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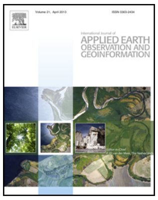

Research paper

Assessment of depth and turbidity with airborne Lidar bathymetry and multiband satellite imagery in shallow water bodies of the Alaskan North Slope

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A B S T R A C T

Airborne Lidar bathymetry (ALB) is an effective and a rapidly advancing technology for mapping and characterizing shallow coastal water zones as well as inland fresh-water basins such as rivers and lakes. The ability of light beams to detect and traverse shallow water columns has provided valuable information about unmapped and often poorly understood coastal and inland water bodies of the world.

Estimating ALB survey results at varying water clarity and depth conditions is essential for realizing project expectations and preparing budgets accordingly. In remote locations of the world where in situ water clarity measurements are not feasible or possible, using multiband satellite imagery can be an effective tool for estimating and addressing such considerations.

For this purpose, we studied and classified reflected electromagnetic energy from selected water bodies acquired by RapidEye sensor and then correlated findings with ALB survey results. This study was focused not on accurately measuring depth from optical bathymetry but rather on using multiband satellite imagery to quickly predict ALB survey results and identify potentially turbid water bodies with limited depth penetration. For this study, we constructed an in-house algorithm to confirm ALB survey findings using bathymetric waveform information.

The study findings are expected to contribute to the ongoing understanding of forecasting ALB survey expectations in unknown and varying water conditions, especially in remote and inaccessible parts of the world.

1. Introduction

The Bureau of Economic Geology (BEG, the Bureau) owns and operates an airborne Lidar bathymetric sensor, Airborne Hydrography AB's "Chiroptera." The Chiroptera uses a near-infrared (NIR) wavelength of 1.064 μm for topographic ("topo") data collection and a green wavelength of 0.515 μm for bathymetric ("hydro") data collection. The effective maximum range is 400 m for the hydro scanner, which operates with a fixed pulse rate of 35 kHz; the topo scanner enables surveys up to 1500 m above ground level and records pulses up to 400 kHz, where returns are interpolated from waveform signals. Both scanners, by design, direct the light beam with an incident angle (from vertical) of 28° in a forward/backward direction to 40° sideways with an elliptical pattern (Palmer scanner). Constant off-nadir shots have the advantage of making refraction-angle corrections possible from a variety of water surface conditions, as well as the advantage of registering returns from vertical surfaces such as building façades and sloped cliffs.

Airborne Lidar bathymetry has been around since the 1970s, when the National Aeronautics and Space Administration (NASA) designed Airborne Oceanographic Lidar (AOL) (Guenther et al., 1979). AOL was an experimental system, and respective field tests proved to be promising for nautical mapping and charting. In the early 1980s, Optech of Toronto, Canada developed the Larsen 500 with collaboration from the Canadian Centre of Remote Sensing, a federal agency (Banic and Sizgoric, 1986). In the early 1990s, Optech developed the first version of the SHOALS system, and the

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Royal Australian Navy and the Swedish Armed Forces followed with their newly designed systems, the Laser Airborne Depth Sounder (LADS) and the Hawk Eye, respectively (Setter and Willis, 1994; Koppari et al., 1994; Lillycrop et al., 1996). Later, in the 2000s, various governmental agencies (e.g., U.S. Army Corp of Engineers, U.S. Geological Survey, U.S. National Ocean Service, Canadian Hydrographic Service, etc.) showed further interest in ALB technologies, which accelerated the manufacturing of more advanced, portable, and capable systems (Guenther, 2001). Earlier systems were too large and cumbersome to operate, and required larger survey aircrafts for mounting; therefore, the costs of operating an ALB device were much higher compared to those of running a topographic-only system. Additionally, ALB systems required much-lower flying altitudes (250–400 m above ground level) that increased flight duration and overall project costs.

The latest ALB systems on the market (as of November 2016) such as RIEGL VQ-880-G, CZMIL-Nova, and Leica Chiroptera-II have dual scanners for both topographical and bathymetric Lidar data acquisition. All these systems have waveform-digitizing capabilities with the option to include a high-resolution downward-looking camera (RGB or spectral) for simultaneous imagery acquisition.

The waveform-producing capacity of ALB systems provides very valuable survey opportunities in diverse shallow water bodies (e.g., lakes, rivers, shorelines), where it was formerly only possible to detect land/water boundaries using discrete pulse scanners. The Chiroptera hydro scanner produces continuing backscatter signals where the green light beams traverse the air/water interface. These signals propagate until they reach the water bottom and reflect back or are absorbed by sediment or organic/inorganic material in the water column. The digitizer records the entire sequence of backscatter events as a waveform signal from transmitter to water surface, water surface to water bottom, and water bottom back to the receiver. The received signal intensity (amplitude) is stored as a function of time (ns), with the distance of the light-beam path measured by determining the time difference between the detection of water surface and water bottom. Water depth is the calculation of corrected range (distance) of the light-beam path to its refracted angle of incidence underwater (Karlsson et al., 2012).

Multiband satellite imaging technology has also proved to be a valuable remote-sensing tool for larger-scale environmental analysis, and a variety of sensors in orbit (e.g., Landsat, IKONOS, QuickBird, RapidEye) support water-quality monitoring. Because there are thousands of post-glaciated lakes of different sizes and depths in the northern United States and Canada, using satellite imagery to understand water column clarity has been a valuable resource for water-quality monitoring (Nelson et al., 2003; Olmanson et al., 2011; Knight and Voth, 2012).

In this study, we analyzed RapidEye high-resolution 5-band imagery to understand the amount of electromagnetic energy reflected from a variety of water bodies with different clarity, size, and depth. We classified our findings and correlated with ALB survey results over the same project location, conducted in the same time frame. Our hypothesis involved investigating whether multiband satellite imagery can be an effective tool for complementing ALB surveys by predicting water column depth and clarity. For this purpose, we also built an in-house stand-alone algorithm to analyze Lidar waveform information that computes depth information in the areas of interest.

2. Materials and methods

In 2012 (Paine et al., 2015) and 2014 (Saylam et al., 2016a), the Bureau conducted ALB surveys of the Alaskan North Slope to determine and understand the local landscape and kettle-lake attributes of an area west of the Dalton Highway and Sagavanirktok River, approximately 75 km southwest of Deadhorse and Prudhoe Bay (W 149° 06′, N 69° 57′). The Alaskan North Slope is an area of low relief having substantial periglacial and permafrost features such as ice-wedge polygons and pingos, which are circular-to-elongated ice-cored mounds that form by injection and freezing of pressurized water in near-surface permafrost (Jones et al., 2012). Shallow thaw lakes (or kettle lakes), generally less than 2 m deep, are a major component of the tundra landscape of the Alaskan North Slope, where they compose 20% of the total area (Selmann et al., 1975). The exclusive microtopography supports various potential fish-habitat water bodies and wetland areas with arctic tundra vegetation. The lakes' depth, ice growth, and decay determine whether the lakes are suitable as habitats for wildlife and aquatic fauna, as well as suitable for industrial development (Jeffries et al., 1996).

The lakes are ice free for only a few weeks in a calendar year, so the field study was scheduled accordingly, in July and August. Study findings were particularly important for the project sponsor because they revealed lakes deeper than 2 m for building ice roads, improving geophysical surveys, and other environmental and industrial purposes. Various water bodies of different sizes and shapes exist in the area, which made ALB data acquisition and analysis a challenging task. Fig. 1 illustrates the extent and complexity of the 2012 and 2014 ALB survey areas (450 km^2 and 750 km^2, respectively), as well as the ALB depth findings of the 2014 survey. The map clearly shows that deeper water bodies are clustered in the south and southwest, and that shallower lakes are mostly located at the central and northern parts of the survey area.

The 2014 ALB survey was flown at a constant altitude of 400 m above ground level, with an average ground speed of 120 knots an hour. To compensate for the changing ground elevation (30 m in the north, 95 m in the south), atmospheric pressure was monitored during flights to maintain a constant altitude. A total of 95 flight lines were flown, with an average of 50 km in length. Each flight line covered an area 280 m in width, including an average of 40% overlap on both sides to increase the Lidar point density and to avoid any breakups between the lines. Hydro and topo scanners were used concurrently at 300 kHz and 35 kHz, respectively; hydro scanner recorded waveform information with 1024 samples. An average flight line consisted of 253 million individual Lidar points (~8 GB of raw data); point density on the ground was 14.2 ppm^2 and 1.8 ppm^2 for each topo and hydro line, respectively.

Ground control points (GCP) were acquired over the taxiway at Prudhoe Bay Airport, using a Trimble R8 GNSS system. These precise points were used to compare the initial and final elevation measurements registered with Lidar returns. The average vertical bias was measured at less than 1 cm, while the standard deviation was calculated at approximately 3 cm. Boresight calibration was completed for both scanners individually, where average roll error was 2 cm, pitch error was smaller than 3 cm for all data sets.

For both the 2012 and the 2014 surveys, we were not able to directly access and sample water from lakes because of environmental restrictions on the arctic tundra land. In addition, the survey area included 4697 distinct water bodies, in a variety of shapes and surface areas, making such an effort unreasonable. Of all water bodies analyzed, 3837 (81.7%) were classified as shallow or very shallow, with measured depths of less than 1 m. Only 216 (4.6%) of the water bodies were deeper than 2 m. We also calculated that 34% of all water bodies were smaller than 2000 m^2 in surface area.

In the survey location, a visual inspection by high-resolution airborne imagery indicated that a few water bodies were affected by a high concentration of suspended material content. Fig. 2 illustrates a lake with a visible bottom and Fig. 3 illustrates a highly turbid water body. Airborne Hydrography AB (AHAB) developed a turbid water enhancement (TWE) algorithm that filters some of the