

# Bathymetry from active and passive airborne remote sensing – looking back and ahead

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## Introduction

Knowledge about the bathymetry of water bodies is of high economic, social, and ecologic importance. Whereas charting bathymetry for navigational purposes is indispensable for ensuring safe shipping traffic, monitoring the quantity and quality of fresh water resources gains more and more importance, especially in the light of climate change. In the European context three water related directives, namely the water framework directive (European Union, 2000), the flood directive (European Union, 2007), and the Fauna-Flora-Habitat directive (European Union, 1992), request monitoring in a periodic cycle. Repeat acquisition of rivers and other inland water bodies is one of the essential tasks in fulfilling the above directives and requires efficient techniques for capturing bathymetry. The same applies to the coastal zone with applications in shore protection after storm events, monitoring of benthic habitats, etc.

Echo sounding is still the prime technique for capturing bathymetry. However, ship-borne data acquisition is inefficient and even hazardous in shallow water areas (Guenther et al., 2000). For surveying the bottom of the riparian area, active and passive optical remote sensing techniques are employed. Three different approaches are in use: (i) Spectrally based depth estimation based on multi-spectral images, (ii) multi-media photogrammetry based on stereo images, and (iii) airborne laser bathymetry. Whereas the prior two are passive techniques using the reflections of solar illumination, the latter is an active method based on green laser radiation.

In this contribution, first, the basics of the above mentioned techniques are reviewed and, second, the potential benefits of fusing concurrently acquired data from either data source (i.e. images and laser scans) are discussed. The latter is the topic of the German Research Foundation (DFG) project “Bathymetry by fusion of airborne laser scanning and multi-spectral aerial imagery” that is work-in-progress at the Institute for Photogrammetry, Stuttgart.

## State of the art

The essential idea of **spectrally based depth estimation** is establishing a relation between multi-spectral image data and water depth (Lyzenga, 1978). This requires understanding the complex interaction of (solar) radiation and water as a function of the wavelength  $\lambda$  (Legleiter et al., 2009).

$$L_T(\lambda) = L_b(\lambda) + L_c(\lambda) + L_s(\lambda) + L_p(\lambda) \quad (1)$$

The upwelling spectral radiance  $L_T$  is composed of the sum of the bottom-reflected radiance  $L_b$ , the radiance from the water column  $L_c$  back-scattered upward before reaching the bottom, the radiance reflected from the water surface  $L_s$ , and contributions from the atmosphere  $L_p$ . All the radiance passing the water surface is generally subject to exponential signal attenuation due to scattering and

absorption in the medium water. The term  $L_b$  is related to both depth and substrate type (i.e. bottom reflectance) and  $L_c$  is purely determined by the waters' optical properties (i.e. turbidity). Depending on the viewing geometry, direct surface reflections (sun glint) expressed by  $L_s$  can make up a large fraction of the recorded radiance  $L_T$  and needs to be dealt with during data preprocessing. For images containing optically deep water, i.e. areas which solely contain reflections from the water column but not from the bottom, a simplified model is applicable. The subsurface radiance for a water depth  $h$  can be written as (e.g., Lyzenga et al., 2006):

$$L(h) = L_S + L_B e^{-\alpha h} \quad (2)$$

$L_S$  hereby comprises contributions from surface-reflections as well as volume scattering from infinitely deep water and  $L_B$  includes transmission losses through the air–water interface as well as the bottom reflectance and volume-scattering effects.  $\alpha$  is the sum of the diffuse attenuation coefficients for upwelling and downwelling light. Eq. 2 clearly reveals the exponential decay of the measured radiance depending on the water depth  $h$  and the optical properties of the water body described by  $\alpha$ . By taking the logarithm of Eq. 2 the relation between image-derived quantities and water depth is linearized and the equation can directly be solved for the water depth  $h$ . However, taking into account that signal absorption and bottom reflectance depends on the wavelength, in practice, multi-spectral data processing is employed to calibrate the remaining unknowns in Eq.2 based on reference data (Lyzenga et al., 2006). Among others, Legleiter (2016) further developed the above model for mapping shallow river bathymetry and (i) proposed the usage of band ratios for depth estimation, (ii) suggested to use hydraulic quantities (discharge, channel aspect, rating curves) for model calibration and (iii) used quantile transformations for more robustly estimating the relation between image derived quantities and water depth. In a nutshell, multi-spectral or even hyper-spectral data can be used to derive both water depth and substrate type (bottom reflectance). The reported accuracy of spectrally derived water depths range from approx. 0.25 cm (e.g., Legleiter, 2016) for clear-water rivers to >1m (e.g. Lyzenga et al., 2006) for coastal water bodies.

A complementary image based approach, focusing on geometry only, is **multi-media photogrammetry**. 3D reconstruction of underwater scenes using stereo image pairs is used for ship wreck exploration in archaeology, in specific industrial close-range applications, but also for capturing the bottom of relatively clear and shallow coastal and inland water bodies (Maas, 2015 and the cited literature therein). The latter is also referred to as photo bathymetry.

Building on the general concepts of photogrammetry, water depths can be derived from aerial stereo images if the interior and exterior orientation of the images are known and if the water surface heights can be estimated with sufficient accuracy. In case a bottom feature is visible in both images, the corresponding apparent image rays need to be corrected due to ray refraction at the air-water interface according to Snells' law. The optical properties of water hereby influence the refractive index of water (i.e. 1.33 for clear water). As opposed to spectrally based methods, differences in bottom substrate type are even favorable for multimedia photogrammetry as this results in image texture, which is a precondition for any stereo photogrammetric surface reconstruction. Even for low texture areas the advent of dense image matching (Hirschmüller, 2008) has opened the floor for high-resolution mapping of shallow water bodies (Wimmer, 2016) where spectrally based methods perform poorly due to the relatively high influence of surface reflections. The theory of multimedia photogrammetry together with a discussion of the error budget is detailed in Maas (2015).

As opposed to the image based techniques discussed so far, **airborne laser bathymetry**, also referred to as airborne laser hydrography, is an active remote sensing technique for measuring the depth of shallow water bodies using a pulsed green laser (Guenther et al., 2000). The sensor-to-target range is estimated by measuring the roundtrip time of a short green laser pulse ( $\lambda=532$  nm) traveling through

both air and water. At the water surface a part of the signal is reflected whereas the remaining part entering the water column gets refracted at the air-water interface and travels to the water bottom with reduced propagation speed. Both effects (refraction, decrease of signal propagation velocity) depend on the relative optical properties of air and water and are described by Snells' law of refraction. The general relation between emitted and received power is described by the laser-radar equation which, for bathymetric applications, is split up into the signal contributions from the water surface, the water column, the water bottom, and background noise including atmospheric (Abdallah et al., 2012; Tulldahl and Steinvall, 2004).

$$P_R = P_{WS} + P_{WC} + P_{WB} + P_{BK} \quad (3)$$

Eq. (3) has the same form as Eq.1 and, in fact, the signal losses in laser bathymetry are equivalent to those described above for spectrally based depth estimation. This also holds for the exponential decay within the water column. A major advantage in laser bathymetry is that the signal attenuation, commonly described by the effective attenuation coefficient  $k$ , can be estimated from the asymmetric shape of the digitized echo waveform (Richter et al., 2017).  $k$  is empirically related to the so called Secchi depth  $d$  referring to the distance from which the black and white quadrants of a 20 cm disk lowered into the water can no longer be distinguished ( $d=1.6/k$ ). Most vendors of bathymetric laser scanners define the maximum penetration depth of their sensors as multiples of the Secchi depth.

Typical measures are threefold the Secchi depth for sensors aiming at maximum penetration depth for mapping relatively deep coastal waters (15-50m) and 1-1.5 times the Secchi depth for so-called topo-bathymetric sensors designed for capturing both shallow inland water bodies (0.5-10m) and riparian topography. The prior use a large laser footprint of several meters, relatively long laser pulses (e.g. 7 ns) and moderate scan frequencies (e.g. 10-50 kHz). In contrast to that, topo-bathymetric scanners use short pulses of (~1 ns), relatively narrow beams (footprint diameter ~50 cm), and high pulse repetition rates (200-550 kHz) resulting in a high point density on the ground of up to 20 points/m<sup>2</sup> for typical flight mission parameters (flying height: 500-600 m a.g.l., flying speed: 100-120 knots).

Capturing the shape of the water surface is a precondition for proper range and refraction correction of the raw measurements. Most bathymetric scanners use an infrared (IR) channel ( $\lambda=1064$  nm) along with the green channel, as there is only very little penetration into the water column at this wavelength. Some instruments go without the IR channel in which case the water surface needs to be modelled using the reflections from the green channel only, although the respective returns are often a mixture of direct surface reflection and sub-surface volume backscattering (Mandlbürger et al., 2013). Especially for small footprint topo-bathymetric sensors, the non-planarity of the water surface (i.e. wave effects) need to be considered for obtaining accurate 3D bottom point coordinates (Westfeld et al., 2017). Depending on water body type (coastal/inland), water clarity, water depth, and water surface roughness during data capturing, depth accuracies in the range of 10-60 cm compared to sonar or terrestrial survey reference data have been reported (Hilldale and Raff, 2008; Kinzel et al., 2013; Fernandez-Diaz et al., 2014; Mandlbürger et al., 2015; Song et al., 2015).

## Research activities

Modern airborne bathymetric sensors (e.g. Riegl VQ-880-G, Teledyne Optech CZMIL Nova, Leica Chiroptera II, etc.) incorporate laser scanners and multi-spectral cameras. This opens the floor for joint data processing of simultaneously acquired active and passive remote sensing data. The following research topics are therefore currently addressed at the Institute for Photogrammetry in the course of the DFG research project "Bathymetry by fusion of airborne laser scanning and multi-spectral aerial imagery":

- The depth estimation techniques described above are used rather exclusively so far. It is expected that exploiting the complementary measurement techniques will result in more accurate, reliable, and complete Digital Terrain Models of the submerged topography.
- Laser bathymetry is a mono-chromatic measurement technique operating in the green domain of the electro-magnetic spectrum. Especially for clear water, certain bands of multi-spectral or even hyper-spectral data may provide better water column penetration. This especially applies to the lower wavelength boundary of the visible spectrum (coastal blue-blue,  $\lambda=430-500$  nm).
- Depths derived from laser bathymetry constitute optimum reference data for calibrating models for spectrally based depth and/or substrate type estimation. This fact can be used to set up automated procedures for processing multi-spectral image data.
- The main advantage of laser bathymetry is that the depth is not derived from radiometric information (signal strength) but via time measurement. Knowing the water depth reduces the unknowns for spectrally based techniques which helps to distinguish substrate soil types, benthic habitats, etc. Fusion of passive image data and active laser scans should therefore improve the object classification (sand, gravel, rock, submerged vegetation, etc.).
- To achieve better classification results, existing state-of-the-art techniques like Conditional Random Fields, which are able to incorporate contextual information, will be applied and extended for the use with comprehensive active and passive remote sensing data as input.
- Whereas the spatial resolution of laser bathymetry is fundamentally limited by the laser footprint diameter, a much higher resolution in the range of the ground sampling distance of a single image pixel can be achieved with dense image matching (DIM). Embedding DIM in a multimedia-photogrammetry framework is tested to derive very high resolution terrain models of the littoral zone.

The outlined research topics are currently addressed by analysing existing bathymetric data of both the German Baltic sea (Song et al., 2015) and an Alpine gravel bed river (Mandlbürger et al., 2015) captured with different laser sensors and camera systems. In addition to that, data acquisition of two mountain lakes in the Stubaier Alps with a topo-bathymetric laser scanner and multi-spectral cameras is currently in progress. For all datasets, reference data from either terrestrial survey or multi-beam echo sounding is available and will be used for validating the results.

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