Highlight

Commercial Implications of Topographic Terrain Mapping Using Scanning Airborne Laser Radar

Martin Flood and Bill Gutelius

The airborne remote sensing industry is characterized by strict deadlines, tight budget constraints and an unrelenting demand for higher data densities with increased accuracy at lower cost. End-users, including everyone from urban GIS administrators to engineering firms doing traditional route planning, are demanding faster turnaround times and more accurate data. Therefore, aerial survey operators must look to more advanced technologies to reduce data processing times and field work expenses. Not limited by the environmental conditions restricting aerial photography, airborne laser scanning technology is emerging as an attractive alternative to the traditional techniques for large-scale geospatial data capture.

The recent development of commercial laser-based topographic terrain mapping systems is driven by the availability of compact ruggedized solid state lasers, high precision airborne inertial navigation systems, and rugged precise high-speed scanners which combine to make high accuracy airborne scanning laser rangefinders practical. With the completion of the GPS and the availability of low-cost multichannel GPS receivers, these technologies enable the creation of affordable laser-based topographic terrain mapping systems. The purchase price of these commercial instruments has been reduced so that cost is no longer a barrier to companies capable of investing in standard aerial photogrammetry equipment. Also, the operational costs of these systems are generally comparable to or better than existing remote sensing technologies.

Laser-based systems offer distinct advantages over existing survey instruments in areas such as forestry surveys or coastal zone monitoring, while offering complimentary data collection in other areas such as airborne spectrometry. A unique advantage of these instruments is that they are capable of penetrating vegetation allowing the ground beneath a tree canopy to be mapped directly from the air. Another advantage of laser-based data capture is that during post-processing it is possible to classify each data point as ground, vegetation, a building or other object of interest such as a power line. Once classified, removing the overlying layers is simple and allows the straight forward generation of, for example, a digital terrain model (DTM) of the ground beneath the tree canopy. Because it is an active illumination sensor, a laser system can collect data at night and can be operated in weather and at low sun angles that prohibit aerial photography. While prototypes for these instruments have been operating for several years, only recently have commercial systems been available. Table 1 compares the features of several commercial laser-based terrain mapping systems with information compiled from the literature.[1]

Operating Principles

Airborne lidar systems are based on the principle of laser ranging and detection similar in function to radar. A detailed discussion of the technical aspects of lidar systems would be inappropriate to include here; more complete information can be found in the literature[2] (Ackermann, 1996). However, there are basic characteristics of a laser terrain mapping system that are relevant in a general introduction to provide a basic understanding of the techniques involved.

Lasers have been a valuable survey tool since the 1970s; however, recent technological advances make it possible to transform any aircraft into the equivalent of an airborne Total Station by combining laser range-

Table 1. Comparison of commercially airborne laser terrain mapping systems

System	Operating Altitude (m)	Laser Wave length (μm)	Pulse Rate (Hz)	Scanner Frequency (Hz)	Swath Width (m)	Platform*	Speed (m/s)	Weight (kg)
AIMS	300	1.064	4000	Variable	30	FW	45	90
ALTM 1020	330-1000	1.047	5000	Variable	680@1000m	FW/H	25-70	57
DATIS	?	?	4000	?	?	FW	?	?
FLI-Map	12-300	visible	5000	?	100@100m	H	23	90
TopEye	500	1.064	7000	?	36@100m	H	10-25	300
TopoSys	<1000	1.540	300	300	250m@1000m	FW/H	18	100

*FW/fixed-wing aircraft, H/helicopter

Highlight

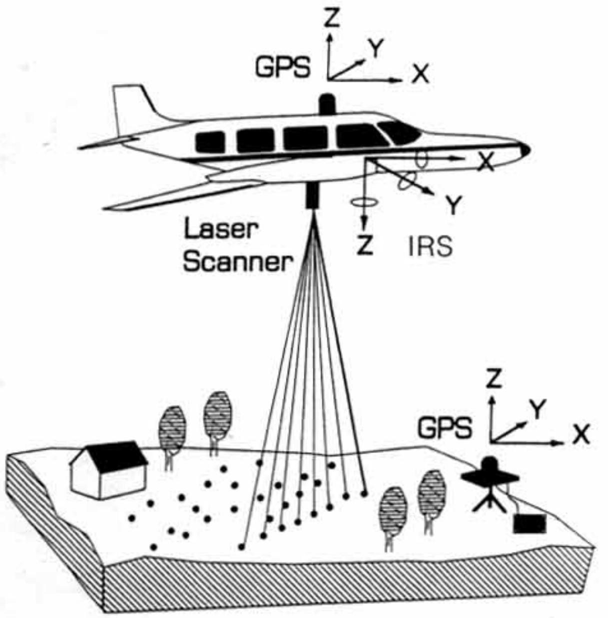

Figure 1. Depiction of scanning airborne laser terrain mapper in operation.

finder technology with the GPS (Figure 1). While technologically advanced in design and function, airborne laser mapping systems are based on simple concepts.

Two GPS receivers are used to locate the aircraft flight path to within 10 cm. One GPS receiver is installed in the aircraft, while the other is situated at a known ground location. The ground receiver identifies and corrects errors in the aircraft's position. A high accuracy laser rangefinder scans beneath the aircraft to produce a wide swath over which the distance from the aircraft to the ground is precisely measured for every laser pulse. The scanner angles also are measured simultaneously with each laser pulse. To correct for the aircraft's movements, either the laser is installed on a stabilized platform or the motions of the aircraft are recorded by an inertial navigation system.

By accurately recording the roll, pitch and heading of the aircraft at the moment of each laser pulse the motion of the aircraft can be corrected by computer software. Once gathered, the angles and distances determine the position of a point on the Earth's surface providing data similar to that of a Total Station. Combining the high resolution, high accuracy elevation data with existing processing software enables mapping products to be produced economically. Large areas can be surveyed for a fraction of the cost of traditional methods.

The result of this combination of technology is a scanning laser terrain mapping instruments which is an all digital system that can quickly and economically collect terrain data at very high sample densities. Commercial systems are available with typical data capture rates equivalent to 100 km²/hr.

Operational Considerations

Some early prototypes of laser-based terrain mapping systems were flown in large fixed-wing aircraft such as NASA's P3-B Orion (Vaughn *et al*, 1996). However, for practical commercial applications an airborne instrument needs to be mounted in either a small single or twin engine fixed-wing aircraft or a helicopter. Mounting can be either external in a sensor pod or internal in a commercial camera mount. Commercial systems now are available with either mounting, and systems have been installed and flown in a variety of platforms including Cessna 337s and 310s, Twin Bonanzas, Piper Aztecs, Piper Navajos, Piper Chieftains, AeroCommanders, Partenavia P68s and AS350 helicopters. This installation flexibility is important when rapid removal and reinstallation is required for the instrument and it reduces operational costs when dedicated aircraft are not an option for the survey company. No additional airborne support equipment is required except what is normally used during aerial surveying, although a GPS-based pilot guidance system is highly desirable. However, since each laser range to terrain is individually georeferenced, crab angles and precise overlap are not critical issues as in photogrammetry. The most efficient systems currently available offer a high degree of automation and the capability for pre-flight planning of all survey parameters. In addition to the pilot, an airborne operator is still required.

The ground support equipment required for these instruments usually consists of one or more GPS reference stations. These are operated by ground crews at known locations, such as benchmarks or monuments, near or within the survey boundaries during the airborne operations. To accurately establish the aircraft position during the flight, GPS data is logged and post-processed together with the airborne GPS data providing a differential GPS solution for the aircraft position.

After the field operations are completed the data requires additional post-processing to achieve the required end-product. Most commercial systems provide PC-based post-processing solutions based on proprietary software developed by each company. In addition, modules for the automatic analysis and classification of various features such as the tree canopy currently are available. Additional classification algorithms are being developed for such applications as automatic power wire detection and classification. The processing computes the laser point coordinates from the independent data parameters: aircraft position, aircraft attitude, scanner angular deflection, and laser pulse time of flight or slant range. A geodetic transformation of the computed points into the local reference coordinate system is done, and the points are sorted in a well-defined database structure for retrieval later. Due to the variety of end-user applications, the flexibility of this data format is important to ensure maximum usage. Typical post-processing times are two or three hours for every hour of recorded flight data with additional processing time required for more sophisticated analysis such as target classification or vegetation removal. During post-processing, systematic errors can be determined and reduced by analyzing the data and the application of proper quality control procedures. If ground control points exist, they can be introduced into the process to confirm the validity of the data. As an example of the end products that can be generated, Figure 2 is a DTM showing a landfill and Figure 3 is the same landfill after a "tree removal" algorithm was applied to the data.

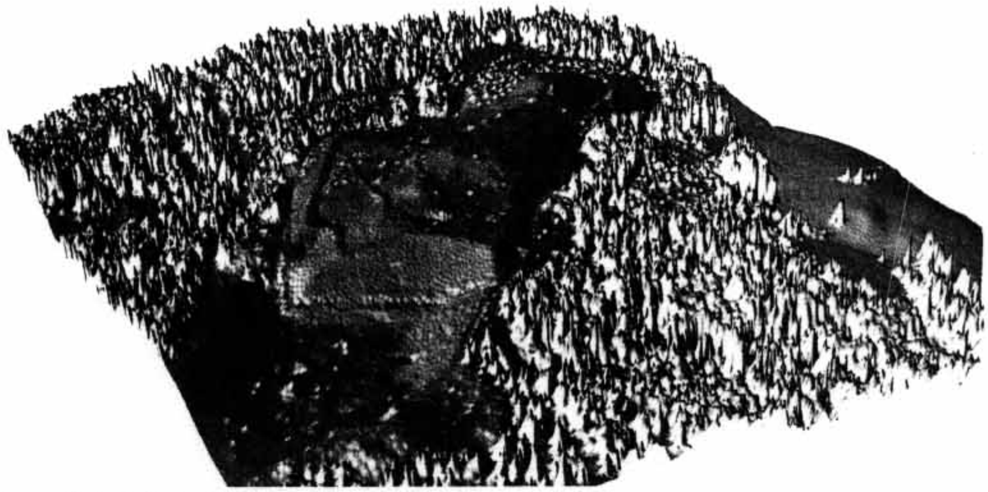

Figure 2. Landfill area before vegetation removal.

Figure 3. Landfill area from Figure 2 after vegetation removal software is applied.

Applications

The practical applications for scanning laser-based topographic terrain mapping systems are diverse and survey companies only now are starting to aggressively apply this technology. To date, these instruments were used to map the forest floor through the tree canopy, to determine the sag of power lines and location of trees encroaching on the wires, to generate 3-D urban models, to study ice-flow, to measure ice pack elevation, and even in simulation studies for a satellite laser altimeter system. As commercially available systems become more affordable and reliable, these techniques should see applications in conventional survey areas as well as open up areas which until now were regarded as too expensive. In some cases, these systems will act as complimentary data collection instruments; in others, they will replace existing instruments due to the cost effectiveness of their data capture, fast turn-around, and reduced operational costs. Two notable emerging application areas are GIS/DTM generation and as an alternative to traditional survey techniques in difficult areas.

GIS/DTM Generation

GISs are increasing in complexity, sophistication, and detail. But despite the increasing sophistication of these tools, at the heart of every GIS is a "base layer" that contains and displays the rudimentary spatial information on which all other GIS "layers" are built. If elevation data is available, then a DTM can be created as the base layer. However, collecting accurate elevation data to describe the terrain can be difficult and is often costly and time consuming. Traditionally, generating elevation data was accomplished by derivation from aerial photogrammetry, scanning pre-existing maps, or by a field survey using standard terrestrial techniques. These methods, though mature and often highly advanced, require substantial effort and long processing times following data acquisition.

A laser-based mapping system is ideal for gathering the topographical data for input to a GIS. Because the laser-based sensor relies on active rather than passive illumination, shadow effects from buildings and trees are not a concern. Rural

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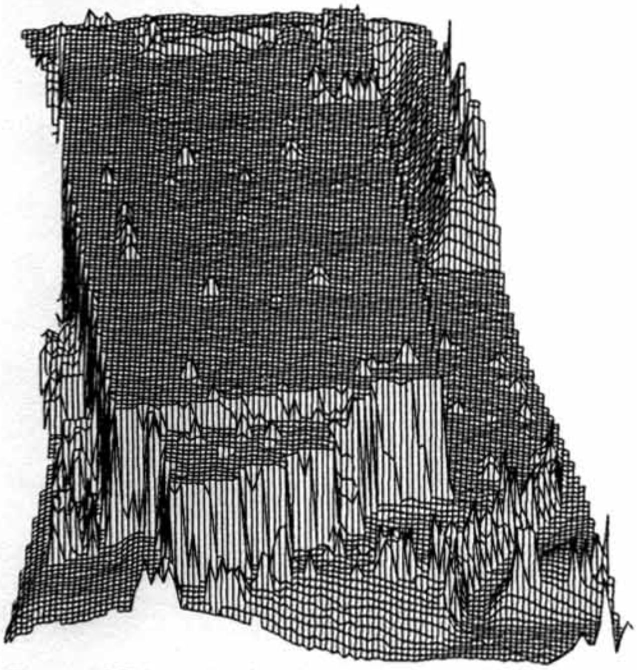


Figure 4. DTM compiled from laser-based survey (Optech/ALTM 1020) data. Image is of an industrial building north of the City of Toronto.

and remote areas can be surveyed easily, even when forested. Because each XYZ point is individually georegistered, aerial triangulation or orthorectification of the data is not required. Some of the specific applications to GIS of laser-based surveys include establishing building footprints and locations (see this issue's cover image for an example of a DTM of the Seattle Kingdome generated from an airborne laser survey); determining building densities (being done in Germany, see Kilian, 1996); delineating ecozones (Allewijn, 1996); mapping road routes; monitoring utilities and utility corridors; establishing electromagnetic wave propagation paths when siting communications and transmission towers (see Kilian, 1996); infrastructure damage assessment following catastrophic events (and critical area determination prior to events such as flood plain assessment); and, natural resource monitoring (e.g. beach erosion, forest clear cutting, flood plains) (Allewijn, 1996).

Available commercial airborne laser terrain mapping systems already are being used for many of the above applications with demonstrations and proof of concept studies being completed to determine other potential applications. Since the final output of the post-processing software is simple ASCII data, it can be used by virtually any off-the-shelf CAD or surface modeling package and the end-products from a single survey are numerous, including DTMs and contour maps. However, due to the density of data points that are generated, service providers need to verify that the software is robust enough to handle the large data sets. A commercially available package, TERRAMODEL, was used to generate the DTMs in Figures 4 and 5 and the contour map in Figure 6.

Replacing Traditional Survey Techniques in Difficult Areas

In some areas, traditional survey techniques such as aerial photogrammetry and field surveys, are impractical or impossible. With traditional aerial photogrammetry it is difficult, if not impossible, to achieve satisfactory results when there is limited contrast, such as is found along beaches and coastal zones and also where vegetation proves too thick for estimation of the ground surface below the canopy. Field surveys using established terrestrial techniques are often too time-consuming or too expensive to use for large areas or areas with limited access. However, these areas can be surveyed economically and practically by a scanning laser system. It is such

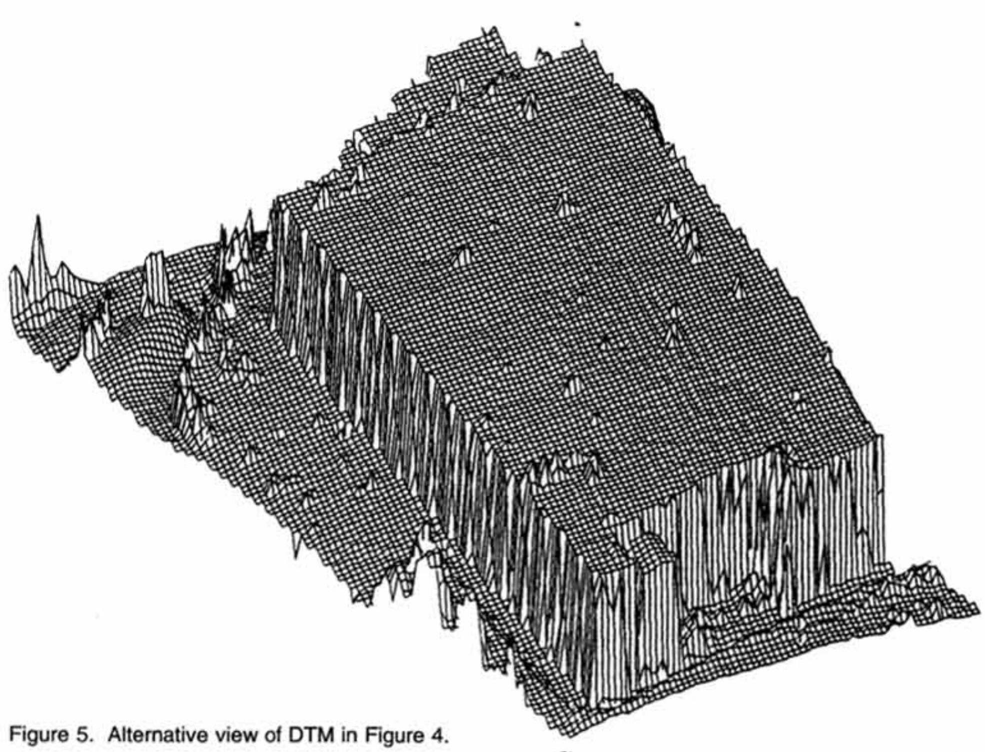


Figure 5. Alternative view of DTM in Figure 4.

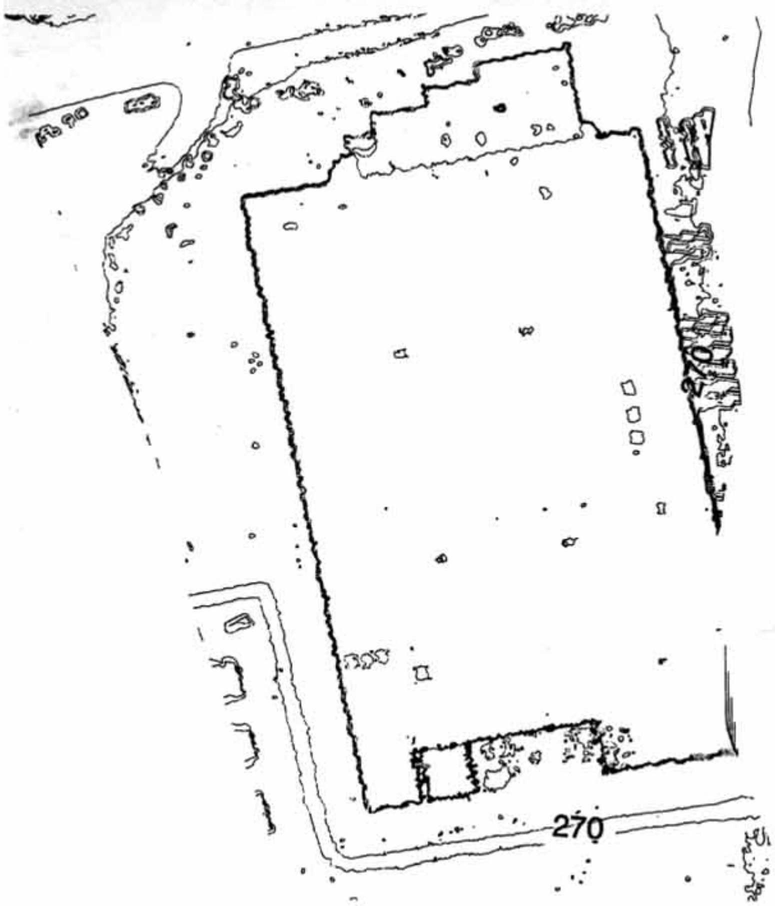


Figure 6. Contour map of building shown in Figures 4 and 5.

areas—where laser-based systems do not have to compete directly with established photogrammetry—which are seeing the most commercial activity and will see the largest growth initially. Examples of such areas include—

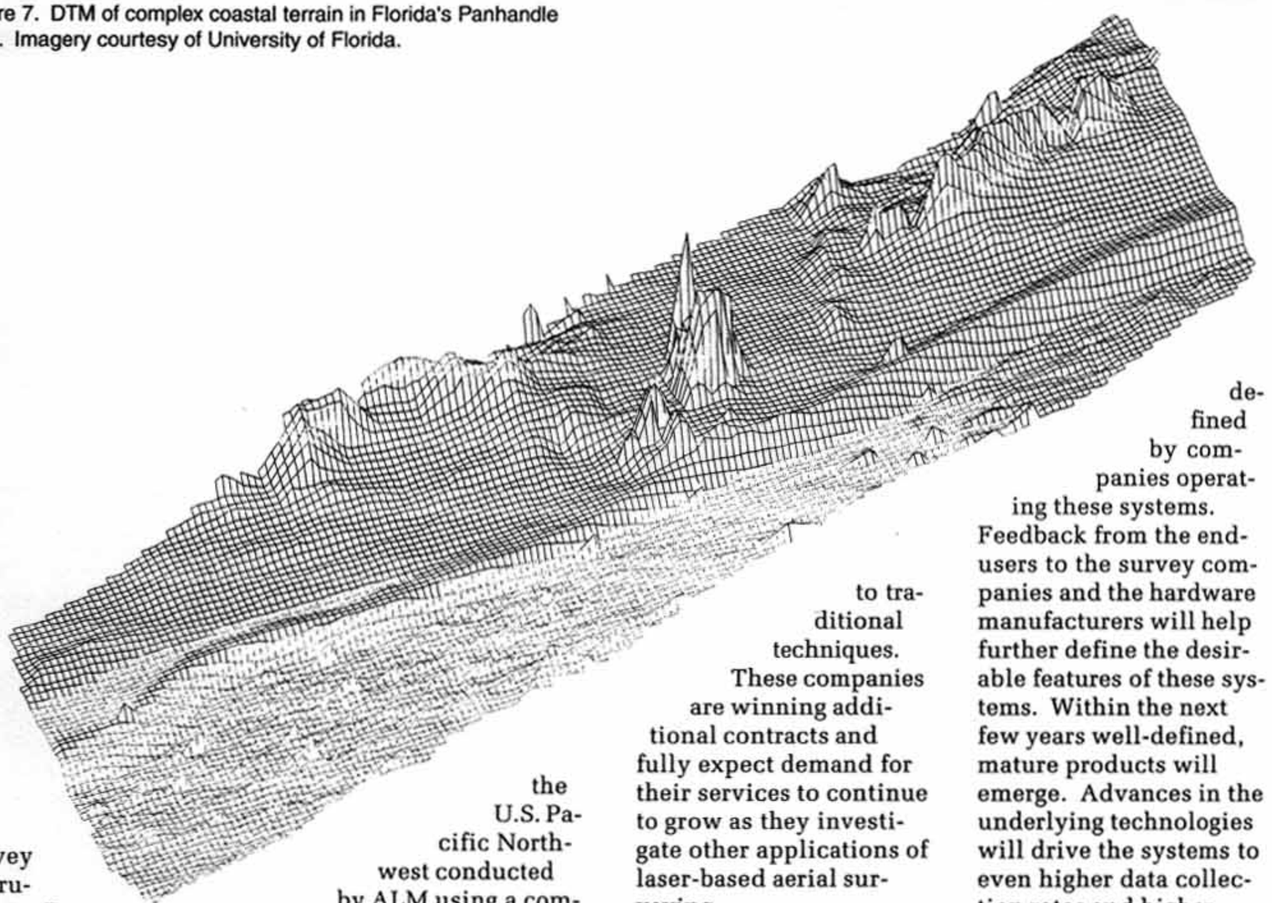
- Coastlines (where strip adjustments along the waters edge are not possible and dune surfaces provide insufficient relief for effective photogrammetric methods of terrain extraction);
- Wetland areas (where no ground control points can be installed due to restricted access, or where damage to a fragile environment could result);
- Forest areas (where vegetation prevents visibility of the ground in aerial photographs and ground cover inhibits field crews);
- Road, pipeline, or power line-planning (where the objective is a narrow corridor of dense data points);
- Openpit mining operations (where the final data is needed within a few hours of collection).
- Providing a DEM for orthorectification of aerial photographs

A specific example from a recent field survey is the use of an airborne scanning laser system to map coastal zones as part of a feasibility test conducted on behalf of the University of Florida, Florida Department of Transportation (DOT) and the Department of Environmental Protection (DEP) in the Florida Panhandle during October 1996 (Bolivar, 1996). A commercially available airborne laser terrain mapping system (Optech/ALTM 1020) was used to map several hundred kilometers of coastline. Traditional methods including a land survey and aerial photogrammetry were employed previously to measure the changes in shoreline features. However, a faster, more accurate method to determine coastal alterations due to storm surges and other severe weather events, as well as long-term, continuous feature changes was required.

A previous terrestrial survey took a team of surveyors six months, to measure profiles of the beach and dunes at 300-m intervals along the beach. Each profile had a few hundred points beginning at the water, continuing to the edge of dune/vegetation region. The same region, of slightly less than 250 km^2, was flown in just over two hours using the laser system, which provided continuous point coverage of the desired grid from beginning to end. After post-processing of the data, the total number of elevation points, individually georeferenced, was approximately 27 million. This translates to a point density of greater than 100,000/km^2. Figure 7 is an example of a DTM generated from this data. Since this survey was done as a feasibility study, no specific cost breakdown information is available; however, based on the duration of the flights, the rapid turn-around time for the data processing, and large volume of data generated, it is probable that a commercial company using a laser-based system could have bid on and won the job at a significantly reduced cost compared to companies using traditional survey techniques, while still keeping operational cost at a reasonable level to provide a respectable margin.

Another specific example of an area where these systems represent a viable economic alternative to traditional survey techniques comes from the forestry industry. Several forestry companies have realized significant time and cost savings by employing companies operating laser-based airborne

Figure 7. DTM of complex coastal terrain in Florida's Panhandle area. Imagery courtesy of University of Florida.



survey instruments. For forestry companies, accurate information on the terrain and topography below the tree canopy is extremely important; however, determining the terrain elevation below tree canopies always had proved difficult for photogrammetrists, while extensive ground-truthing is usually too expensive. The practical application of laser surveying to this problem was demonstrated by companies such as Airborne Laser Mapping (ALM) of Seattle, Washington, or TopScan GmbH of Munster, Germany which routinely map heavily forested areas and use the unique features of the instrument to generate accurate DTMs of the forest floor despite the heavy tree cover. Recent surveys in the U.S. Pacific Northwest conducted by ALM using a commercially available system (Optech/ALTM 1020) demonstrated a minimum 20-30% penetration of coniferous canopies. Surveys in Northern Europe by TopScan demonstrated similar deciduous canopy penetration (varying with tree-type) in summer and up to 70% in winter. It is this unique ability to measure ground elevations directly through the tree canopy that is one of the major advantages these instruments offer over traditional photogrammetry when operated in heavily forested areas.

Companies already exploiting this technology comment that the use of an airborne scanning laser terrain mapper was crucial to completing projects at a significantly reduced cost compared to traditional techniques. These companies are winning additional contracts and fully expect demand for their services to continue to grow as they investigate other applications of laser-based aerial surveying.

Future Commercial Developments

As the mapping world becomes increasingly digital, and mapping budgets are tightened, using more cost effective technologies is necessary for survey companies to compete. Scanning airborne laser radar systems represent an emerging technology that is making the transition from the proof-of-concept, prototype stage to a readily available, affordable, reliable commercial survey instrument. Due to the unique nature of the instruments, the various application areas where these instruments provide competing or superior operational performance and cost-effectiveness still are being defined by companies operating these systems. Feedback from the end-users to the survey companies and the hardware manufacturers will help further define the desirable features of these systems. Within the next few years well-defined, mature products will emerge. Advances in the underlying technologies will drive the systems to even higher data collection rates and higher accuracies while a continued emphasis on sophisticated post-processing of the data will open up additional application areas and provide enhanced information to the end-users. As more systems are delivered to survey companies, manufacturers will have to address issues of reliability, practical installation, and service and maintenance, but it is clear from current field work results that those companies which have already or are willing to invest in this emerging technology will have a distinct advantage over their competitors for the next few years.

Notes

1 For an excellent introduction to the subject of laser radar refer to

"Laser Remote Sensing" by Raymond Measures, Kreiger Publishing Company, Malabar, Florida (ISBN 0-89464-619-2).

References

Ackermann, F. "Airborne Laser Scanning for Elevation Models." *GIM* October 1996.

Bolivar. L. *et al.* "Airborne Laser Swath Mapping Aids in Assessing Storm Damage." *The Florida Engineer* Winter 1996.

Samberg, Andrei. "Airborne Laser Mapping Systems." *Maankäyttö* 3 (1996): 6-9.

Vaughn, *et al.* "Progress in Georeferenceing Airborne Laser Altimeter Measurements." 2nd Intl. Airborne Remote Sensing Conference and Exhibition, San Francisco, CA, 24-27 June 1996.

About the Authors

Martin Flood is Team Leader, Terrestrial Survey Team at Optech in Toronto, Canada. He can be reached by email at martin@optech.ists.ca.

Bill Gutelius is an ALTM Product Specialist at Optech. He can reached by email at billg@optech.ists.ca.