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Local-scale flood mapping on vegetated floodplains from radiometrically calibrated airborne LiDAR data

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ABSTRACT

Knowledge about the magnitude of localised flooding of riverine areas is crucial for appropriate land management and administration at regional and local levels. However, detection and delineation of localised flooding with remote sensing techniques are often hampered on floodplains by the presence of herbaceous vegetation. To address this problem, this study presents the application of full-waveform airborne laser scanning (ALS) data for detection of floodwater extent. In general, water surfaces are characterised by low values of backscattered energy due to water absorption of the infrared laser shots, but the exact strength of the recorded laser pulse depends on the area covered by the targets located within a laser pulse footprint area. To account for this we analysed the physical quantity of radiometrically calibrated ALS data, the backscattering coefficient, in relation to water and vegetation coverage within a single laser footprint. The results showed that the backscatter was negatively correlated to water coverage, and that of the three distinguished classes of water coverage (low, medium, and high) only the class with the largest extent of water cover (>70%) had relatively distinct characteristics that can be used for classification of water surfaces. Following the laser footprint analysis, three classifiers, namely AdaBoost with Decision Tree, Naïve Bayes and Random Forest, were utilised to classify laser points into flooded and non-flooded classes and to derive the map of flooding extent. The performance of the classifiers is highly dependent on the set of laser points features used. Best performance was achieved by combining radiometric and geometric laser point features. The accuracy of flooding maps based solely on radiometric features resulted in overall accuracies of up to 70% and was limited due to the overlap of the backscattering coefficient values between water and other land cover classes. Our point-based classification methods assure a high mapping accuracy (~89%) and demonstrate the potential of using full-waveform ALS data to detect water surfaces on floodplain areas with limited water surface exposition through the vegetation canopy.

1. Introduction

1.1. Local-scale flood mapping

Geoinformation of the spatial extent of flood events supports decision-makers at different administrative levels. Most of the developed remote sensing methods for flood mapping have been used for surveying large flood events with predominantly open water areas. Such large open water bodies have been successfully surveyed with passive and active remote sensing systems (Feyisa et al., 2014; Pierdicca et al., 2013; Smith, 1997). Inundation mapping is challenging, however, in areas with dense vegetation cover such as river floodplains where surfaces are dominated by herbaceous plants interspaced with bushes and trees. Here the mixture of water and vegetation generates a spectral signature that depends on the vegetation structure and physiological stage, resulting in a broad range of spectral values that often overlap with

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the signatures of other land cover (LC) classes (Silva et al., 2008). In the case of microwave data, plants emerging from water reduce specular reflection, and the double-bounce effect may not occur as it is more pronounced for taller vegetation (Crasto et al., 2015; Silva et al., 2008).

Floodplain inundation is frequently characterised by localised patterns and may be referred to as "local-scale flooding" (LSF) (Hirschboeck, 1988; Verstraeten and Poesen, 1999). LSF inundates low-lying wetland areas and lowland riverine floodplains adjacent to watercourses and is often characterised by frequent, regular and prolonged occurrences. Although small in expanse, LSF can lead to high economic costs from loss of crops, property and infrastructure damages (Verstraeten and Poesen, 1999) and may occur as a precursor to extensive flood events (Hirschboeck, 1988). Mapping of LSF supports evaluations of wetness and soil conditions of agricultural lands and may help to determine the usability of floodplain areas for farming purposes. Detailed information about the spatial and temporal occurrence of LSF is beneficial for environmental protection (EC, 1992, 2000), flood risk management (EC, 2007), spatial planning, wetlands management (MacKay et al., 2009), and the support schemes for farmers under the European Union's Common Agricultural Policy (EC, 2009).

An analysis of the complex patterns of intermixed vegetation and water patches found on inundated floodplains requires detailed data. Airborne laser scanning (ALS), which refers to airborne LiDAR (light detection and ranging), meets this requirement, assuring precise and dense measurement data. Additionally, it enables vegetation to be penetrated through openings in the foliage, providing information about the surface under the canopy (Glennie et al., 2013). The prime use of ALS of the delivery of detailed topographic data has been also extended to LC mapping (Alexander et al., 2010; Antonarakis et al., 2008; Brennan and Webster, 2006). Because the single-wavelength airborne LiDAR sensors mainly utilise light from the near- or short-infrared spectrums, which is subject to high water absorption, the resulting values of the radiometric data, acquired simultaneously with the geometric measurement, are lower for water surfaces than for other LC types, enabling their discrimination (Höfle et al., 2009).

The utilisation of LiDAR data has already been shown to be useful for mapping different types of inland and coastal water surfaces. Some studies focused on mapping water as one of several LC classes (Antonarakis et al., 2008; Brennan and Webster, 2006), and its differentiation with respect to the other classes was mainly based on the lower mean value of rasterised LiDAR intensity data. Other examples of application of rasterised LiDAR data include the work of Lang and McCarty (2009) who mapped inundation in a forested area by thresholding the rasterised LiDAR intensity data, a study of Smeeckaert et al. (2013) who used the Support Vector Machine (SVM) algorithm for carrying out a large-scale mapping of water covered areas using purely LiDAR geometric data, and work where open water areas in the Arctic region were mapped with both geometric and intensity data (Crasto et al., 2015). Rasterisation performed in the above-mentioned studies, however, often leads to data loss, decreasing the level of detail that may be derived from LiDAR data. Only few studies have made direct use of LiDAR point cloud data to map water surfaces. Brzank et al. (2008) and Schmidt et al. (2013) used geometric and radiometric LiDAR data to distinguish water from mudflats by fuzzy logic and the conditional random fields. In the latter, the full-waveform (FWF) LiDAR was used for the first time to map water objects. Höfle et al. (2009) analysed the water surface of mountainous rivers and developed a region-growing approach to segment the 3D point cloud and, in a subsequent step, to classify the segments into a water class using point features such as elevation, intensity, intensity density, intensity variation and roughness. The processing chain also included modelling of the laser dropouts (cf. Section 3.5), which were subsequently used in segmentation together with registered laser echoes.

The presented methods, though, have focused on mapping mostly open water areas with no or limited vegetation cover. In such a setting laser shots are predominantly reflected from extended targets of water surfaces (i.e. targets larger than the laser pulse footprint area). However, for densely vegetated areas (e.g. grassy floodplains), the radiometric value of a laser pulse may also be influenced by vegetation elements located within a single laser pulse footprint (e.g. blades of grass). Therefore, the practical application of the presented methods for mapping water on vegetated floodplains may be highly limited. To the authors' best knowledge, no analyses have been conducted to date of the response of radiometrically calibrated FWF LiDAR data to the complex composition of water and vegetation elements within a single laser pulse. We assume that better knowledge of the technical details of laser pulse interaction with water and vegetation surfaces will facilitate a more accurate mapping of flooded areas and delineation of flooding extent.

1.2. Radiometric calibration of LiDAR data

In addition to the measurement of 3D coordinates, full-waveform LiDAR sensors provide radiometric observable, the amplitude that reflects the strength of the backscattered echo. However, this quantity may vary for the same object, depending, among others things, on the measurement range, scanning geometry or atmospheric conditions (Hopkinson, 2007). In order to use LiDAR radiometric data in various applications and compare datasets acquired by different LiDAR systems and during variable atmospheric conditions, they need to be converted to an absolute physical quantity and corrected for the aforementioned factors (Höfle and Pfeifer, 2007; Wagner, 2010). The physical principles of radiometric calibration of full-waveform LiDAR data are documented and discussed in several publications (Briese et al., 2008; Lehner and Briese, 2010; Wagner et al., 2006; Wagner, 2010). The prime physical quantity resulting from radiometric calibration is the backscatter cross-section (σ) [m^2], which represents the characteristics of the reflecting target, accounting for its size, reflectivity and directionality of scattering (Wagner et al., 2006). The value of σ, however, depends on the size of the laser footprint and changes accordingly. Normalizing σ to the footprint area produces the backscattering coefficient (γ) [$\mathrm{m}^2\,\mathrm{m}^{-2}$]. In this way, γ becomes independent of the system settings and the flying altitude and is recommended as a more appropriate quantity for analysing geophysical properties of the landscape (Wagner, 2010). Despite advances in the theory of radiometric calibration and its advantages for LC classification (Alexander et al., 2010), radiometric calibration is still not a standardised pre-processing step in LiDAR based projects. However, Alexander et al. (2010) compared the use of amplitude, σ and γ in a decision tree classification of urban LC classes and showed that classification, which used the coefficient γ, resulted in the highest accuracy and gave stable and highly transferable values between different study areas and LiDAR datasets acquired at different conditions. Further, Höfle et al. (2012) performed an extensive testing of geometric and calibrated full-waveform observables for object-based vegetation mapping. They showed that using only radiometric full-waveform observables (e.g. backscattering coefficient) was insufficient to map vegetation, but the combination with geometric features provided high accuracies.

In summary, radiometric calibration is a procedure that provides absolute physical quantities, transferable between projects utilising different LiDAR datasets acquired at different landscape settings, which can ultimately improve the discrimination of landscape features.