AIRBORNE LASER MAPPING FOR HIGHWAY ENGINEERING APPLICATIONS[1]

Ron Berg, M.A.Sc., O.L.S.
Deputy Chief Surveyor
Ministry of Transportation Ontario
301 St. Paul Street
St. Catharines, Ontario, Canada, L2N 3R1
ron.berg@mto.gov.on.ca

James Ferguson, B.Sc., O.L.S.
Mosaic Mapping Systems Inc.
(formerly GEOsurv Inc.)
89 Auriga Drive
Ottawa, Ontario, Canada
jamesf@geosurv.net

ABSTRACT

Airborne laser mapping integrates three technologies into a single system to produce accurate digital terrain models (DTM) of the earth's surface. The three technologies, Light Detection and Ranging (LIDAR) using laser, Global Positioning System (GPS) satellites, and Inertial Navigation Systems (INS), have all been available for several years. Developments in all three technologies have allowed the integrated system to be utilized in an airborne environment with increasing levels of accuracy.

The Ministry of Transportation Ontario (MTO) decided to investigate the potential of airborne laser mapping for its highway engineering surveys and route planning studies. Traditionally, conventional photogrammetric mapping is collected in a project area for preliminary highway design. This is followed by more accurate ground surveys in critical areas (ie. pavement surfaces) at the detail design stage. MTO wanted to determine whether airborne laser mapping could provide an alternative to its traditional process.

Two pilot projects have been conducted, one on a 23-kilometre stretch of existing 2-lane highway, and another cross-country through 17 kilometres of forest. On each project, a digital terrain model was generated from the LIDAR point data. Corresponding digital imagery was individually rectified and mosaiced, then draped over the DTM to facilitate map compilation of existing ground features. The GPS and INS data were utilized in both processes to spatially reference the data.

The resultant DTM and vector data were compared to ground audit surveys conducted by total station throughout the project areas. The individual LIDAR point data has proven to be less accurate than conventional photogrammetric mapping data collection. However airborne laser mapping offers some distinct advantages, such as high point density and canopy penetration, that can result in a superior digital terrain model under certain conditions. This paper examines the achievable accuracy, benefits, and limitations of airborne laser mapping for highway engineering applications.

INTRODUCTION

A Lidar system combines a narrow-beam laser with a receiver system. The laser produces an optical pulse that is transmitted, reflected off an object, and returned to the receiver. The receiver accurately measures the travel time of the pulse from its start to its return. With the pulse travelling at the speed of light, the receiver senses the return pulse before the next pulse is sent out. Since the speed of light is known, the travel time can be converted to a range measurement by Distance = (Travel Time x Speed of Light)/2. By combining the laser range, scan angle, laser position from GPS, and laser orientation from INS, accurate X,Y,Z ground coordinates can be calculated for each laser pulse.

---

[1] Much of this paper was previously published in Berg, R. and J. Ferguson, 2000. A Practical Evaluation of Airborne Laser Mapping for Highway Engineering Surveys. ION GPS 2000 Proceedings, September 2000, Salt Lake City, Utah, USA.

Laser systems capable of making centimetre-level accuracy distance measurements have been around for many years. Technological advances in the complementary fields of GPS and INS, along with ever-increasing computing power and storage capabilities have allowed for the development of an integrated system for use in an airborne environment. With absolute accuracy claims on the order of 15 cm in the vertical component (eg. Fowler, 2000a, Hill et al, 2000), airborne laser mapping has potential applications in the highway planning and design process.

The Ministry of Transportation Ontario (MTO) typically acquires 1:3000 aerial photography on its highway engineering projects. This is followed by 1:500 photogrammetric mapping accurate to 30 microns (at photo scale) for hard surface features and 75 microns for soft surface features, which translates to 9 cm and 23 cm respectively for 1:3000 photography (MTO, 1994). Ground surveys accurate to 2 cm are conducted on the critical hard surface features such as pavement, and a digital terrain model is then generated from the combined photogrammetric and ground survey data for detail design.

It was thought that LIDAR would be beneficial to MTO if it could provide an accuracy similar to that of the photogrammetric mapping products normally produced. Some of the potential advantages of LIDAR over ground surveys or photogrammetric mapping include:

1. A DTM can be collected and processed much more rapidly.
2. LIDAR can be less expensive as project size increases.
3. LIDAR can be flown under less restrictive conditions than aerial photography. It can be flown year-round during the day without regard to sun angle since avoiding shadows is not an issue, and it can also be flown at night
4. LIDAR has the ability to penetrate canopy. Given the high density of raw data points enough shots should hit the ground in moderately forested areas to provide a reliable DTM. LIDAR has a distinct advantage here, because even though aerial photography may also reveal holes in the canopy, the photogrammetric process requires that the same ground point be visible in two overlapping photographs in order to measure the ground elevation.
5. Some LIDAR units can record multiple returns (ie first pulse, last pulse) as well as pulse intensity, to aid in classification of features such as vegetation, buildings, and bare ground.

PROJECT EXPECTATIONS

A 23-kilometre stretch of 2-lane highway was chosen as the initial pilot project. This project contained a large forested area off the highway corridor where re-routing was being considered, so it was a prime location to assess the LIDAR data. This off-highway area was approximately 1 by 2.5 kilometers. The remainder of the corridor was mapped to 75 metres either side of centreline. The project was under strict time constraints and it was hoped that the complete LIDAR DTM, feature mapping, and imagery could be delivered more rapidly than by photogrammetric mapping. Furthermore the project was not given final go ahead until July, 1999 when leaves and ground vegetation were present, and it was anticipated that LIDAR could be advantageous under these conditions.

Project specifications included:

- LIDAR data points collected for the DTM must have horizontal and vertical accuracies less than 15 cm for hard surface features (i.e. pavement) and less than 20 cm for soft surfaces (i.e. original ground).
- Preparation of a Digital Terrain Model in AutoCAD 14/Softdesk 8 project format. (Now AutoCad Land Development Desktop)
- Feature collection and layering according to MTO standards.
- A single digital orthophoto for the entire project.

MTO specifications had to modified for this project to accommodate differences in imagery, DTM generation, file formats, etc. between the LIDAR process and conventional photogrammetric mapping. Also, the accuracy requirement for hard surface features was reduced from 9 cm to 15 cm. A project report is given by GEOsurv (1999).

In June, 2000 a second LIDAR project was undertaken by MTO. The project area was a 1.5 by 17 kilometre cross-country swath off the highway corridor, again where re-routing was being investigated. LIDAR was again considered for this second project since the timeframe was short, the data would be gathered in leaf-on conditions, and a ground survey would be cost-prohibitive and take too long to complete. A project report is given by GEOsurv (2000).

This paper focuses on the first project in detail since the results and issues of the second project are similar in nature. Some commentary from the second project will be provided where appropriate, especially with respect to the ability of LIDAR to penetrate canopy, which was investigated more thoroughly on the second project.

THE LIDAR SYSTEM

GEOsurv owns and operates an Optech ALTM 1020 system. The ALTM system is comprised of a high frequency optical Spectra Physics Laser, a Litton Inertial Navigation System (INS), and is connected to a Trimble 4000SSI GPS receiver to provide precise position, timing and event marking.

The ALTM system specifications are as follows:

- 330 to 1000 metre above ground operating altitude
- 5000 Hz measurement rate
- 0 to ∀20 degrees scan angle
- Maximum 30 Hz scan frequency at 20 degrees
- 0 to (0.68 x altitude) swath width
- 2-3 cm single-shot range accuracy
- 15 cm (1 sigma) elevation accuracy
- better than (1/2000 x altitude) horizontal accuracy

(Optech, undated)

A Kodak DCS420 natural colour / colour infrared camera was used (in natural colour mode) with a Nikkon 28mm f/2.8 lens locked to infinity. The camera and lens were calibrated using a specific target array and in-house software to determine the effective focal length, radial lens distortion, and intersection of the optical axis and detector array. The camera and the ALTM 1020 scanning head were then aligned and mounted on a single rigid aluminum plate such that their optical axes were parallel and the scanning plane of the ALTM 1020 was parallel to the rows of the camera detector array. Calibration flights were performed over pre-surveyed, coordinated buildings and other ground features to verify system alignment and calibration.

The mounting plate holding the camera and the ALTM 1020 were held by a metal frame over the observation hole in the floor of the aircraft (Cessna 337) in a vertical viewing position. The frame was equipped with vibration isolators.

METHODOLOGY

To facilitate DTM generation, image display and vectorization on the first LIDAR project, the project corridor was divided into 23 segments. The segments are not of regular size since the corridor width varies between 150 and 1000 metres, and the road is not straight north-south. The total area mapped was approximately 580 hectares. An index map of the 23 project segments is shown in Figure 1.

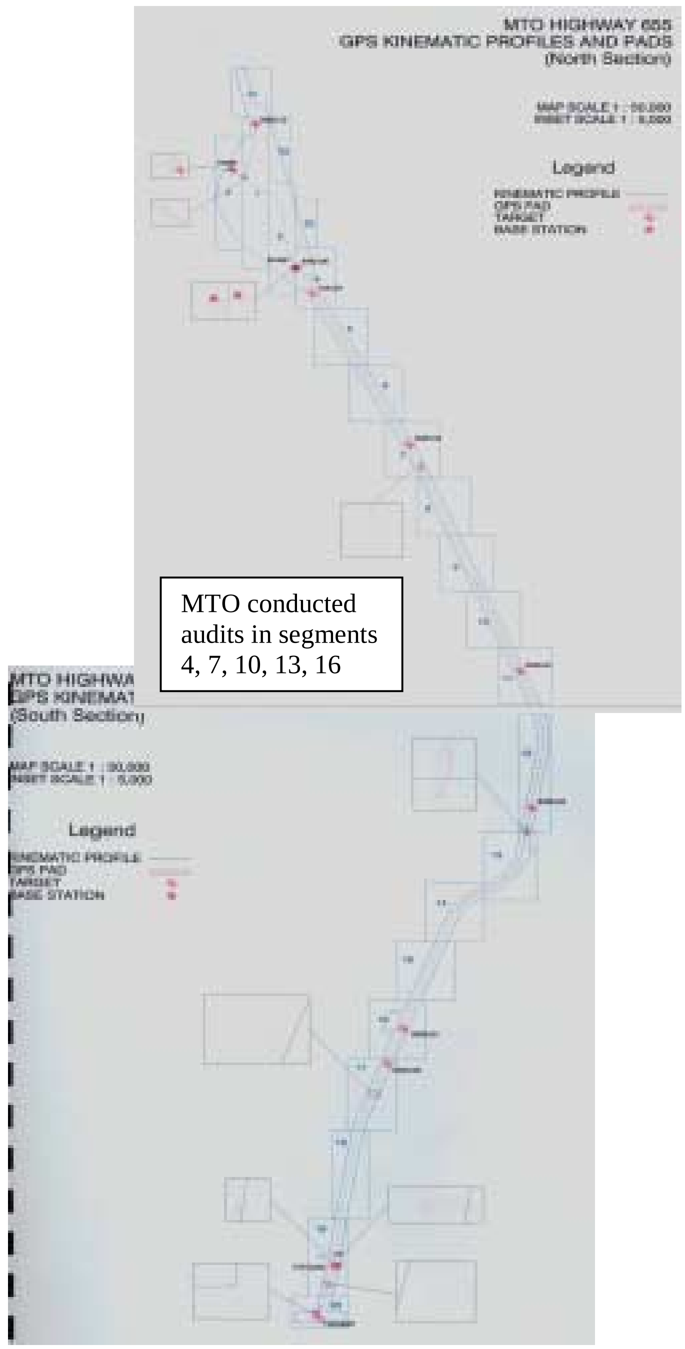

Figure 1 - Project 1 Index Map

GPS Control

The GPS ground work was broken into five elements: (1) reconnaissance of existing control, (2) base station selection and survey for the airborne data acquisition, (3) targeting and survey of checkpoints for the digital frame camera, (4) survey of check pads and check profiles for comparison to the Lidar data, and (5) survey of photo ID points.

A 1998 MTO GPS survey established 2nd-order intervisible pairs of control points at approximate 3 km spacing throughout the project area. A precise levelling route also existed along this highway. These stations provided the control framework for the project and were used to establish base stations, targets, profiles, check pads and MTO audits. Fast Static GPS surveying was done using 3 Trimble 4000SSi GPS receivers. A single survey network was created including the ties between the base stations acquired during the airborne data acquisition phase. Nad83 and CGVD29 were the horizontal and vertical datums respectively, and GSD95 was used as the geoid model.

Profiles and check pads were measured using a car set up with a dual frequency GPS antenna, collecting data relative to one of the base stations at 1 second epochs. The vertical height of the antenna on the car above the asphalt was measured so it could be applied to the final result. Profiles were taken as close to the road centreline as possible. In addition, several open flat areas were profiled (parking lots, road intersections). These sets of profiles were used to extract any vertical bias from the LIDAR system. To quality control the horizontal component of the LIDAR and image data, GPS fast static surveys were done on guard-rails, road edges and rock cuts.

Digital Terrain Model

The laser is positioned over an opening in the aircraft floor and scans a swath up to 20 degrees each side, measuring distances to the earth's surface along with the corresponding scan angles. The laser emits pulses at frequencies of up to 5000 Hertz. These pulses are reflected off the ground, vegetation or man-made structures at different time intervals, so the varied distances between the emission and reception can be calculated.

With such high pulse emission rates, the laser can obtain as many as 300,000 3-dimensional points per minute. For this project, the nominal flying height was 500 metres above ground. Due to the narrow and sinuous shape of the corridor and to ensure Lidar point density, 25 flight lines were needed to cover the entire area. With an aircraft speed of approximately 100 knots, and the frequency and width of the laser scan, the ground point density was collected as close as 1.5 metres in open areas. The data are closer than this where overlaps between flight lines occurred.

During each laser profiler flight, the raw laser data are recorded on 8mm data cartridge tape. These tapes are capable of storing vast quantities of data at a high capture rate. The GPS and inertial navigation data are recorded at the same time. These two sources provide high accuracy positional and attitude information for the system.

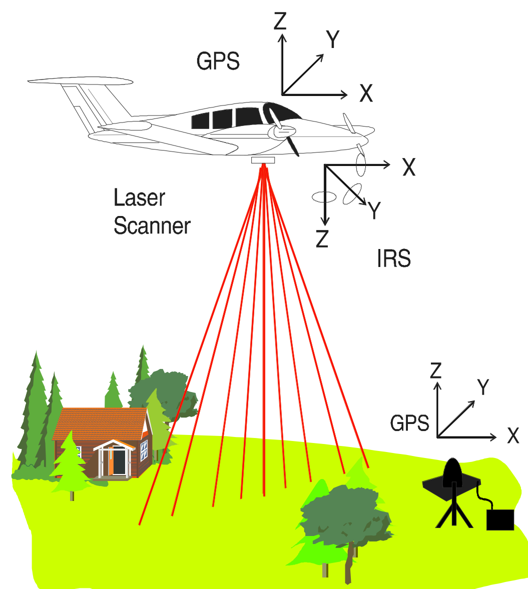

Figure 2 - LIDAR Positioning System

The 3-dimensional GPS solution (X, Y, Z) is used to position the laser scanner each second, while the INS data records the roll, pitch and heading of the aircraft to determine the system's orientation in space. The GPS solution is computed from differential kinematic processing, using data collected simultaneously at the aircraft and at base stations on the project site. During post-processing the GPS position solutions and INS orientation are combined with the laser ranges to calculate accurate (X,Y,Z) coordinates for each laser return.

The GPS and inertial data are processed in tandem to achieve the best positional result. Once the position and orientation of the aircraft are known at each epoch (1-second interval for GPS and 50Hz for the INS), then these data are integrated with the laser ranges to calculate accurate (X,Y,Z) coordinates for each laser data point on the ground. Up to 5000 laser ranges are acquired each second, thereby creating files with millions of data points. The data are processed using the proprietary ALTM laser suite of software to produce an ASCII file of (X,Y,Z) coordinates. The data can then be transformed into formats compatible with numerous CAD software packages.

System Calibration

It is well-known that aerial triangulation results based on an airborne kinematic GPS solution to position camera centres can have a systematic vertical bias when compared to triangulation based on ground control. Part of this vertical bias may result from atmospheric errors affecting the airborne GPS solution, and must be resolved through proper system calibration.

The Federal Emergency Management Agency (FEMA) guidelines state that there must be a manufacturer's calibration and a total LIDAR system calibration prior to project initiation (FEMA, 2000). The project calibration requires repetitive fly-overs of identifiable features with known dimensions to ensure that corrections for differences in atmospheric conditions between the aircraft and the ground are applied, and that any vertical gradient or horizontal offsets are identified.

For this project calibration flights were performed over pre-surveyed, coordinated buildings and other ground features to verify system alignment and calibration. These flights were made just prior to mobilization to the project site. Several passes were made in varying directions to enable detection of systematic pitch, roll and yaw errors in both the laser and image data.

As a result of the project calibration and ground truthing in various locations throughout the project area, a vertical bias of 23 cm was added to the LIDAR DTM. GEOsurv has generally witnessed a vertical bias ranging between 10 - 20 cm on their LIDAR projects, with the ALTM 1020 system they operate. Subsequently, on the second project a vertical bias of 20 cm was discovered in the LIDAR data.

Imagery

The digital camera and the ALTM 1020 were operated simultaneously during the data-acquisition flights. The camera was set to acquire an image every 2.5 seconds. Each time the camera shutter was activated, an electrical pulse was sent to a GPS receiver, which recorded the GPS time of the pulse. After an image was acquired, and before the next one was acquired, the image was downloaded from the in-camera memory to a hard disk on a computer connected to the camera with a SCSI-2 link. In-house software on the same computer was used to control the camera.

The images were acquired with a nominal ground-projected pixel dimension of 15 centimetres. During the flights, sample frames of the images were displayed to check for image quality. After the flights, the images were recorded on magnetic tape.

The processing of the image data required the following inputs: (1) the original image frames, (2) differentially corrected platform position data (from the GPS), (3) platform orientation data (from the INS), and (4) georeferenced spot elevations (from the LIDAR data).

In-house software was used to create a digital terrain model with a 15 cm cell dimension from the spot elevations for each of the 23 project segments. Each image frame was individually differentially rectified using a DTM and the image's measured position and orientation (from items 2 and 3, above). For each project segment, the individual image frames were composed into an image mosaic for that segment. The differential rectification and mosaic composition were accomplished automatically with in-house software.

Classification

Classification is the process whereby the acquired LIDAR points are filtered, and those representing above ground features (such as trees, buildings, and hydro lines) are extracted, to obtain a DTM that represents the ground surface. This task passes the data through an intensive filtering process where various classes of points are separated. General parameters are set for terrain type (i.e. flat, rolling, hilly) and terrain cover (i.e. open, light vegetation, medium vegetation, heavy vegetation), along with other parameters that help fine-tune the automated classification.

For this project, the classification was primarily vegetation data removal, separating these data from the ground layer data. Where applicable, building data were also removed. After all automated filtering had been completed, a rigorous manual analysis and edit was performed and a finer refinement of vegetation and building removal was undertaken using TerraModel 9.5. While the classification process often removes 80% or more of the undesirable above ground features, it can also erroneously remove objects such as natural terrain (hills, rock cuts) or man-made features (dams) that should be retained in the bare earth DTM. Thus the classification process must be monitored closely and verified by independent checks, as discussed further below.

Surface Generation

Once vegetation and building elevations were removed from the raw points, the data were gridded at 1 metre postings, cut into map sheets and segments and then exported as ASCII X,Y,Z files. This cleaned and gridded data was imported into AutoCAD Land Development Desktop and the surface was generated using the point data and the segment boundary as a breakline. The surface was saved as a Land Development Desktop project in the DTM directory of each segment.

Vector Collection

The vector data were collected using AutoCAD Map 3 and Land Development Desktop according to the standards and feature codes outlined in MTO's "Draft Photogrammetry Feature Code Definitions" (MTO, 1999). The features were collected from the digital orthoimages which where brought into AutoCAD in GeoTiff format. The vector collection was done without the aid of stereo imagery.

QUALITY CONTROL

Digital Terrain Model

Quality control for the project was done at several stages in the processing cycle. The GPS was analyzed using FLYKIN™ kinematic GPS OTF (On The Fly) software, as well as ALTM kinematic GPS software to meet pre-determined statistical criteria. Since the GPS data are processed immediately after each flight, any re-flights required due to poor satellite constellation or insufficient returns were integrated into a subsequent day's survey mission. Each flight consisted of setting up two base stations to collect data. Using two base stations satisfied the following critical criteria: (1) if one base station failed there would be a second back-up and (2) both GPS trajectories were compared on each flight as an independent check to verify that the positional data were correct. The GPS data was of high quality for all flights, so data from the base station closest to the aircraft was utilized to minimize the absolute error of the aircraft position.

The inertial data was analyzed at the output stage of laser processing. Log files were output, any peculiarities with respect to velocities or drift were noted, and a determination was made as to whether a re-flight was necessary.

The primary quality control tool for the laser ranges is the percentage of returns that are received back at the laser after it has emitted a signal. The acceptable range for returns, typically between 90% and 98%, were met for this project. Lower percentages are normal over water and other poor reflectivity surfaces.

After each day the laser data was analyzed for any anomalies using the CAD package Terramodel, as well as with statistical analysis tools written by GEOsurv. Specifically, points located in the overlap sections between adjacent flight lines were checked for consistency. Also points located in the overlap sections flown on different days were verified. This allowed two independent answers to be compared.

The final LIDAR DTM, with vegetation removed and gridded, was also compared to the kinematic surveys, check points, photo-id points, and MTO audits. In general, the DTM matched favourably and within prescribed tolerances for all these datasets on hard surfaces. There were some larger than expected discrepancies compared with MTO audits in areas such as ditches, rock, and grass lands along the road right of way. These local variances could not be corrected in the LIDAR dataset. These discrepancies are discussed further below.

On the second project comparisons were made between MTO audits and the LIDAR datasets under canopy. These comparisons are also discussed below.

Imagery

Thirteen targets were placed on the ground within the scene. Each target consisted of a white vinyl 6 by 6 foot sheet with a black "iron cross" design silk-screened on them. The centre of each target was surveyed to 10 cm precision. The ground-surveyed horizontal positions of the target centres were compared to their horizontal positions as given by the rectified image data. The adjustment procedure reduced absolute distance discrepancies in those positions to a pixel dimension or less (15 cm).

As an independent quality control check, additional GPS surveying was done to verify the horizontal accuracy of the rectified imagery. Some positional errors of over 20 cm were found and those segment tiles were redone.

Vectors

The horizontal position of the vector data was compared to ground GPS surveys done by GEOsurv and also by MTO field crews. The three sets of data were compared in AutoCAD and TerraModel. No significant errors were found. The ground surveys also served as quality control for the horizontal accuracy of the imagery.

MTO Audits

MTO conducted ground surveys by total station in 6 locations throughout the project area. In each audit location a small topographic survey was performed covering several hundred metres, capturing all relevant features in the highway right-of-way such as centreline, edge of pavement, gravel shoulders, ditches, rock cuts, and original ground. DTM's were created from this data and compared to the DTM's generated from the LIDAR data. Results of these comparisons are discussed below. On the second project, MTO conducted audits in 2 locations along the highway corridor and under canopy.

SUMMARY OF SECOND PROJECT

The second LIDAR project undertaken by MTO was much larger, covering approximately 3800 hectares along an irregular 1.5 by 17 kilometre cross-country swath off the highway corridor. The terrain was typical Canadian Shield consisting of numerous rock outcrops, forests, grasslands, lakes, rivers, and a few roadways. LIDAR was again considered for this second project since the timeframe was short, the data would be gathered through extensive forests in leaf-on conditions, there was limited ground access to the site, and a ground survey would be cost-prohibitive and take too long to complete.

MTO project specifications were the same as on the first project. GEOsurv utilized the same ALTM 1020 LIDAR system on this project, however problems with the digital camera prevented its use. Instead, 1:6000 scale GPS-controlled colour aerial photography was flown using a Zeiss RMK TOP15 metric camera with FMC (Forward Motion Compensator). The aerial photography was collected independently of the LIDAR data. The aerial triangulation block consisted of 138 models. Diapositives were scanned at a resolution of 18 microns, and the digital imagery was rectified using the model setup parameters obtained from the block adjustment.

The cleaned (vegetation removed) LIDAR data was compared to control points, kinematic ground profiles, and check pads to check for any systematic biases and to verify accuracy. After comparing the data to 900 ground truth points and analyzing MTO audit data, it was discovered that the LIDAR DTM was 20 cm too low; a value consistent with other projects. 20 cm was added to the raw LIDAR values to correct for this systematic bias.

With the exception of the aerial imagery acquisition, the second project followed much the same as the first project with respect to MTO project specifications, deliverables, methodology and quality control. Similarly, the issues discussed below were common to both projects.

ISSUES

File Size

The imagery had to be tiled to reduce the file size given the pixel resolution and the aerial coverage. The imagery was mosaiced according to the 23 project segments, then each segment was broken down further into 2 or 3 tiles. Similarly, DTM files based on the original segments were too large to work with efficiently in AutoCAD/Softdesk, so they were tiled to match the imagery. The LIDAR system collects a tremendous amount of data points and a method for reducing the file sizes without sacrificing accuracy is needed. At the time of writing, there are some data thinning algorithms being developed by the user community to address this issue.

At the outset of the second project, GEOsurv and MTO undertook an evaluation of different DTM generation methodologies. The purpose of the evaluation was to find which methodology produced the smallest file size while maintaining accuracy. Sample DTM's were generated from the raw LIDAR points, gridded points, and two different sets of contours. The evaluation showed that a DTM generated from gridded points provided the best dataset. The other methodologies, while reducing file sizes, degraded the accuracy of the data.

Ditches

Due to the ground point density (1.5 to 2.0 metres for these surveys), LIDAR may have difficulty hitting and subsequently allowing proper definition of, narrow features such as the bottom of ditches. The resulting DTM may not properly identify these important breaklines. For this project, elevation errors outside the contract specifications were encountered when comparing the LIDAR data to the MTO audits.

Ground or photogrammetric surveys are typically conducted by picking up all breaklines. A V-shaped ditch would be collected with a minimum of three strings, two for the tops of slope and at least one at the bottom of the ditch. Because the LIDAR places a point every metre or so, the statistical probability of hitting the actual bottom of the ditch is low, though it will hit near the bottom and on the sides of the ditch. Furthermore, water and vegetation at the bottom of the ditch only reduce this probability. It should be noted that on this project the probability of actually completely missing the ditch was quite low since most sections were flown with three times overlap, therefore

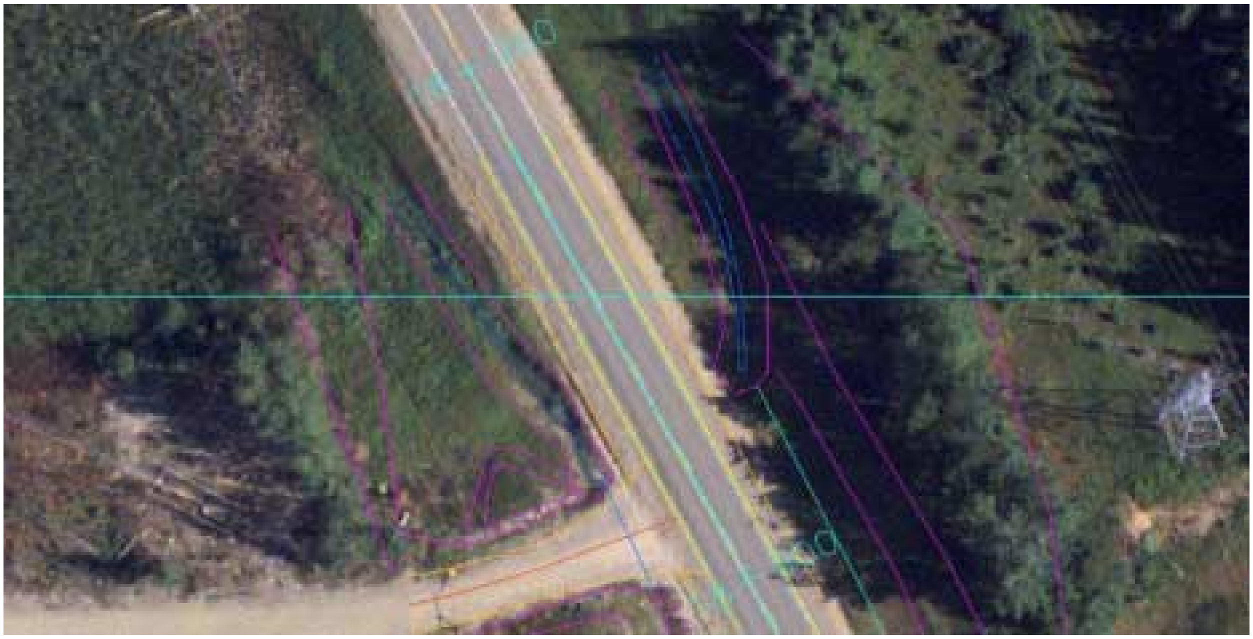

Figure 3 - Digital Imagery overlaid with MTO audit strings in Ditch Area

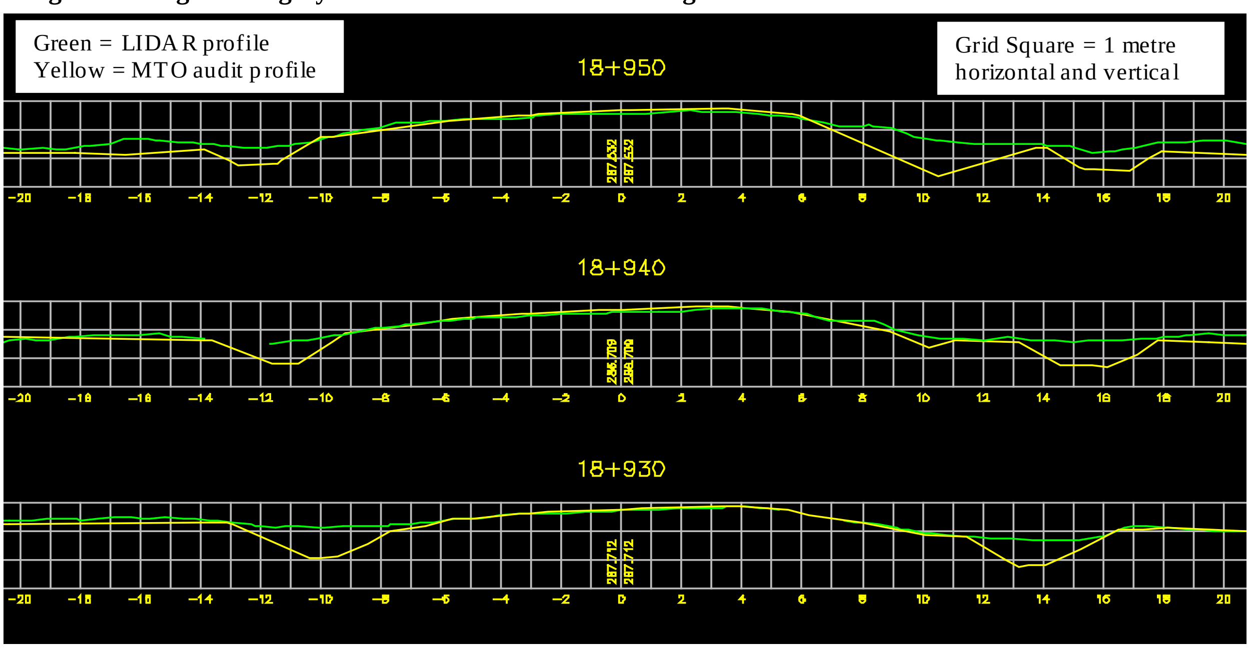

Figure 4 - Profiles of the DTM from LIDAR (green) and MTO audits (yellow)

increasing the point density.

Figure 3 shows an area where ditches were present, with MTO audit strings overlaid on the imagery. The dashed blue strings represent the bottom of the ditches and the adjacent magenta strings show the tops. Figure 4 shows profiles through these ditch areas. While the LIDAR DTM matches the MTO audits very well on the roadbed, it failed to pick up the ditches on both sides of the road. The LIDAR data shows only a slight dip in these locations and is in error by up to 1 metre.

Resolving this problem may require insertion of breaklines by manually selecting valid LIDAR points along the feature (i.e. bottom of ditch), with subsequent re-generation of the DTM respecting these breaklines. However it may be difficult to identify enough points to truly represent the bottom of the ditch. Alternatively, a higher LIDAR point density may improve feature definition in such areas. This could be accomplished by reducing aircraft speed, reducing flying height, increasing flight line overlap, or increasing laser frequency (i.e 10Khz or 25Khz). A higher LIDAR point density would result in a greater probability of striking narrow or small features, thereby providing a more precise DTM over these features.

Photogrammetric mapping provides a better representation of narrow features since accurate breakline data points can be collected directly along the feature of interest. For MTO applications it may be necessary to supplement LIDAR data with photogrammetric mapping in areas where critical breaklines must be collected.

Rock Cuts

MTO field audits revealed that rock cuts were automatically extracted with vegetation and buildings during the classification process. Rock is an extremely important factor in the cost of highway construction and must be properly identified. GEOsurv had to go back and manually restore points on the rock cuts from the raw data. The problem was not a laser problem (unlike the ditches and grassy areas) but a post-processing problem where the ALTM automated vegetation removal software assumes the rock cuts are buildings and removes them. A similar problem was reported on another project (Fowler, 2000b) where the ALTM software assumed that flood protection berms surrounding farmhouses were dense vegetation features and it automatically extracted them. In that case, the video tracking record had to be used to monitor the software extraction results.

Manual editing procedures were adjusted to find areas where the ALTM software had removed points unnecessarily. This was done using the imagery and the raw, unfiltered LIDAR points to look for these unwanted "holes" in the DTM. Any mistakenly dropped points were imported back into the classified or filtered points before the DTM grid was generated.

Figure 5 shows an area where the rock cuts had been automatically extracted by the ALTM software. Steep banks up to about 8 metres high exist as shown in Figure 6. In several areas, even once the LIDAR points defining the rock cuts were restored, there were still some large discrepancies between the LIDAR and MTO audit data along the rock cuts. The survey of rock can be somewhat subjective at times since it is not always easy to define a clear top and bottom of cut, and terrain along a rock cut is often very rugged. The LIDAR data follows the general pattern of the ground audit data. However in this particular case, the LIDAR appeared to smooth the sheer rock cut on the right side throughout its 60 metre length. Some of the reasons for the misinterpretation of these rock cuts include shadowing (obstructed laser line of sight) and decreased point density on vertical features. Furthermore, on sloped surfaces horizontal error increases since the laser footprint is spread across a greater range of elevations. This in turn has a negative impact on vertical accuracy. Such potential problem areas should be noted in advance during site reconnaissance and planned for to ensure that appropriate coverage, scan angle, flight line overlap, and point density is achieved during the LIDAR flight mission.

On the second project, rock cuts were once again automatically extracted during the classification process and had to be restored during the manual editing stage. The large rock cuts were recovered manually, but MTO field audits revealed that small (1 - 2 metre high) rock cuts had still been missed along roadways. The low rock cuts looked like shrubbery to the vegetation removal software. Tolerances within the vegetation removal program had to be reduced to retain more of these small rock cuts, and the road corridors had to be checked thoroughly by manual methods. This again stresses the importance of LIDAR data verification through some other means such as aerial imagery or field investigation.

Grass Surfaces

MTO's audit surveys revealed numerous discrepancies of up to 0.5 meters along the highway right-of-way in areas grown over with tall, dense grass, mainly between the ditches and forests. This type of vegetation does not allow the LIDAR beam to reach the ground because of the density of the blades and stalks. This dense vegetation is also too low for the vegetation removal software to recognize. Therefore the LIDAR DTM may be significantly higher than reality in those areas, depending on the height and density of the grass.

It may be possible to use image processing software to assist in identifying these grassy areas. From this classification, polygons could be generated to isolate those areas in the DTM in order to apply an elevation correction. However, the value of the correction would have to be determined by ground surveys and would not likely be uniform for all areas since the grass may be of different heights and densities. Applying such corrections without any field surveys could lead to new errors in the data. GEOsurv, among others, is constantly researching methods to better define the classification process, and is working on some raster techniques to address the issue.

Although it would not be possible to determine ground elevations in these grassy areas by photogrammetric methods either, these areas would be identified for exclusion from DTM surface generation on MTO applications. Similar identification and exclusion processes must be incorporated into the quality control of the LIDAR DTM, which implies a heavy reliance on the imagery. It is important to identify the limitations and conditions under which the LIDAR technology may not provide a true representation of the ground surface.

Figure 5 - Digital Imagery overlaid with MTO audit strings in Rock Cut Area

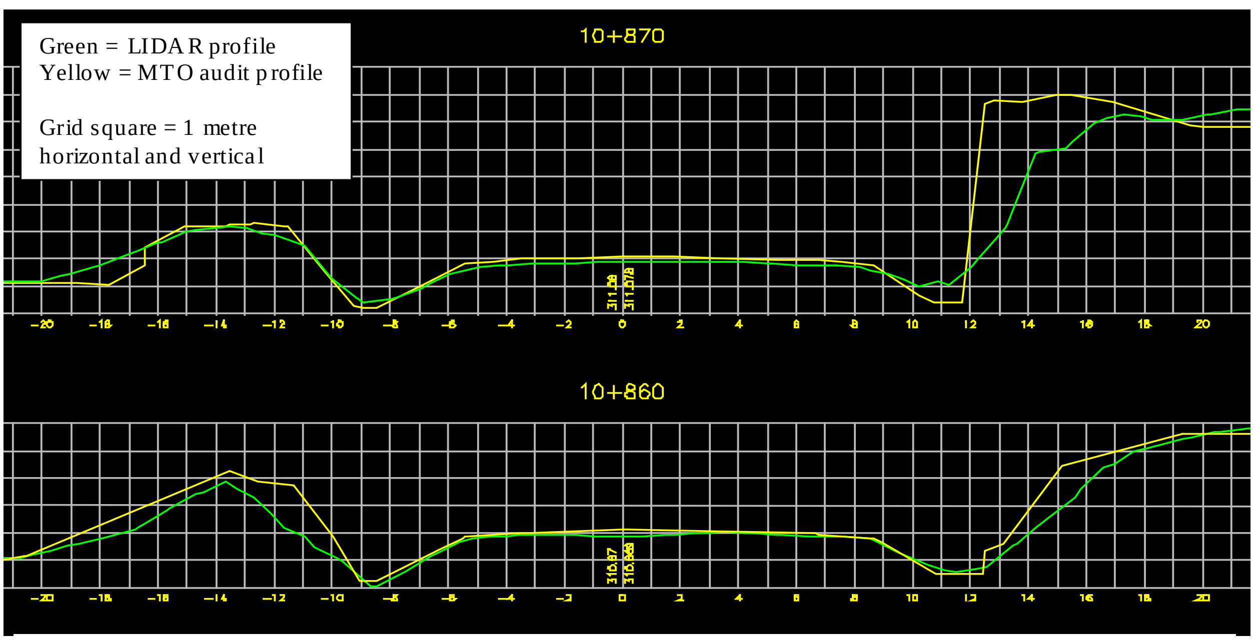

Figure 6 - Profiles of the DTM from LIDAR (green) and MTO audits (yellow)

Canopy

On the second project, in addition to audits conducted along the highway corridor, forested areas were investigated to determine how well LIDAR could penetrate the cover and provide valid data under the canopy. The MTO audits were conducted in 2 areas of the project. Vegetation in these areas consisted of 3 to 10 metre high deciduous trees and some low ground cover. Looking up, there was perhaps 30-60% light penetration through the canopy. If these areas were surveyed by photogrammetric methods, the photogrammetrist would have to outline the canopy and label it an "Excluded Area", meaning that reliable elevation data could not be provided at these locations.

Comparisons between the LIDAR data and MTO audits under canopy were fairly good, with differences generally in the 0.3 to 0.7 metre range, but approaching 1 metre at times. Although it would not be possible to conclude that the project specifications of 20 cm on soft surfaces were met under canopy, LIDAR provided data that would not have otherwise been obtained by photogrammetric means. Furthermore, a ground survey on this project would have taken several months to complete, been much more costly, and would not provide the same density of data.

However it is imperative that users be made aware of the accuracy of data supplied to them. MTO can use data that does not meet specifications, provided its accuracy is known. Any data obtained under canopy is of value but should be noted as an "excluded area" of lesser accuracy where appropriate.

For MTO mapping applications, it appears that the LIDAR technology would be best employed under the same leaf-free, vegetation-free (and snow-free) conditions as is required of conventional photography. This implies that LIDAR would also be restricted to spring and fall flying schedules. GEOsurv's experience with beam penetration in typical boreal mixed forests, is that ground hits account for 40 to 60% of the total points under “leaf on” conditions, and for 60 to 80% of the total points under “leaf off” conditions. Variations in these percentages occur as a result of changing the flying height, laser scan angle and flight line spacing.FEMA's guidelines state that DTM accuracy must be separately evaluated and reported on for all main categories of ground cover such as bare-earth, low grass, high grass, crops, low trees, and full tree coverage (FEMA, 2000). In some cases, LIDAR has failed to perform as well as expected in vegetated areas, in large part because of "leaf-on" conditions that should have been avoided.

MTO has ongoing concerns about how to validate the reliability of the LIDAR DTM at discrete locations throughout a project. The topic has been raised as a result of MTO audits that showed variation from the project specifications in certain areas (i.e. forested areas, ditches, rock cuts) on both projects. A technique of graphically viewing the distribution of data points in a "point density map" has been investigated. MTO and GEOsurv are discussing this concept to determine its merits as a quality assurance tool. Another possibility is to analyze the return intensity values of the laser pulses as recorded by some LIDAR systems. The intensity values may provide an aid to determining which LIDAR points have reached the ground and which have been blocked by foliage or some other above ground feature. As an added benefit, the intensity data provides a greyscale image of the project area that may also be useful for LIDAR data validation.

CONCLUSIONS

The most direct application of LIDAR is creation of a digital terrain model. Using LIDAR, large areas can be surveyed and a DTM generated within days, rather than the weeks or months it takes by photogrammetric or ground survey methods. The larger the project area, the more cost-effective LIDAR becomes.

For the first project undertaken in this study it is estimated that LIDAR cost 1.5 times more than photogrammetric mapping, and 3 times less than ground surveys. Both projects included imagery acquisition and feature code mapping, which made LIDAR less cost-effective, and also increased project duration to be comparable with that of photogrammetric mapping. For the costs associated with acquiring a DTM alone, LIDAR is the more economical method.

LIDAR provides benefits on cross-country projects because of the density of points and their ability to penetrate canopy. With the high density of raw data points, enough shots should hit the ground in moderately forested areas to provide a reliable DTM. Given this ability, LIDAR can be flown under less restrictive conditions than aerial photography, which is generally flown in leaf-free conditions. Unfortunately an unforeseen problem surfaced in that the LIDAR was unable to penetrate low ground vegetation. Thus for MTO applications, it appears that the LIDAR technology would be best employed in the spring and fall under leaf-free and vegetation-free conditions, depending on the desired accuracy of the DTM and mapped features. Leaf-free conditions would also aid canopy penetration.

Although the LIDAR can be flown day or night in various weather conditions, if feature mapping is needed then imagery must be acquired, and this restricts flying conditions. Imagery must be acquired under cloud-free conditions with due regard to sun angle. LIDAR is generally more economical and faster for DTM production, however it may not have much of a cost or time advantage when feature mapping is included.

LIDAR does not appear to be as good for feature mapping since the raw data points may not be located directly on the feature ie. bottom of ditches. Also, the LIDAR data does not define breaklines along features to control the generation of the DTM. Photogrammetric mapping or ground surveys will provide a better representation of mapped features since accurate breakline data points can be collected directly along the feature of interest in the desired location. Use of stereo imagery would aid LIDAR in identifying features such as tops and bottoms of ditches, vegetation, and rock outcrops.

Some of these problems may be avoided or reduced by mounting the laser on a helicopter. The reduced speed and manoeuvrability of a helicopter would ensure that the laser is always directly in the centre of the corridor, which would significantly increase the number of ground points. The increased density of ground points would increase the accuracy along features like ditches.

MTO audits verified that the accuracy of the LIDAR data was 15 cm or better on well-defined surfaces such as pavement, and was variable on other surfaces up to about 0.5 m. Low vegetation, rock, and ditches caused unexpected problems with discrepancies exceeding 1 metre in some cases. The accuracy of the LIDAR DTM under canopy was in the 0.3 to 1.0 metre range. Thus it is important to identify the limitations and conditions under which the LIDAR technology may not provide an accurate representation of the ground surface, and classify the LIDAR data accordingly.

In spite of these localized areas that may be less accurate than photogrammetric or ground survey DTM’s, the overall accuracy of the Lidar DTM, along with potential reduced cost and production time, can make it competitive with photogrammetry. Both methods have advantages and disadvantages that the user must be aware of. The photogrammetrist can place points precisely on features and breaklines, however he must be able to see the ground. LIDAR can penetrate moderate canopy and provides a far greater density of points for terrain modelling. If the LIDAR was flown when vegetation is low and trees are leaf-free, it appears that this technology can achieve MTO's photogrammetric accuracy requirements on soft surface features. Given that critical hard surface features will be surveyed by other methods to a much higher accuracy, LIDAR may compete with photogrammetric mapping on MTO's highway planning and design process.

ACKNOWLEDGEMENTS

The authors would like to thank GEOsurv staff and MTO Northern Region Surveys and Plans staff for their assistance on these projects. Much of this paper pertaining to the first LIDAR project was previously published in Berg, R. and J. Ferguson, 2000. A Practical Evaluation of Airborne Laser Mapping for Highway Engineering Surveys. ION GPS 2000 Proceedings, September 2000, Salt Lake City, Utah, USA.

BIBLIOGRAPHY

Federal Emergency Management Agency, 2000. Appendix 4B. Airborne Light Detection and Ranging Systems. In *Flood Insurance Study Guidelines and Specifications for Study Contractors*.

Fowler, R.A., 2000a. The Lowdown on LIDAR. *Earth Observation Magazine*, March, 27-30.

Fowler, R.A., 2000b. LIDAR for Flood Mapping. *Earth Observation Magazine*, July, 23-26.

GEOsurv Inc., 1999. MTO Project 99-525 Final Report.

GEOsurv Inc., 2000. MTO Project 99-625 Final Report.

Hill, J.M., L.A. Graham, and R.J. Henry, 2000. Wide-Area Topographic Mapping and Applications Using Airborne Light Detection and Ranging (LIDAR) Technology. *Photogrammetric Engineering and Remote Sensing*, 66(8), 908-914.

Ministry of Transportation Ontario, 1999. Draft Photogrammetry Feature Code Definitions.

Ministry of Transportation Ontario, 1994. Photogrammetric Surveys Digital Terrain Model Data Capture and Processing Guide, Version 1.6.

Optech Inc., undated. ALTM 1020 Specifications.