Wide-Area Topographic Mapping and Applications Using Airborne LIght Detection and Ranging (LIDAR) Technology

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Although the technology has been around a few years now, there are still only a small number of firms in the world that manufacture airborne light detection and ranging (LIDAR) system technology. A somewhat larger number of firms provide airborne LIDAR mapping services based on this technology (Wehr, A. and Lohr, U. 1999a). Yet, to date, tens of thousands of square kilometers of LIDAR data have been acquired in the United States and other countries for research, feasibility studies and actual applications projects. The reason why so many miles of data have been collected may have to do with the data's flexibility and value. It is more likely that the reason so many miles are being collected is that the number of applications and uses for the data are growing exponentially.

For most applications, LIDAR data does not replace the work of the surveyor or photogrammetrist, but wide-area LIDAR is beneficial for information on thousands of square kilometers and accepted by clients as both economical and accurate. Users are requesting the development of a variety of value-added LIDAR data products such as bare earth DTMS, geomorphic-structure mapping, building renderings, mathematical model integration, vegetation parameters, change detection and others.

LIDAR data are being enhanced with the integration of other data sets, including spectral, hyperspectral and panchromatic imagery, Geographic Information System (GIS) data and mathematical model integration. LIDAR sensors are being integrated with digital cameras, spectral and hyperspectral scanners, and thermal imagers. The sensors also are being upgraded so that scientists can better acquire and analyze such parameters as the returning pulse waveform (frequency shifts) and amplitude. Algorithm development is resulting in software used to create orthorectified imagery (satellite, aerial photography and digital-camera imagery) using LIDAR elevation data. Wide-area LIDAR data collection rapidly is becoming the standard and preferred data set for specific earth science and engineering applications.

Advantages

There appears to be a developing consensus in the mapping community that airborne LIDAR is a cost-effective alternative to conventional technologies for the creation of digital elevation models (DEMs) and DTMs at vertical accuracies of 15 centimeters to 100 centimeters. Photogrammetric techniques can be prohibitively time-consuming and costly to perform large-area projects at these accuracy levels.

Another emerging technology, Interferometric Synthetic Aperture RADAR for elevation (IFSARE,) also offers promise in this area, but these systems do not generate elevation data below a vertical accuracy of 1 meter. Due to issues underlying microwave reflections and interaction with manmade environments, IFSARE for detailed mapping of urban landscapes is limited because of building layover/shadows and lack of systematic mapping of urban canyons.

LIDAR data do not exhibit the parallax observed in aerial photography/imagery, for a laser hit on the Earth or a feature is located precisely where it is relative to Earth coordinates. LIDAR data can be acquired during the day or night because the selection of sun angle to avoid shadows is not an issue. Nighttime data acquisition also provides reduced clouds, calmer air and minimal air traffic over major urban areas. Raw LIDAR data are digital and can be acquired, processed and delivered in a matter of days or weeks instead of months. Delivery time is a function of the size of the study area and the complexity of associated value added products.

All significant Earth surface features such as resolution-dependent buildings, trees, levees and other structures are represented in the raw LIDAR data. Mapping of this number and variety of Earth features is usually costly and time-prohibitive when using photogrammetry. In addition, some airborne LIDAR units record multiple returns, or echoes, from a single laser pulse. This feature helps to create "bare earth" DEMs below a tree canopy and also provides detailed information about tree density, height, canopy cover and biomass for characterizing the structure of vegetation and habitats.

Software is being implemented that uses LIDAR data to orthorectify digital camera imagery, aerial photography and high-resolution satellite imagery such as that from Space Imaging Inc.'s IKONOS, the world's first commercial 1-meter panchromatic remote sensing satellite. Great potential exists for developing many new and improved earth science and engineering applications that use the detail of LIDAR data.

Perhaps most importantly, LIDAR data can be much less expensive to acquire and process than conventional data for wide-area mapping and analysis projects. Traditional approaches for the development of precise elevation data sets have previously required the acquisition and analysis of many stereo pairs of aerial photography, considerable ground surveying and extensive post-collection analysis. LIDAR has taken this expensive, labor-intensive and time-consuming task and reduced it to an affordable, flexible and manageable process.

As the airborne remote sensing industry builds upon technology and refines itself, new uses, processes and practical applications for the collected elevation and mapping data continue to emerge.

Over the last few years, airborne LIDAR technology has become **the** accurate, timely and economical way to capture elevation information to DEMs and DTMs. Efforts to use higher end computer systems and leading edge technology in the post-processing arena have allowed the spread of acceptance, higher accuracy levels and the development of numerous applications.

LIDAR is a significant component of Airborne Laser Terrain Mapping Systems (ALTMS), which uses lasers to measure the elevation of the Earth's surface, including natural and manmade features. ALTMS uses a LIDAR unit mounted in an airplane, coupled with positioning instruments and computers, to produce a highly accurate, digital, topographic data file. That in turn can be used directly to produce contour maps, three-dimensional images of the topography, virtual reality visualizations or can be entered directly into numerous models and analyses that require elevation data. ALTMS includes a fully integrated, high-resolution digital camera, and LIDAR and digital photographic images may be acquired simultaneously. The digital photographic images are precisely geo-referenced and can be entered along with the digital LIDAR data set into modern orthorectification software to produce high fidelity and detailed orthorectified aerial photography.

Products Applications

While the uses for LIDAR data and the resulting bare earth DTMs and DEMs continue to find new applications, some of the basics include hydrology and floodplain mapping, telecommunications planning and analysis, transportation assessment, urban landscape, natural resource and forest management.

Hydrology/Floodplain Mapping. Floodplain mapping is a primary application for these new, high-resolution LIDAR data sets. In the last few years, the Federal Emergency Management Agency (FEMA) has modified its mapping requirements to include the acquisition and use of LIDAR data to create new Flood Insurance Studies and associated Digital Flood Insurance Rating Maps. As a result, Harris County Flood Control District (HCFCD) is using LIDAR data to plan and execute one of the first completely digital floodplain mapping projects in the country. The HCFCD in Texas acquired a LIDAR data set and contracted the engineering firm of Dodson & Associates, Inc. to conduct a floodplain mapping project for Brays Bayou, which runs through Houston. Global Positioning System (GPS) generated basin cross-sections from field survey crews were integrated with the U.S. Army Corps of Engineers (COE) Hydrologic Engineering Center's River Analysis System hydraulic model. The resulting hydrograph was used to create a predicted water surface over the bare earth LIDAR-generated DTM. The processing is performed through use of a proprietary Arc/Info Avenue extension, with results viewed in ArcView.

Similar uses of LIDAR data for floodplain mapping include a project in Devils Lake, North Dakota. This particular area of the country faces annual flooding in the spring from melting snow runoff. Data collected during the winter months will be used to estimate damage and flood areas while looking for ways to prevent damage in the future. Another use includes the Orleans District COE that is working on a drainage enhancement project in three parishes surrounding New Orleans, Louisiana.

Figure 1 represents a flood simulation on a bare earth model with road planimetrics and building footprints to develop lowest adjacent grade of a portion of Devils Lake, North Dakota.

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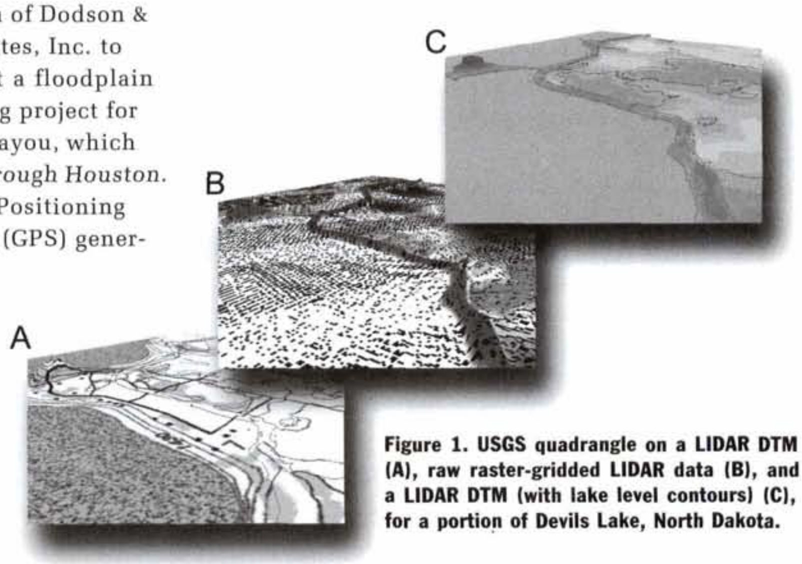
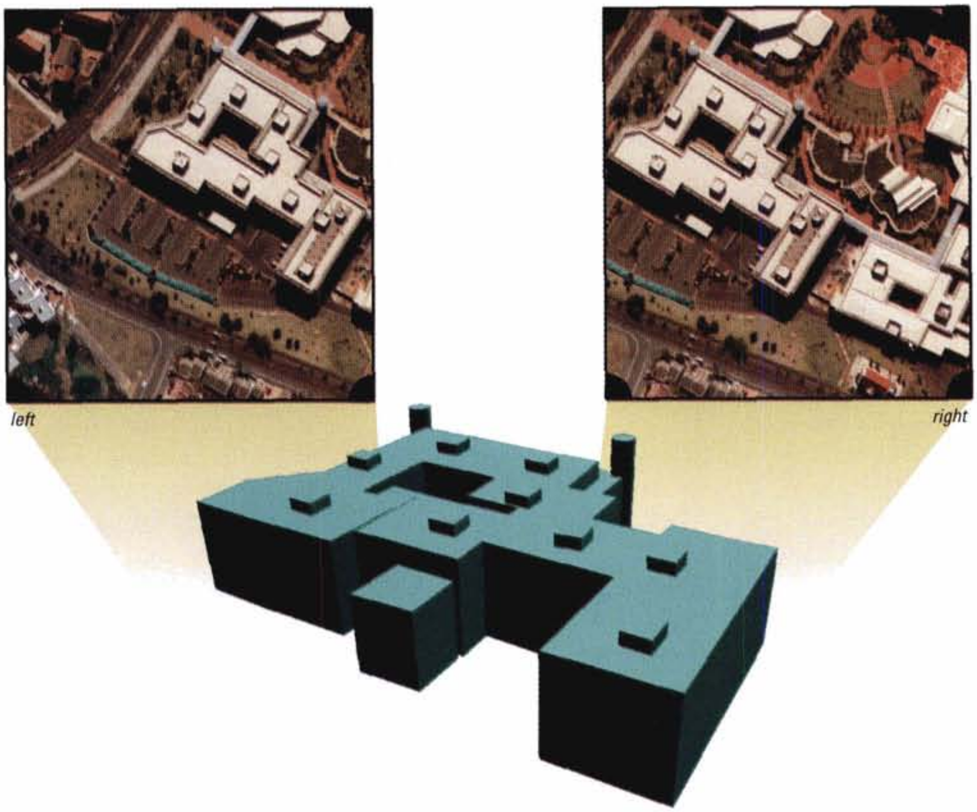


Figure 1. USGS quadrangle on a LIDAR DTM (A), raw raster-gridded LIDAR data (B), and a LIDAR DTM (with lake level contours) (C), for a portion of Devils Lake, North Dakota.

Do-It-Yourself 3D



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Telecommunications

Throughout the telecommunications, broadband and LMDS industries, exceptional growth and expansion have become the norm. Requirements for the industries' planning and build-out include terrain elevation and ground cover data and building outlines. LMDS also requires line-of-sight (LOS)/link margin analysis between transmitters and receivers because buildings and trees easily obstruct high-frequency radio waves. To ensure a clear path (LOS at considerations of 28GHz) and determine areas viable for development, telecommunications companies must rely on accurate and detailed data sets that offer information about natural and manmade obstructions. Because high-frequency radio waves travel only a short distance of 3-5 kilometers before fading, a dense pattern of transmitters is required to cover a large area. Finally, the industry has expressed a spatial accuracy requirement of at least one meter in x, y and z to ensure proper planning. Because of its flexibility, accuracy and timeliness, these industries have started acquiring LIDAR-generated building renderings for use in the line-of-sight modeling. Providers who must rely on building and foliage databases that describe both the footprint and elevation of potential obstructions have learned that LIDAR is the answer for these applications too. The LIDAR data sets provide three-dimensional building outlines and exact footprints of buildings and trees/canopy cover with their associated heights faster than any traditional technology and can keep up with the demand posed in the field. These data are being used to evaluate radio frequency, wave interference and traffic capability.

Transportation

Transportation departments across the United States are acquiring and assessing the use of wide-area LIDAR data for numerous infrastructure projects.

The Texas Department of Transportation (TXDOT) is using LIDAR data to design a major highway renovation project for an overly congested portion of Interstate 10 on the west side of Houston. The LIDAR data are being used to represent existing or, as-built, structures on a bare earth DTM. The planned design is digitally overlaid on the baseline LIDAR data. Resulting three-dimensional renderings are first viewed and evaluated by the district's engineering design staff. The resulting edited rendition, in a three-dimensional fly-through format, is planned for presentation at public meetings. Figure 2 presents a segment of the LIDAR-generated bare earth and tall buildings product along a segment of Interstate 10 in Houston.

Figure 2. LIDAR-generated bare earth and tall building rendering along I-10, Houston, Texas.

TXDOT also envisions applications of LIDAR data for planning, hydrology/drainage studies, litigation support, environmental analysis/permitting, subsidence/maintenance planning and near-real time emergency response/traffic routing.

More than just roads, transportation includes the navigation of ports, channels and levees with increased commercial shipping needs. This too is an area where LIDAR data has practical applications. Data containing specific and highly accurate terrain information can be used in the simulation courses for piloting through congested waterways. Using LIDAR data and aerial photography, clients have been able to establish what infrastructure exists in ports where logistics and timing prevent actual visitations for training. Engineers are using the data sets to help determine where to make modifications to structures and eleviate bottlenecks that cause flooding along the course of waterways.

Finally, as airports continue to expand services and facilities to meet increasing demand, accurate mapping data is essential. Engineers, in the developing and planning stages of modification or new airport siting, are conducting studies involving noise abatement, line-of-sight and landing patterns for optimal performance and minimal impact. Line-of-sight and obstruction mapping are valuable for this purpose and possible with the terrain mapping data produced from ALTMS. Engineers and designers also can use the data to determine easier access to terminals.

An example of one recent project using LIDAR data for transportation includes the representation in Figure 3. The data depicts LIDAR-de-

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Figure 3. Bare earth/DTM rendition of LIDAR data of Mt. Tsukuba, Japan.

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rived bare earth DTM of Mount Tsukuba, Japan. This data will be used in a number of applications to address the growing stress on the transportation infrastructure in Tokyo and surrounding areas.

Urban Landscapes

Numerous urban applications of LIDAR data require the rendering of buildings above 10 meters or three stories (Haala et al., 1998; Lemmens et al., 1997). Figure 4 is a LIDAR data-generated tall building rendition of downtown Houston, which is draped on a USGS Digital Orthophoto Quadrangle. To support urban applications, an airborne data acquisition procedure has been developed that generates the spatial resolution and between-building laser shot hit configuration that meets the majority of urban-user requirements. LIDAR data do not have the shadow and parallax problems of aerial photography or the shadow and building layover issues of radar data with respect to tall buildings. An international risk analysis company has acquired a LIDAR-derived building data set of downtown Houston to integrate a wind stress/damage model that would simulate the effects of a Level 5 hurricane. Another consulting firm will use the same raw LIDAR data to depict the flood effect of just such a major hurricane event to support emergency-response planning and public awareness. Interest in these applications has developed rapidly since Hurricane Mitch, which devastated several countries throughout Latin and North America in 1998.

Figure 4. LIDAR-generated tall (above 10-meter) building rendition of downtown Houston, Texas draped on a USGS Digital Orthophoto Quadrangle (DOQ).

Another use of LIDAR data in urban settings includes the issue of air pollution. LIDAR-derived building footprints or polygons can be used to model the movements of varying wind conditions by individual city. As air movements are better understood, the behavior of chemical and pollution plumes also can be studied. This particular application is being developed for compliance and mitigation of various cities to the Environmental Protection Agency's air pollution standards. Management specialists are also looking at the possibility of using the data to develop emergency-response scenarios to potential catastrophic chemical leaks and spills.

Natural Resource Management

High-resolution LIDAR data are unique to other remotely sensed digital elevation data sets in that they are more economical than conventional sensing or orthogrametric methods. The ALTMS is also able to capture the approximate height of most resolution-dependent Earth features such as trees, shrubs, marsh grasses, levees and buildings, among others. Scientists are beginning to assess the use of LIDAR-derived measurements in vegetation community and habitat characterization. Forest measurements such as tree height, density, biomass and canopy cover are being derived for input to forest growth/production models, ecological assessments and environmental permits (Blair et. al., 1999; Eggleston et al., 2000; Maclean and Martin, 1986; Nelson et al., 1997; Nilsson, 1996; Young et al., 2000).

Large projects involving natural resource management include the Puget Sound, Washington LIDAR data set collected in the spring of 2000. It will be assessed for such applications as the preservation of salmon fisheries and habitats, and seismology earthquake studies.

To illustrate, Figure 5 represents LIDAR-generated coastal marsh vegetation heights for a portion of Orleans Parish. The USGS's National Wetlands Research Center in Lafayette, Louisiana also is assessing the application of these LIDAR-derived elevations of expansive marsh grass communities in coastal Louisiana (Gomes Pereira and Wicherson, 2000; Shrestha and Carter, 1998; Yegorov et al., 2000).

Forest Management Applications

New LIDAR data sets are also providing precise measurements of various forest parameters. These new wide area measurements include tree density, height, canopy cover, road or corridor access and ground elevations. The information will allow basic research and immediate commercial applications. Ecologists and wildlife managers are using the data to assist in applying information to better characterize, model and manage habitats and associated natural resources.

LIDAR technologies also show promise on the commercial side for forestry companies that need a more economical approach to derive commercial harvest estimates of standing timber volumes. These forest measurements can be applied to establish roughness coefficients for determining the resistance of flow to water during flood events. The results of these studies enable FEMA and other communities to map flood plain boundaries and flood insurance rate maps. Working with the other industries like telecommunications, foresters use the data to provide specific absorption rate information for forested areas at various wavelength frequencies. Additionally, forestry, engineering and defense institutions can use the measurements to develop equipment mobility and traffic studies in foliage-thick areas.

Figure 5. LIDAR-generated coastal marsh vegetation heights for a portion of Orleans Parish, Louisiana.

Wide-Area LIDAR Mapping Data Protocols

In the design of wide-area mapping projects, a trade off must be made between the collection costs, the complexity of the final data product and the users' desire for the most detailed information possible.

A Harris County, Texas data set collected by TerraPoint, LLC in 1998 represents 4,491 square kilometers at a 3.05 meter laser ground space posting and 30 gigabyte storage size. This project provided the opportunity to assess commercially viable applications based on user recommendations. For subsequent wide-area projects, the ground-posting density was doubled, resulting in a posting of 1.52-meter between laser hits. The scan angle and control of beam divergence significantly minimizes data shadow effects and creates long beam paths suitable for vegetation penetration, bare earth and urban/building applications (Means, 2000).

Error Budget and Accuracy/Geomorphologic Quality

The accuracy of LIDAR data sets is dependent on the following factors: accuracy of sensor components [e.g., inertial measurement unit (aircraft/sensor altitude); Global Positioning System (GPS); laser ranging and scan angle measurements; accuracy of ground survey control (procedures and GPS); land cover; and data processing (e.g., datum, projection conversions, QA/QC, etc.)]. The four survey control components are base stations, calibration sites, ground control points and LIDAR survey calibration points. This information is combined with the associated calibration results to produce trip

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lets (x, y, z) for each laser strike point. The inherent error budget of the sensor hardware technology is about 0.2 meters (vertical), yet resulting independent accuracy assessments of raw data have often been better than 0.2 meters (vertical). The raw, wide-area data accuracy is in the range of 0.15 meters to 0.3 meters root mean square error (RMSE) in z and about 0.6 meters to 1 meter in x and y. This accuracy can be enhanced with additional ground survey control.

Limitations

The lasers in LIDAR systems that map Earth features generally operate in the near-infrared portion of the spectrum. Certain Earth features such as water (depending on the angle and turbidity), new asphalt, tar roofs and some roof shingles often absorb laser pulses in this wavelength. Moisture, including rain, clouds and fog, also typically absorb the laser signal and appear as holes in the data set that can be verified and edited using imagery and/or a triangular irregular network (TIN) model.

Segmentation and extraction of above-ground features often is desired in applications requiring the creation of a bare earth DTM. Extracted and classified features such as trees and buildings later can be put back for insurance and other applications. Robust methods for more automated feature extraction and classification are under development.

Finally, LIDAR data sets, especially when coupled with imagery, are quite large. Users must be prepared to augment computing resources to store and process the information. Frequently, as with other digital spatial data, users may require enhancements to the basic LIDAR data. These requested enhancements might include additional data formats, data models, data segmentation and/or compression and other value-added products and/or software [e.g., bare earth, building polygons, lowest adjacent grade, three-dimensional rendering, etc.].

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