Airborne lidar on the Alaskan North Slope: Wetlands mapping, lake volumes, and permafrost features

JEFFREY G. PAINE, JOHN R. ANDREWS, KUTALMIS SAYLAM, THOMAS A. TREMBLAY, AARON R. AVERETT, TIFFANY L. CAUDLE, THORALF MEYER, and MICHAEL H. YOUNG, BURGAU OF ECONOMIC GEOLOGY

Wetlands and shallow, freshwater lakes are common on the Alaskan North Slope, a permafrost-dominated coastal plain above the Arctic Circle. New approaches are needed to augment traditional remote sensing and ground-based field activities that would enable rapid and accurate discrimination of wetlands from uplands and estimation of lake depths and volumes over areas being considered for exploration and production activities. Using a new airborne lidar instrument that combines laser ranging at near-infrared wavelengths for topography and green wavelengths for bathymetry, we flew a pilot study over a 490-km² area south of Prudhoe Bay to measure surface topography at a density of about 20 points/ m² and water-body depths at a density of about 2 points/ m². High-resolution digital elevation models, having vertical accuracies of a few centimeters, have been generated from the topographic laser data. These models and associated point clouds are being used along with high-resolution, colorinfrared imagery to map permafrost landscape features such as soil/ice polygons and pingos and identify microtopographic features that influence soil moisture and, consequently, wetlands distribution. Bathymetric lidar data are being used to produce elevation models for the water surface and the water bottom, allowing water depths to be determined for shallow, freshwater lakes and anastomozing stream channels. Water penetration to depths greater than 6 m has been achieved in lakes with reported turbidities ranging from 0.7 to 4.3 nephelometric turbidity units (NTU). Advantages of the airborne approach compared to conventional wetlands and

water-body depth surveys include the ability to (1) cover large areas rapidly, (2) produce more accurate watervolume estimates in reasonably clear water, and (3) guide ground-based, labor-intensive wetland surveys to areas where soil is most (or least) likely to be saturated.

Introduction

We conducted a pilot study in the Prudhoe Bay area on the Alaskan North Slope (Figure 1) in August 2012 using a new airborne lidar (light detection and ranging) and imaging system to rapidly map lake depths and assist in wetlands mapping. The new system combines a high-pulse rate, near-infrared laser that is used to map topography, and a green laser that penetrates water of reasonable clarity to map bathymetry to depths beyond 10 m under ideal conditions. Using data acquired during the 2012 survey, we are exploring how best to apply this new technology to environmental mapping in permafrost-dominated terrain north of the Arctic Circle.

Environmental issues being addressed with the system include (1) discriminating likely uplands and wetlands on a microtopographical scale on the low-relief Alaskan North Slope using high-resolution elevation models, and (2) determining depths and volumes of shallow Arctic lakes to determine potential water availability to support unconventional oil and gas exploration and production activities. We are attempting to apply topographic lidar to identify areas where soil is likely to be water-saturated (a key factor in mapping Arctic wetlands), and to apply bathymetric lidar to rapidly survey lake depths and determine water volumes. In a remote area such as the North Slope, where few roads exist and off-road access is severely restricted, wetlands mapping and lake surveys are labor-intensive, logistically difficult, and expensive. Current satellite-based remote sensing does not provide adequate spatial resolution to identify small and subtle topographic features that strongly influence soil moisture and wetlands distribution. Information acquired using airborne lidar promises to radically increase our ability to measure lake depths, calculate water volumes, and focus ground-based wetlands investigations on those areas most likely to have water-saturated soil, a fundamental discriminator in wetlands mapping.



Figure 1. (a) Landsat 5 Thematic Mapper (TM) image of the Deadhorse survey area, Alaskan North Slope, along the Beaufort Sea. (b) Digital elevation model (30-m cell size) of the Deadhorse area constructed from TM data. Landsat 5 image and topographic data acquired in June 2009. Landsat data from the U.S. Geological Survey.

Methods

The airborne lidar system (Airborne Hydrography AB's Chiroptera, Figure 2) used for the North Slope survey consists of a near-infrared (1.0 μ m wavelength) laser system pulsing at 400 kHz, a green (0.5 μ m) laser system pulsing at 36

kHz, and a 50-megapixel, three-channel digital camera that acquired color-infrared images to aid wetlands delineation. The near-infrared laser system acquired topographic data at single-pass point densities greater than 20 points per m² at a flight height of 400 m. These data were used to create high-



Figure 2. (a) The Chiroptera system and the system mounted in a twin-engine aircraft for the North Slope survey. (b) Elliptical (Palmer) scanning pattern employed by the Chiroptera topographic and bathymetric lasers and generalized illustration of water-surface and water-bottom returns.



Figure 3. Chiroptera data samples from test flights and the North Slope survey area. Elevationscaled, near-infrared lidar point clouds of (a) the Texas Capitol and surrounding buildings; (b) four-engine aircraft on the tarmac at the Deadhorse, Alaska airport; and (c) The University of Texas campus. (d) Sample data from the bathymetric laser including (left) a single flight swath across a water-filled channel, (right) a recorded waveform with marked water surface and waterbottom returns, and (bottom) a cross section across the water-filled channel showing land surface, water surface, and water-bottom returns.

resolution topographic models of the 490 km² survey area south of Deadhorse, Alaska (Figure 1). Topographic data acquired with the near-infrared laser can be displayed as point clouds (Figure 3) or gridded to produce digital elevation models (DEM). The water-penetrating green laser produced bathymetric point densities of 1-2 points/m² at the 400-m survey flight height. The bathymetric system recorded waveforms from which reflections from the water column, including the water surface and the water bottom, were identified (Figure 3). The speed of light in water, when combined with time delays between identified arrivals in the waveform, determines water depths for individual pulses.

Information derived from the detected surfaces, such as total water volumes for lakes and incremental water volumes greater than threshold depths that govern the presence of year-round fish populations, for example, were calculated by differencing detected upper and lower water surfaces. Spatial accuracy of the topographic and bathymetric lidar data, which is governed by the accuracy of aircraft trajectories and attitude derived from GPS and an inertial management unit, is commonly 10 cm or less.

Mapping topographic features: Permafrost polygons and pingos

Airborne and ground-based laser systems have been used for many years to produce high-resolution DEMs. The Alaskan North Slope is an area of generally low relief having important periglacial and permafrost features such as soil and ice polygons and pingos (hydrolaccoliths, or roughly conical ice-cored structures mantled with soil that can be tens of meters high; Pidwirny, 2006). Standard topographic data over this region within the Arctic Circle consists of small-scale (1:63,360) USGS topographic maps contoured at 25-ft (-8-m) intervals and DEMs created from satellite data at 30-m spatial resolution. These maps have insufficient lateral and vertical resolution to effectively delineate critical permafrost features or the elevation-influenced distribution of wetlands. High-frequency topographic lidar systems can produce high-resolution elevation models at single-pass point densities greater than 20 points/m² (Figure 4). At the survey-area scale, these lidarderived maps of the North Slope depict the general elevation decrease on the coastal plain from the foothills of the Brooks Range on the south to the Sagavanirktok River delta and associated deposits adjacent to the Beaufort Sea on the north.

Lack of backscattered laser reflections from specular surfaces such as lakes and rivers leaves gaps in the lidar data where water stands at the surface. These gaps can also be useful in identifying surface water bodies.

Full-resolution (400 kHz) laser returns reveal topographic detail that cannot be achieved with available satellite, aerial imagery, and ground-based surveying methods. We constructed a detailed DEM (25-cm resolution) from full-resolution lidar data at a well pad along the Sagavanirktok River and the adjacent highway and compared that to the 30-m resolution DEM constructed from Landsat 5 Thematic Mapper data (Figure 5). Critical permafrost-related features such as soil and ice polygons that are a few to a few tens of meters across are not detectable using lower-resolution data, but are well captured and readily mappable at topographic lidar resolution. DEMs such as these allow discrimination of individual soil polygons and the lower-elevation areas between them. Elevation profiles across individual polygons can be used to classify them as low- or high-centered. This information is then used to better predict water movement and soil moisture patterns in wetland and upland environments. Lidar data are also routinely converted to 3D surfaces (Figure 6) that can be viewed to highlight critical surface features and aid analysis and interpretation of permafrost terrain.

Pingos are distinctive permafrost features found on the Alaskan North Slope and in other Arctic and subarctic regions. These soil-mantled, ice-heave structures thrust upward from the coastal plain, forming roughly conical shapes that can dominate the low-relief landscape. Topographic lidar data and high-resolution imagery greatly assist in characterizing and monitoring the growth or decay of these features over time at rates that can reach a meter or more per year. Lidar data (DEMs and profiles) acquired across a pingo in the northern part of the survey area (Figure 7), for example, reveal that it is a 17-m high and 160-m wide conical structure that occupies a basin that is about 3 m below the surrounding coastal-plain surface. High-resolution (5-cm pixel size) imagery overlain on the DEM (1-m cell size) enhance the appearance of the summit crater, the central ice core, mantling soil, and flank crevices.

Within the seismic exploration realm, potential applications of high-resolution topographic models derived from airborne lidar surveys such as this one on the North Slope include the ability to more accurately correct topographyrelated statics problems on seismic surveys and to optimize the design of seismic surveys to avoid statics problems that could be caused by wetland and permafrost features.

Lake and stream bathymetry

The numerous freshwater lakes on the Alaskan North Slope are relatively clear, shallow, and can support fish populations if the water depths are greater than about 2.1 m (ASRC, 2012). These lakes are also potential water sources for iceroad construction and hydrocarbon-development activities. In 2011, ASRC staff conducted fathometer and fish population studies in 26 lakes near the Sagavanirktok River using helicopters to transport field crews and small boats. The lakes surveyed by boat in 2011 had surface areas between 4 and 191 hectares, measured depths as deep as 3.5 m, and water clarity (a key factor controlling bathymetric laser penetration depths) ranging from 0.7 to 4.6 nephelometric turbidity



Figure 4. Comparison of (a) USGS topographic map (1:63,360 scale) and (b) digital elevation model (DEM) constructed from nearly 600 million topographic lidar data points over the North Slope survey area. Point density at full resolution is about 15–20 points/m². Dark areas on the DEM are lake and river surfaces with no topographic laser returns.

units (NTU) (ASRC, 2012). The 2012 airborne lidar survey covered an area that included all the lakes surveyed by boat in 2011, providing an opportunity to compare results from the different surveying methods and analyze airborne bathymetric lidar data from the hundreds of lakes within the area of interest. Analysis and ground-truthing of North Slope bathymetric lidar data continues, but initial results are encouraging.

Amplitudes of returns from the bathymetric laser are recorded as a waveform (Figure 3d) from which interpreted features such as the water surface and water bottom are

extracted. DEMs can be created at varying resolutions from each return type. Survey area-wide DEMs of the water-bottom return define the location and extent of water bodies as well as the elevation of the water bottom, depicting generally decreasing elevations southward on the coastal plain (Figure 8). A larger-scale view of tile F3, a 4×4 km area along the Sagavanirktok River, clearly shows water-bottom elevation variations within several lakes west of the river and the intricate anastomozing pattern within the numerous individual stream channels that together form the Sagavanirktok River (Figure 8). Information on water depths in channels such as these would be difficult to obtain using traditional marine or ground-based surveying methods. Stream cross sections produced from data such as these, when combined with measured stream velocities, could provide highly accurate flowrate measurements in braided streams where water clarity is sufficient to allow laser penetration to the water bottom.

The water surface and water bottom can be combined to determine water depths and total or incremental water volumes below threshold depths. North Slope survey examples of these surfaces include one from a shallow lake in the F3 area that measures about 500 m across (Figure 9). The water surface has a lidar-determined elevation of about 48.6 m. Total apparent relief on the water surface, which could be caused by wind setup, waves, or possibly by density contrasts associated with depth changes, is about 7 cm (Figure 9a). Water-bottom returns appear to extend over the entire lake, reaching

a maximum depth of about 2.2 m. The lake-bottom surface (Figure 9b) clearly shows the location of deeper channels and between-channel bars related to deposition from local streams such as the one that flows into the southern part of the lake. Boat-based surveys of this lake acquired in 2011 indicate a turbidity of 2.0 NTU and a maximum measured depth of 2.5 m.

A second example from another North Slope lake (Lake 18) surveyed by boat in 2011 shows excellent agreement between fathometer- and lidar-derived lake depths (Figure 10). Lake 18, an elongate water body that has a surface area of



Figure 5. Comparison of typical resolution achieved in DEMs created using (a) Landsat 5 Thematic Mapper data acquired in July 2009 (30-m cell size) and (b) full-resolution topographic lidar data (0.25-m cell size) over a 400 × 400 m area on the west bank of the Sagavanirktok River. Visible features on the lidar DEM include soil/ice polygons, the Dalton Highway, channels of the Sagavanirktok River, and part of the Merak 1 well pad in the southern part of the image. Landsat 5 data from USGS.



Figure 6. Perspective view toward the northwest of the Merak 1 well pad (foreground), the Dalton Highway, and permafrost-related soil and ice polygons in the North Slope survey area. Image constructed from full-resolution topographic lidar data.



Figure 7. Topographic models, elevation profiles, perspective views, and RGB imagery of a large pingo (height = 17 m and width = 160 m) in the northern part of the North Slope survey area.

about 5.3 hectares and a maximum depth of 3.6 m, is the deepest lake surveyed by boat (ASRC, 2012). Measured water clarity in 2011 was 2.3 NTU, slightly more turbid than the first example. Despite the greater depth and higher turbidity, lake-bottom laser returns were identified across the entire lake (Figure 10). Comparisons of sonar- and lidar-derived depths show good general agreement in overall shape of, and depth to, the lake bottom. Point-by-point depths at selected locations compare reasonably well: 3.6 m by sonar and 3.8 m by lidar in the southern deep pool, 2.6 m by sonar and 2.6 m by lidar on a shallow shelf in the middle of the lake, and 3.6 m by sonar and 3.7 m by lidar in the northern deep pool. Maximum measured depths are only slightly different: 3.6 m by fathometer, 3.8 m by lidar. Density of coverage obtained by lidar averaged about 1 point/m² over the entire lake, providing greater coverage than is practical with a boat-based survey.

Lake volume

Water-bottom DEMs of individual lakes generated from dense bathymetric lidar point clouds (Figure 11) enable detailed morphological characterization of the lakes as well as accurate water-volume estimates. Analysis of airborne lidar data indicates that there are 283 lakes within the survey area that are larger than 0.8 ha. The largest has a surface area of 234 ha. In all lakes combined, the total volume of water is calculated to be 20,343,051 m³, although the estimated



Figure 8. DEM constructed from full-resolution bathymetric lidar returns classified as water bottom (lake or river floor) for the (a) North Slope survey area and (b) tile F3, a 4×4 km area along the Sagavanirktok River.

volume of individual lakes varies greatly from less than about 100 m³ to as much as 1,657,598 m³. Average lake volume for lakes with surface area greater than 0.8 ha is 72,138 m³.

Most lake volume occupies shallow water. Of the 283 lakes analyzed, only 84 (30%) are deeper than 1.5 m and only 39 (14%) are deeper than 2.1 m. Just over 35% of the total lake water volume (13,200,306 m³) is found in water depths of 0.3 m or less. Almost 4% (724,813 m³) of the total

lake water volume is at depths greater than 1.5 m in 84 of the lakes, and less than $1\% (116,753 \text{ m}^3)$ of the total water volume is at depths greater than 2.1 m.

Comparisons of water volumes calculated using August 2012 lidar data with volumes calculated using boat-based fathometer data acquired in August 2011 (ASRC, 2012) show that, for most lakes, the lidar-calculated total volumes are greater by an average of 9%. The statistical relationship between lidar- and fathometer-based volumes is excellent (Figure 12). Differences in calculated volumes from lidar and fathometer approaches could represent real volumetric differences resulting from water-level differences between the two survey dates, or they could be artifacts of one or both methods. For example, lidar sampling of the water bottom is more complete than fathometer data would be, particularly in shallow water not accessible by boat. Alternatively, misclassification of water-bottom returns in lidar data could lead to erroneous water-depth calculations that would cause errors in volumetric calculations, as would errors in water-surface elevations. Work is ongoing to verify and improve lidar-derived estimates of water-surface, water bottom, and water depth that should further improve total and incremental volume estimates for the generally shallow North Slope lakes.

Conclusions

Airborne topographic and bathymetric lidar systems permit rapid surveying of upland, wetland, lacustrine, and riverine environments in critical periglacial and permafrost terrain such as those on the Alaskan North Slope. Unprecedented topographic detail achieved using a near- infrared laser pulsing at rates as high as 400 kHz allows applications that include mapping small geomorphic features (such as soil and

ice polygons), better defining the role of microtopography in wetland distribution, monitoring topographic change over time that can accompany permafrost change at a vertical scale of a few cm, and perhaps aiding the design of seismic surveys to avoid permafrost- and wetlands-related statics problems during acquisition as well as making better topography-based statics corrections processing. High-resolution during DEMs of the land surface in remote regions such as the North Slope, where detailed topographic information has not been available, allow better delineation of drainage basins and prediction of soil moisture that are critical to wetland classification. Bathymetric lidar has been shown to penetrate reasonably clear North Slope lakes and streams to depths as great as 6 m at single-pass densities of about 1 point/m², allowing precise calculations of total and incremental water volumes that are important parameters for determining which lakes are likely



Figure 9. (a) Water-surface and (b) water-bottom DEMs constructed from full-resolution bathymetric lidar data for a shallow lake west of the Dalton Highway. Total apparent relief on the water surface is about 7 cm. Water-bottom returns were recorded to the maximum depth of the lake at about 2.2 m.



Figure 10. Comparison of (a) sonar-derived water depths acquired during boat-based surveys in August 2011 with (b) bathymetric lidar-derived water depths acquired during the August 2012 airborne survey on the North Slope. Water depths in comparable lake positions are similar. Fathometer data from ASRC (2012).



Figure 11. Bathymetric lidar point cloud of two adjacent North Slope lakes consisting of returns classified as ground, water bottom, and shallow-water bottom after removal of noisy data. Returns within water bodies constitute the water-bottom surface. Vertical exaggeration is 30×.

to support fish populations. Detailed maps of lake-bottom morphology provide a unique and comprehensive data set to support studies of the formation, sedimentation, evolution, and future change of these common Arctic landscape features.

References

- 2011 Great Bear lake studies report, North Slope, Alaska, 2012: ASRC Energy Services.
- Pidwirny, M., 2006, Periglacial processes and landforms, in Fundamentals of Physical Geography, second edition: accessed 17 May 2013, http://www.physicalgeography.net/fundamentals/10ag.html.

Acknowledgments: Funding for this project was provided by Great Bear Petroleum Operating, LLC under contract no. UTA12-000752. Ed Duncan and Karen Duncan, Great Bear Petroleum,



Figure 12. Relationship between water volumes calculated for 26 North Slope lakes using a boat-based fathometer in 2011 (ASRC, 2012) and airborne lidar in 2012.

provided logistical support for the airborne survey and field investigations. Airborne Hydrography AB staff Petter Kullenberg, Daniel Andersson, and Torbjörn Karlsson participated in data acquisition, preliminary data processing, and algorithm development to identify water-surface and water-bottom laser returns. Joseph Christopher of ASRC Energy Services, Inc. provided fathometer-based bathymetric data from select North Slope lakes and guidance on wetland mapping. Rick Miller offered numerous helpful review comments. Publication authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin.

Corresponding author: jeff.paine@beg.utexas.edu