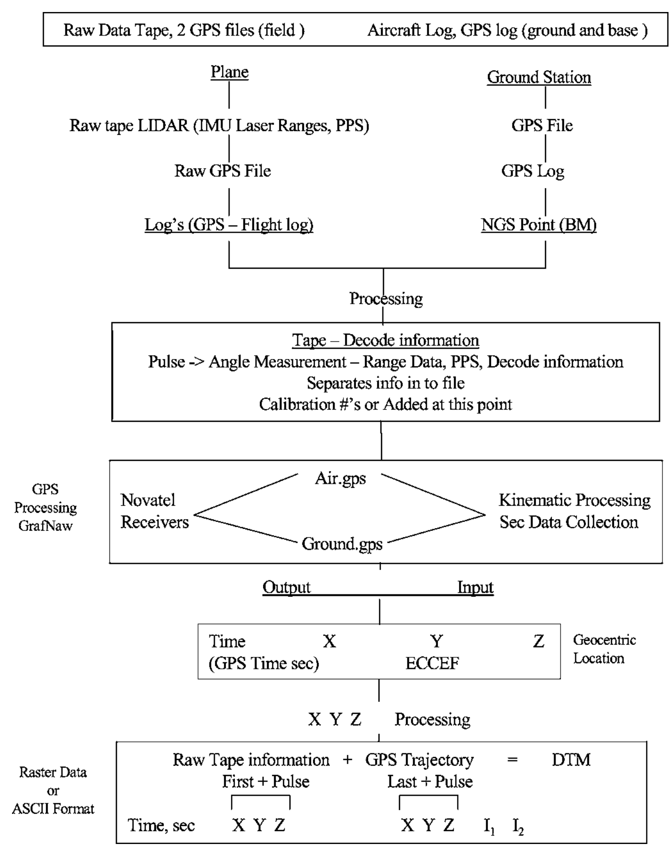

Fig. 2. Schematic of LIDAR data processing activity flow

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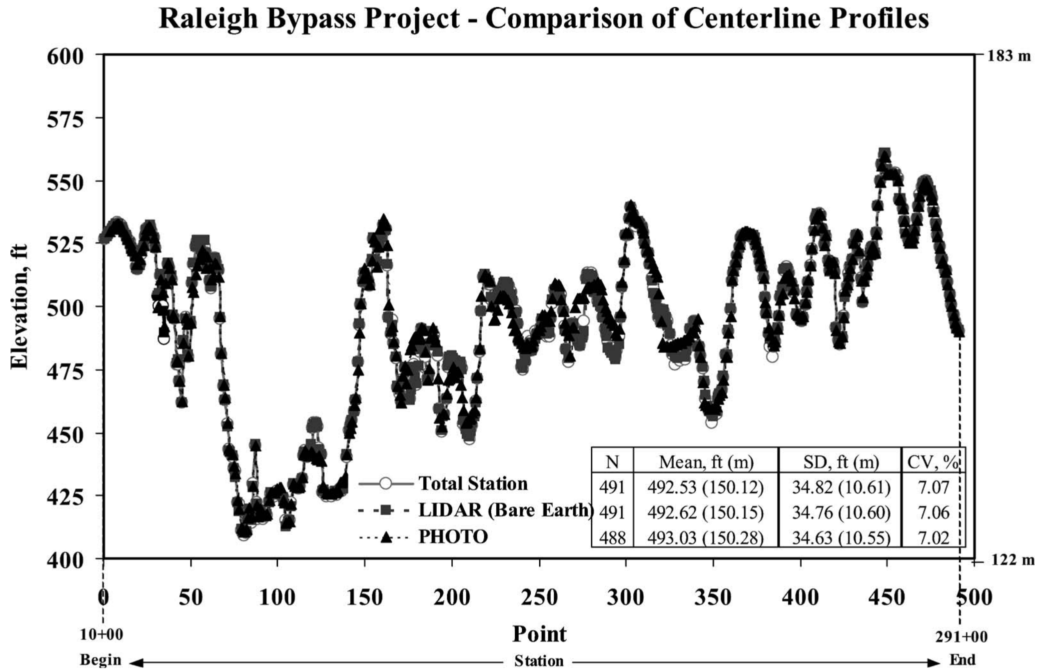

Fig. 3. Plots of centerline elevation profiles for TOTAL, LIDAR, and PHOTO data

removal" software discriminates between the first return and second return of the laser points and produces a bare earth DEM without vegetation cover, tree canopy, and buildings and tall structures. Further application of ASCII LIDAR data files in North American Datum of 1983 (NAD83) coordinates was facilitated by a topographic mapping software and a standard computer aided design (CAD) software. Some of the useful outputs are: development of DEM and digital terrain model using the triangular irregular network (TIN) linear interpolation procedures, a DTM model with color-coded elevations, a bare-earth DEM, a contour map overlying the georeferenced photo raster image and three-dimensional (3D) views, and overlay of the centerline alignment of the highway to calculate earthwork quantities.

Comparison of Three Topographic Survey Methods

Data Processing for Centerline Profile and Cross Sections

The elevation data from the conventional ground survey (called TOTAL in this study) along the centerline profile and several cross sections were used for groundtruthing because this is the best and most accurate topographic survey method with an accuracy of better than 3 mm (0.01 ft or 0.12 in.). Terrain mapping software packages were used for extracting the elevation data at the desired points from the DTM developed using each of the remote sensing airborne topographic survey methods (called PHOTO and LIDAR in this study). This is accomplished by overlaying the centerline profile from the control total station survey on the desired DTM. An interpolation scheme is used in the DTM to extract elevations corresponding to the points of interest on the ground. The same GPS control points were used by all three methods to process the spatial coordinates x and y. Similarly, the elevation data for the cross sections were calculated by the two airborne remote sensing methods and compared with the ground-based total station data for elevation accuracy.

The centerline profiles from the three methods are reasonably close; however, more data points are available in the DEM generated by the LIDAR method. Few laser data points are available on some locations due to the vegetation removal algorithm used. At many places the LIDAR points are spaced at less than 0.6 m (2 ft). Also, on SR 35 and SR 18 within the project boundary, the laser points are very dense because these were reflected on pavements. These observations are significant and demonstrate the extensive coverage of the LIDAR points on the ground and reveal an effective data analysis process, considering that a major part of the proposed alignment is wooded and that the laser points are spaced randomly. This implies that earthwork quantities and drainage analysis using the ground survey may not be as accurate as that from the LIDAR because of the large extent of the ground point density of the LIDAR data.

Elevation Data Comparison Using Mean Difference and Intraclass Correlation

Fig. 3 shows centerline elevation profile plots from the three methods for the entire project on an exaggerated vertical scale. This full data set was used for most of the analysis presented here. In order to evaluate the accuracy of the elevation (Z) values from the LIDAR and PHOTO methods against those from the groundtruth TOTAL method, a comprehensive scientific analysis was undertaken using these centerline elevation data sets and additional cross-section elevation data sets. Mean differences and intraclass correlations were calculated for each of these scientific studies. For each data set no statistically significant difference was found in the mean elevation data from the three methods at 95% confidence level, as discussed in detail in the following sections.

Mean differences, assessed using the independent samples t-test and Cohen's d, were calculated to determine whether LIDAR laser or PHOTO methods produce mean Z values that differ on average from those of the groundtruth TOTAL method. The t-test for independent samples tests the hypothesis of no

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Table 2. Summary Results of Centerline Profile Elevation Data

Total station (ground)		LIDAR		Photo	
M	SD	M	SD	M	SD
(a) Means (M) and standard deviations (SD) of measurements of Z by TOTAL, LIDAR, and PHOTO methods[a] (matched data)					
492.31	34.82	492.40	34.76	493.03	34.63
Comparisons	t	p	d	Intraclass correlation (95% CI)	
(b) Mean differences and intraclass correlations centerline profile elevation data					
Z					
Total station versus LIDAR	0.041	0.967	0.003	0.9997(0.9996–0.9997)	
Total station versus Photo	0.324	0.746	0.021	0.9917(0.9900–0.9931)	

Note: t represents t statistic value; p represents the probability of the observed difference given the null hypothesis; d represents the number of SDs separating sample means; CI means confidence interval.

[a]$n=488$ for each method.

mean differences (called the "null hypothesis" or Ho) and produces the probability of obtaining the observed mean difference between samples by chance if the null hypothesis was true. The effect size estimate, Cohen's d, represents the number of standard deviations separating the two sample means (Cohen 1988).

The intraclass correlation (ICC) method (McGraw and Wong 1996) was used to characterize the similarity of measurements across the methods. Unlike the Pearson R, which quantifies the bivariate relationship between variables representing different measurement classes (e.g., a person's height in cm and a person's weight in kg), ICCs are designed to measure the relationship between variables of a common class, i.e., that share both metric and variance. The elevation data from the three methods have the same unit of measurement, which is feet (ft) in this analysis. Various forms of the ICC exist, representing different study models and data characteristics. The "absolute agreement with the two-way mixed effects model" was chosen for the Raleigh Bypass elevation data because: (1) each data point is random (i.e., is replaceable with any other data point); (2) each of the three topography measuring methods used in the Raleigh Bypass study is fixed (i.e., was chosen by the researcher and study sponsors); and (3) absolute differences as well as rank order similarities between the groundtruth TOTAL and LIDAR or PHOTO methods are of interest. The SPSS software was used for statistical data analysis (SPSS 1999).

First, the centerline profile elevation data from each method were processed to ensure that only match data sets at the same stations were analyzed. Table 2 shows the results of mean differences and intraclass correlations. The centerline elevation data show that the mean differences in measurement of elevation Z by groundtruth TOTAL method and the two other methods are very small and not statistically significant ($p > 0.05$), indicating that they are easily attributable to chance factors. The effect size (d) for group mean differences, which represents the number of standard deviations separating the two sample means, ranges from 0.003 to 0.021. This indicates that the two pairs of distributions (groundtruth and LIDAR; groundtruth and PHOTO) overlap almost 100%. ICCs (>0.99) reveal almost perfect agreement between data obtained from the groundtruth method and those from the other two airborne LIDAR and PHOTO methods.

The Z elevation data from each method for 21 cross sections along the horizontal alignment were reviewed to ensure that only match data sets at the same stations were analyzed. Fig. 4 shows the mean elevation data plots for these cross sections. Consistent with previous results, mean differences and ICCs reveal almost identical data generated by the groundtruth TOTAL method and generated by the LIDAR and PHOTO methods. Therefore, this scientific analysis validates the accuracy of both the LIDAR and PHOTO elevation data, subjected to data collection and processing protocols used in this project.

RMSE Analysis for Elevation Data Accuracy

The national mapping standards for positional accuracy of spatial data (Minnesota DOT 2002) use root mean square error (RMSE) and National Standard for Spatial Data Accuracy (NSSDA) to evaluate the accuracy of a test method (LIDAR or PHOTO in this case) with the standard control method (TOTAL in this case). Both statistics have the same unit as that used for measurements (cm or in.) and can be used to evaluate horizontal or vertical accuracies. In this study all horizontal points were established by the control TOTAL method; therefore, only the vertical accuracy of LIDAR elevation (Z) data is evaluated using the following equations

$$\text{RMSE} = \text{square root of}[\{\Sigma(Z\ \text{control} - Z\ \text{test})^2\}/\text{number of data points}]$$

$$\text{NSSDA} = \text{RMSE for } Z \text{ at the } 95\% \text{ confidence level} = 1.96 \times \text{RMSE}$$

The summary statistics of the elevation data from the three methods indicates 150.12, 150.15, and 150.28 m mean elevation from TOTAL, LIDAR, and PHOTO methods and only around 7% coefficient of variability. The RMSE value of 0.28 m and NSSDA value of 0.54 m for the control, TOTAL, and LIDAR methods are relatively lower than those values for the TOTAL and PHOTO methods. A correlation analysis of elevation data shows an almost 1.000 R value for TOTAL and LIDAR with lesser scatter than 0.992 R value between TOTAL and PHOTO. It is noted that the accuracy of ground elevation extracted from the PHOTO method can be improved if the mission is flown at a lower altitude than 730 m used for the aerial photography mission in this study and during leaf-off periods. Recall, the aerial photography mission was flown in April 2000 during the leaf-on period.

For the purpose of corridor planning and preliminary alignment design and earthwork estimate, the vertical accuracy of the bare-earth LIDAR data with RMSE value of 0.28 m is adequate, considering that numerous steep slopes are present in this wooded site. For detailed engineering analysis and highway alignment de-

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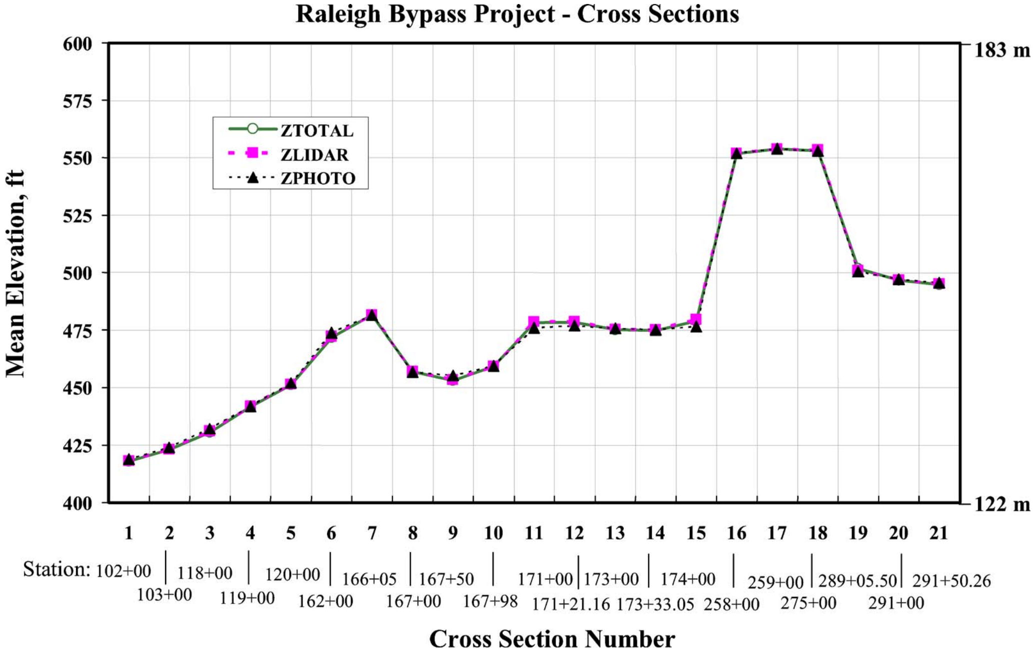

Fig. 4. Mean elevation data plots for 21 selected cross sections

sign, it is preferred to use DEM for the entire highway corridor with higher accuracy of 0.15 m RMSE and to generate more precise 0.3 m (1 ft) contours. The detailed engineering design of highway alignment also warrants the establishment of the proposed centerline on ground by 30.5 m (100 ft) staking and measurement of ground elevation by using a total station. Therefore, additional analysis of the LIDAR elevation data was conducted to quantify the effects of steep slopes and wooded terrain on the RMSE calculation. Similarly, cross-section leveling by total station was done on both sides of each 30.5 m (100 ft) centerline station including all break points. This was done on the Raleigh project as shown by the total station TOTAL elevation data.

To study the effect of steep slopes and wooded terrain on RMSE and NSSDA values of the LIDAR data, further data analysis was conducted. The areas of steep-sloped terrain (ST) along the centerline were marked by examining the centerline total station data showing a 10% or higher slope, which are about 62% of all data points. The rest of the 38% site was considered rolling and flat terrain (RT), which showed less than 10% slope. The RMSE value of all RT areas is 0.21 m (0.68 ft). Next, the wooded terrain (WT) areas were identified with the assistance of orthophotos and by the vegetation removal software. The LIDAR elevations of these WT areas (21.6% of all RT data points) were replaced by the corresponding elevations measured by the total station (TOTAL) method. The RMSE value of all 491 LIDAR data points (including the replacement by the TOTAL data in WT areas) is now reduced to 0.13 m (0.42 ft or 5.12 in.). The resulting NSSDA vertical accuracy is 0.26 m (0.84 ft or 10.0 in.) at 95% confidence level. The average RMSE value for 21 cross sections is 0.39 m for the LIDAR elevation data without any replacement. Approximately, 40–45% cross sections fall within the wooded areas. The average RMSE value is 0.16 m for all these datasets when the LIDAR elevation data in wooded areas are replaced by the total station elevation data. The RMSE value is reduced to 0.14 m for 95% datasets by excluding cross section 15.

For comparison with the vertical elevation data accuracy results of the Raleigh Bypass project, some other studies of LIDAR-derived elevations for highway applications indicate up to 0.15 m RMSE values for flat terrain, 0.23–0.38 m for sloped terrain, and higher values for ditches and rock cuts (Minnesota DOT 2002; Pereira and Janssen 1999; Shrestha et al. 1999). In the Raleigh Bypass study with 62% of the site having steep slopes, the RMSE of all LIDAR centerline elevation data is 0.28 m (within the lower bounds of other reported data for sloped terrain) before any replacement; and the RMSE reduces to 0.13 m after replacement of these data by the total station elevation data in wooded areas.

Limitations of Three Topographic Survey Technologies

The following key limitations are associated with each of these three technologies for collecting topographic data and using them for highway planning and design:

1. Ground-based total station: Too expensive to create detailed topographic maps, time consuming, and sometimes problems with access to property, several operating field constraints of time of day, and adverse weather conditions. However, ground-based total station survey must be conducted for centerline staking and construction grade control;
2. Photogrammetry: Field operating constraints associated with the aerial photography (no nighttime mission and poor visibility/cloudy in daytime), leaf-on survey not suitable for the required DTM accuracy, leaf-off survey needed for more accurate ground elevations (possible only in late fall or early spring leaf-off periods with no snow on ground, limiting the available months for flying missions), time consuming, and labor intensive photogrammetry analysis for generating DTM; and
3. Airborne LIDAR: Some constraints associated with the LIDAR topographic data are; data holes in the areas of water bodies, suspect data in steep slopes and ridges, inadequate data to define ditches and breaklines, and need of orthophotos for planimterics. These constraints limit the ability to use LIDAR-generated DTM as a sole terrain model for final alignment and design.

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Table 3. Summary of Total Costs and Duration of Work for Each Method and Recommended Combined Approach

Item	Total station	Airborne LIDAR	Photogrammetry	
(a) Summary of the overall total costs and duration of work for each method				
Total cost	$ 165,696	$ 23,137	$ 24,705	
Time (estimated net period of work) (months)	10	1.5[a]	2	
(overall period in which work was conducted) (months)	(36)	(31)	(12)	
Item	Combined approach	Total station	Airborne LIDAR	Aerial photogrammetry[b]
(b) Summary of the overall accuracy, total costs, and duration of work for the recommended combined approach				
Elevation accuracy (RMSE); Desired results=0.15 m	0.13 m	Control	0.28 m	1.36 m (leaf-off period)
Total cost	$ 112,298	$ 165,696	$ 23,137	$ 24,705
Time (months)	6.5	10	1.5	2

Note: Total cost of each method includes data collection and office data processing cost based on actual record of payment made to subcontracts and in-house time cards of the project staff employed by the service provider; Total cost of the combined approach is estimated from the low-altitude airborne LIDAR mission and aerial photography, in addition to centerline staking by total station and correction of LIDAR derived elevations; and Time taken by each method is based on actual time logs for data collection and time cards of the office data processing staff employed by the service provider.

[a]Includes reanalysis of LIDAR bare-earth elevation data with partial replacement by the TOTAL elevation data in wooded terrain areas.

[b]Combined approach requires only georeferenced raster image; no photogrammetry.

Cost Data, Time Saving, and Economic Feasibility

Cost data collection and analysis based on equipment cost, operating and field data costs, and data processing costs were conducted for each of the three methods of topographic surveys and DTM data for the Raleigh Bypass site. These costs were extracted from the service provider's time sheets, summarized, and provided to the researcher team on cost summary forms. The following assumptions were used: (1) all equipment and data processing facilities are available in-house or preleased; (2) all operators and crew/staff members are adequately trained; and (3) the required DTM and DEM outputs for each method is for the 9 km (5.9 mi.) long project site covering an area of about 4 km^2 (1,000 acres).

Table 3 part (a) provides a summary of the total cost, estimated period of field survey and office data processing work, and overall period of work. The project was put on hold from the beginning of December 1999 through the beginning of May 2000. A break in the ground-based total station survey work was encountered again from December 2000 to May 2001. The combined costs of LIDAR for contour maps and ground based total station for layout and staking is expected to be substantially lower than the cost of the conventional total station survey without LIDAR data, as shown in part (b) of Table 3.

A comparative evaluation of all three topographic survey methods was made using the following criteria: (1) field equipment robustness and durability; (2) field data collection and processing; (3) operating restrictions; (4) office data processing; (5) data quality and usefulness; (6) permanent record of ground surface; (7) cost of equipment and operation; (8) cost effectiveness; (9) user preference; and (10) overall ranking.

A numeric rating scale of 1–5 (poor, marginal, acceptable, good, excellent) was used for criteria 1–9. For example, for criterion 1 (field equipment robustness and durability–high field automation reliability) applied to the total station ground survey method, a numeric scale of 4 implies a "good" rating and that the rater "almost always" agrees with the given statement. The highest sum of rating scores is given the highest ranking. By this simple analysis of rating scores, the three topographic methods are ranked from highest to lowest in the following order: LIDAR (excellent), PHOTO (good), and TOTAL (acceptable). This qualitative ranking analysis is in no way meant to diminish the value of conventional photography and ground survey methods or replace these prevalent trusted older technologies.

The benefit of completing the field airborne mission in hours instead of weeks and months is quite obvious because of the nonintrusive survey from the sky and lesser effort consumed in office data processing of the LIDAR data, compared to the traditional photogrammetry. This will result in enormous savings in time and associated delay costs, especially for large size projects. In a recent study using LIDAR over photogrammetry, 71% saving was estimated for a 26 km^2 (10 mi.^{2}) corridor and 50% saving for a 74 km (46 mi.) corridor (Veneziano et al. 2002).

Recommended Approach for Topographic Mapping for Highway Projects

A combined approach is recommended to develop an accurate DTM in a cost effective and efficient way for highway planning and design. This approach combines the benefits of each of the three technologies and supplements their limitations by the strength of each technology. The RMSE result of 0.13 m (5.12 in.) for all 491 centerline data points including the TOTAL data replacement of the LIDAR elevations in the wooded area is well within the desired higher elevation data accuracy of 0.15 m (0.5 ft or 6 in.) that is warranted for detailed engineering analysis, highway alignment design, and calculation of earthwork quantities for bid cost estimates. This is the basis of the above recommended approach to use a combination of the three methods in using LIDAR-generated DEM for highway planning and design that provides the most cost-effective and time-saving strategy for expediting construction. The final recommended approach is as follows:

1. Use the low-altitude high-resolution airborne LIDAR topographic data and georeferenced aerial photography (at medium to high altitude to save cost), obtained in a significantly short amount of time, for corridor assessment, highway planning, and preliminary alignment design;

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2. Conduct centerline staking and ground total station topographic survey on full stations and breakpoints;
3. Use these data to replace the LIDAR elevations in the wooded areas, steep slopes, residential buildings, and urban built areas to achieve final topographic data within the desired high elevation data accuracy of 0.15 m (0.5 ft or 6 in.); and
4. Use this high-accuracy corrected LIDAR topographic data and generate 0.3 m (1 ft) or larger interval contours for detailed engineering analysis, highway alignment design, and calculation of earthwork quantities for bid cost estimates.

The combined cost of the LIDAR mission, the aerial photography mission, and the related data processing effort is about \$48,000 for this 9 km long and 4 km^2 highway project. This is much lower than the cost of the conventional total station survey, staking, and data processing for about \$166,000. The recommended combined approach saves 33% of the budget and 35% of time, as shown in Table 3 part (b). Therefore, the recommended approach of a combination of these three topographic technologies saves both time and cost in providing acceptable topographic data for highway planning and design, and expedites construction. The "new technology problems" associated with LIDAR may affect the productivity and time saving because of the highly specialized extensive training of both field data collection and office data processing staff and frequently observed high turnover of trained staff. As technology matures, this problem will dissipate.

In summary, a combination of LIDAR mapping as a complementary terrain mapping technology with the conventional ground survey for centerline staking and construction control is the most cost-effective system that can save significant time and overall costs. The key to successful implementation of the LIDAR remote sensing technology is to establish the correct combination of all three methods (and perhaps modern high-resolution satellite imagery in the absence of aerial photography) for cost-effective applications of transportation corridor assessment and detailed highway planning and design. By combining the funding sources of state and local county levels, the airborne LIDAR mapping data can be jointly collected and shared for multiple cooperating user agencies. This can lower the cost considerably at county and regional levels.

Accurate terrain mapping is essential for efficient and cost-effective highway planning and design, expediting construction projects and environmental impact assessments, and enhancing infrastructure asset management by using a geographical information system (GIS) for defining georeferenced locations, storing attribute data, and displaying data on maps (Uddin 2003a). Collecting good quality geographical coordinate data by traditional manual methods may require a substantial investment depending upon the size of the assets. High-resolution commercial satellite imagery is available in 1 m and submeter spatial resolution, and their effective timely use has been demonstrated after the 2004 Asian Tsunami destruction in the Indian Ocean region and the 2005 Hurricane Katrina disaster in New Orleans and the Mississippi Gulf Coast region. In planning, design, and construction of highways high-resolution satellite imagery is a cost-effective alternative to traditional aerial photo raster imagery. The use of georeferenced multispectral satellite imagery for serving a raster image layer for initial highway planning, land use/land cover (surface) classification, and extraction of transportation features saves time and cost (Guienko and Doytsher 2003; Boriboonsomsin and Uddin 2006).

Conclusions and Recommendations

Airborne LIDAR topographic technology presents several potential advantages over the traditional methods of photogrammetry and manual field survey. Data collection by field survey using total station tools can produce very accurate information. However, this method requires a team to measure distances and angles in the field and is thus time consuming and expensive. Photogrammetry is time consuming and is constrained to daytime operations in cloud-free conditions and within a limited leaf-off period. With LIDAR, time consumption can be considerably reduced, since the data collection speed is very high, data acquisition can be conducted any time of day or night and in some types of weather unsuitable for aerial photography, and the data are collected and stored directly in digital format. The ability to operate in difficult terrain, in cloudy weather, and at night is extremely beneficial from cost-saving perspectives and considerations of expediting the total construction project.

This real-world highway alignment project has been a good example of common reasons for long delays in highway corridor planning and survey resulting from unexpected interruptions by disputes brought by land and property owners, on-site problems related to terrain, and weather and season related natural constraints. The conventional aerial photography combined with modern GPS interface is plagued by operating restrictions for leaf-off periods and only daytime operation. It still needs much manual photo scanning to convert analog image to digital raster image, and manual interpretation to obtain a DTM and contour map for topographic applications.

Extensive statistical analysis of centerline 30.5 m (100 ft) spaced stations and 21 cross sections by the Interclass Classification method showed almost perfect agreement between data obtained from the three methods. The results showed that the RMSE value of elevations reduced from 0.28 to 0.13 m after replacement of wooded area data with the total station data; and the resulting NSSDA vertical accuracy became 0.26 m at the 95% confidence level. A comprehensive cost analysis was also performed in this study. The time saved from the LIDAR terrain data for route location, horizontal alignment, and roadway design will be enormous, resulting in significant reductions in the overall highway design and construction period. Cost savings will be substantially higher for larger areas, difficult terrain, heavily populated areas, or congested urban areas.

The following approach is recommended to develop an accurate DTM in a cost-effective and efficient way for highway planning and design. This approach combines the benefits of each of the three technologies and supplements their limitations by the strength of each technology.

1. Use low-altitude LIDAR elevation data and aerial photos (at medium to high altitude to save cost) for corridor planning and preliminary alignment design;
2. Conduct centerline staking and total station ground-based survey on full stations and breakpoints, as normally required for detailed alignment design;
3. Replace the LIDAR elevations by the total station data for wooded areas as identified from filtered LIDAR data files and aerial photos, and generate corrected DTM and contours; and
4. Use corrected LIDAR-generated DTM and contours to perform detailed engineering analysis, horizontal and vertical alignment design, geometric design of intersections and other components, and precise earthwork quantity calculations for construction cost estimates.

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The recommended combined approach saves 33% of the budget and 35% of time. The key to successful implementation of the airborne LIDAR remote sensing technology is to establish the correct combination of all three methods and modern high-resolution satellite imagery for cost-effective applications of transportation corridor assessment and detailed highway planning and design. This approach can provide acceptable topographic data accuracy and be cost effective, as shown by the detailed cost analysis in this study. It is further recommended that performance-based specifications be developed for airborne LIDAR data acquisition and digital terrain mapping for highway-specific applications in planning and design.

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