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Analysis and correction of ocean wave pattern induced systematic coordinate errors in airborne LiDAR bathymetry

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ABSTRACT

This contribution investigates the effects of ocean wave patterns on 3D underwater point coordinate accuracy for LiDAR bathymetry. The refraction of the finite diameter laser pulse passing the air/water interface is modeled differentially in a strict manner. Typical wave patterns and sensor configurations are simulated, and their impact on the 3D coordinates at the bottom of the water body are systematically analyzed. It can be shown that waves have a significant effect on both the planimetry and depth coordinates of underwater topography 3D point cloud coordinates, especially for modern small footprint LiDAR systems. Planimetric effects may reach several decimeters or even meters, and depth coordinate errors also reach several decimeters, even in the case of a horizontal water body bottom. The simulations show that the simplified assumption, that wave effects average out (as is made in most LiDAR bathymetry data processing tools) is not even fulfilled for large footprint systems (spreading the laser beam to a diameter of several meters at the water surface) under certain wave pattern conditions. Modern systems with smaller beam divergence are much more sensitive to wave-induced variations of the refraction conditions and will experience significant wave pattern dependent coordinate errors.

The results presented here form a basis for a more strict coordinate correction, if the wave pattern can be modeled from the LiDAR bathymetry water surface reflections or from other observations. Moreover, it will be shown that the induced coordinate errors contain a non-zero bias in addition to a local wave surface dependent quasi-random part, which allows for the formulation of wave pattern dependent correction terms in order to increase the accuracy of LiDAR bathymetry by removing systematic wave pattern dependent effects.

1. Introduction

Knowledge on marine phenomena is necessary and beneficial for many reasons: observations of seabed topography, geology, habitats and ecosystems are of high value for environmental protection. The maritime or so called blue economy including fisheries, offshore industry, tourism, shipping and shipping administration depends on such knowledge and its changes, too. As a result, European law requires hydrographic information on the state of European waters (Marine Directive 2008/56/EC; Steinbacher and Pfennigbauer, 2010). The European Commission (2013) further aims to provide a seamless multi-resolution digital seabed map of European waters, to be completed by 2020.

Bathymetry refers to the determination of the depth of water bodies (relative to the water level), including ocean, sea, rivers and lakes. Bathymetry data describe the topography of the seabed as a three-dimensional underwater terrain model, which is an essential component in understanding the underwater environment. Bathymetric measurements are typically made by echo sounders collected from ships (Theberge and Cherkis, 2013). A modern multi-beam echo-sounder receives hundreds of narrow beams in a fan shape at very high angular resolution. The topography of the seafloor is then determined by the time it takes for the sound pulse to return back to the sensor. Multi-beam sonar operation is most efficient in deep water where large swath widths can be acquired. In shallow water, shipborne sonar is less efficient or simply not possible if coastal areas or rivers are non-navigable (Guenther, 2000). Airborne LiDAR data acquisition as a complementary technology can thus close important gaps in bathymetric data.

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Airborne LiDAR bathymetry (ALB) is a technique to derive the underwater topography by airborne laser scanning (e.g. Irish and Lillycrop, 1999; Pfeifer et al., 2016; Fig. 1). The technique captures both the surface as well as the bottom of the water body by scanning with pulsed green or near infrared and green laser wave lengths simultaneously. ALB is an efficient technique for hydrographic purposes in shallow waters. The maximum water depth that can be measured depends on several factors (Guenther, 2000): at the system level, flying height (typical altitudes range between 200 m and 600 m) and laser characteristics (long and high energy laser pulses are favorable) strongly influence the maximum penetration depth. To ensure high pulse energy plus eye-safe operation, many ALB instruments spread the laser beam to a diameter of several meters at the water surface. Major environmental factors are the turbidity of the water body and the reflectivity of the water bottom, whereby maximum range is often specified as multiples of the Secchi depth (Preisendorfer, 1986). Typical (eye-safe) ALB systems can measure underwater topography from 10 m depth for slightly turbid water to up to ~50 m depth for very clear water. At higher turbidity, the maximum ALB depth range can be much lower than this (Quadros et al., 2008). In Richter et al. (2017), the relationship between turbidity and maximum depth range is inverted, deriving water turbidity parameters from the decay of the digitized return pulse echo waveform.

Geometric modeling in airborne LiDAR bathymetry is more complex than in conventional laser scanning. Refraction effects of the laser pulse passing the air/water and water/air interfaces have to be taken into account. This includes the consideration of the reduced velocity of light in water ($\approx 225{,}000$ km/s) and refraction as well as further geometric effects of underwater/multimedia photogrammetry (Maas, 2015). The simplest method assumes a horizontal planar water surface at which the laser beam refraction is governed by Snell's law. However, even small deviations from planarity lead to significant measurement errors. Strictly speaking, the local wave-induced water surface inclination needs to be known for every single laser pulse. Otherwise, wave shape leads to a geometric displacement of the point at the bottom of the water body. This effect can be significant, up to the meter range, depending on water depth and wave parameters as well as on laser footprint size at the water surface.

Many of the early airborne bathymetric LiDAR sensor systems operate with a large beam divergence of up to 21 mrad (Guenther, 1985). The irradiated surface spot diameter of such a beam profile can easily amount to several meters on the water surface. This 'large footprint' will often cover multiple wave cycles and therefore may justify the assumption that wave effects are averaged out ('passive wave correction'; Guenther, 1985). However, Guenther (1985, 1986) states that there are errors associated when calculating the depth on the basis of a weighted average water level only, with their magnitudes very difficult to estimate.

ALB is recently gaining much attention due to new sensor developments allowing for a much higher spatial resolution in scanning underwater topography. Detailed underwater terrain models with ground sampling distances of less than 0.5 m can be collected using short and narrow green laser pulses emitted at high pulse repetition rates (e.g. up to 550 kHz for the RIEGL VQ-880-G). The beam divergence of the laser pulse is consequentially getting smaller (0.7 mrad for the RIEGL VQ-880-G) which results in considerably smaller footprints (in this case in a 42 cm incident beam diameter at 600 m flying height). Operating such 'small footprint' ALB systems allows for much higher point densities, but requires new considerations of the assumptions made in the geometric modeling, as the effects of waves on the water surface cannot be neglected anymore when modeling refraction.

The geometric influence of waves on underwater stereophotogrammetric measurements has been treated by a number of authors in the past (e.g. Okamoto, 1982; Fryer and Kniest, 1985; Tan, 1989). Coordinate errors in so called two-media, later multimedia photogrammetry were first compensated analytically by applying a radial correction term to the image coordinates to correct for refraction effects (Rinner, 1948). Kotowski (1988) developed a more general solution and calculated image and object information as well as interface parameters in a rigorous manner. A module for tracing optical rays through an arbitrary number of different optical media (with different refractive indices) was implemented into the collinearity equations of a bundle adjustment. The approach was extended by Maas (1995) and Mulsow (2010) and can now be integrated as a multimedia-module in standard photogrammetric tools. This flexible ray-tracing module is well suited for industrial/technical close range photogrammetry, even with non-planar media interfaces, but cannot adequately compensate for more complex surfaces like wavy water.

The need for strict water surface modeling thus still remains for ALB applications, and intensive investigations are currently underway. Indications that the actual water surface geometry may be taken into account are given in a patent from RIEGL Laser Measurement Systems GmbH (Ullrich and Pfennigbauer, 2011). The approach is based on the intersection of the incident laser ray with a triangular mesh of water surface points. This refraction correction is implemented in current ALB processing software (RiHYDRO; RIEGL LiDAR 2015 User Conference). However, neither information on the fundamental principle of the method nor on validation can be found in literature. Additionally, the laser ray is considered to be an infinitesimal small line only. Effects caused by a finite diameter laser beam penetrating a curved surface are neglected. In Mandlburger et al. (2013), a water surface model in a regular grid structure of 0.5 m is comparatively derived from near infrared and green laser signals. The approach is based on a statistical processing chain, applied to aggregated neighboring echoes, and thus requires an adequate number of detectable echoes. In the case of sparse water surface echo density, Mandlburger et al. (2015a) propose a semi-automatic approach using river cross-sections (Vetter et al., 2011) to efficiently reconstruct a continuous Digital Water surface Model (DWM). Mandlburger et al. (2015b) combine airborne topographic and UAV-borne (unmanned aerial vehicle) laser scanning information in order to support ALB data acquisition. They conclude that the assumption of a horizontal planar water surface is sufficient for ALB applications is sufficient for moderate wave crest heights of less than 5 cm. This is substantiated by the fact that the deviations of all water surface models calculated are, with respect to the mean water level, below the ranging accuracy of the sensors. However, the influence of (albeit small) short-term changes in water surface dynamics on bottom reflections were not examined. Karlsson et al. (2012) investigated the impact of the sea state on ALB measurements using simulations and empirical measurements. The results of the study showed that there is a relationship between the laser beam pattern underwater and the water surface conditions. The effects of wave patterns on refraction in airborne LiDAR bathymetry were analyzed in Westfeld et al. (2016). This work was focused on riverine environments, simulating water surface conditions of a dedicated past airborne survey campaign.

The work presented here focuses on ocean waves. The aim of the paper is to investigate the effect of ocean waves on LiDAR bathymetry water body bottom coordinates under strict consideration of refraction effects. Obviously, this effect of wave patterns on refraction at the air/water interface (and the water/air interface respectively) is only one part of the entire ALB laser beam path interaction. The laser ray is further subjected to influences such