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Airborne Laser Scanning for calibration and validation of inshore satellite altimetry: A proof of concept

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ABSTRACT

Recent developments in satellite altimetry are leading to improved spatial resolution, allowing applications in the coastal zone and over inland waters. Validation of these sensors near the shore remains a challenge, since the process of upscaling from single point measurements (gauges or GPS buoys) to the radar altimetry footprint is a source of uncertainty. Meanwhile, Airborne Laser Scanning (LIDAR) has been proven capable of delivering accurate water surface heights rapidly over large areas. Here, we show a proof of concept by comparing airborne LIDAR heights over Lake Balaton, Hungary with near-concurrent Envisat and Jason-2 altimeter heights and water level gauge data. The accuracy of LIDAR heights was improved by strip adjustment and absolute georeferencing to ground control points; waveform retracking improved the accuracy of altimetry data. LIDAR heights were averaged within the outlines of the altimetry footprints. Bias is measured for LIDAR and altimetry with respect to gauge heights, and standard deviation of heights measures the vertical dispersion of footprints within one track. Results show standard deviation of heights is in the order of millimeters for LIDAR and 40–50cm for altimetry and bias with respect to gauge heights is 5cm for LIDAR compared to 40cm for altimetry. We conclude that LIDAR may be used for calibration and validation of high resolution satellite radar altimetry over inland waters.

1. Introduction

For decades, satellite altimetry has contributed to our knowledge of the geoid and ocean currents. In the last years, new processing methods have allowed using altimetry over coastal areas and inland water bodies as well (e.g. Calmant et al., 2008; Berry et al., 2005; De Oliveira Campos et al., 2001; Schwatke et al., 2015b).

With the arrival of new sensors such as SIRAL (SAR/Interferometric Radar Altimeter) on Cryosat-2 (launched 2010), which is a SAR (Synthetic Aperture Radar) altimeter, and AltiKa on SARAL (Satellite with ARgos and ALtika) (launched 2013) measuring with a Ka band radar, improved inland water level time series are possible (Verron et al., 2015; Nielsen et al., 2015; Villadsen et al., 2015). The Cryosat-2 mission has the downside of a long-repeat orbit (369 days) and SIRAL is not constantly measuring in SAR mode. The AltiKa instrument on SARAL is more sensitive towards atmospheric water content (Schwatke et al., 2015a) and is since July 2016 in a drifting orbit phase with the repetitive ground track no longer maintained.

In 2016, the new altimeter mission Sentinel-3 was launched which carries a SAR altimeter again but operates on a repeat orbit. New insights on the water cycle at local scales and applications such as lake level and river discharge monitoring are expected from this mission (Donlon et al., 2012).

In the near future, SWOT (Surface Water and Ocean Topography) will be a satellite altimeter based on interferometric RADAR, measuring over a swath and not only a profile, with the aim to observe river, lake and ocean height (Durand et al., 2010) with a resolution of tens of meters at a vertical precision in the order of a centimeter and height accuracy of 10 cm as written in the SWOT Science Requirements Document (Rodriguez, 2016). SWOT is planned to provide height for rivers wider than 100 m and lakes larger than $(250\ \mathrm{m})^2$, with launch expected in 2021 (Solander et al., 2016).

Verifying the accuracy of high-resolution radar altimeters over inland and coastal waters remains a challenge as this requires data from the same location in the same reference frame, but with better vertical accuracy (Bonnefond et al., 2011). The classical approach is using water gauges, which are linked by levelling

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to a terrestrial elevation network and a geoid model. Heights of onshore gauges have to be transferred to offshore coastal altimetry footprints through a detailed local geoid and tide model. Besides the potential inaccuracies of the tide gauge height itself and the problems of transferring the measured water surface height to an offshore location, comparing a single point measurement at a gauge to an elevation measurement of an altimetry footprint several kilometers across may generally be problematic (Morris and Gill, 1994). Proximity to the shore is known to affect not only local water surface topography, but also the altimetry measurement itself (Bonnefond et al., 2013). All in all, tide gauge-based calibration has delivered accuracies up to 1 cm of standard deviation (STD) for a single measurement point (Bonnefond et al., 2011).

For inland water bodies the problems of transformation between gauge position and altimeter footprint are different. For rivers, exact overlap between gauges and altimetry footprints is rare. For inland lakes in case of hydrostatic equilibrium, it can be assumed that the water level is equal everywhere over the lake with regard to the correct geoid model (Schwatke et al., 2015b), and exact co-location of the footprint and gauge is not required. However, since no geoid model is perfect, in some cases deviations may be observed (Zlinszky et al., 2014). Additionally, many if not most inland water gauges do not have an absolute height which is linked to a terrestrial height network. In these cases, it is only possible to compare water level changes derived by altimetry measurements with water level changes measured by the gauge, without absolute height calibration.

Alternatively, GNSS (Global Navigation Satellite System) buoys have been proposed for comparison (Bonnefond et al., 2003b; Watson et al., 2003). Whereas these are still affected by upscaling of point measurements to altimetry footprint areas, they are independent from the proximity to the shore, can be placed within altimetry footprints on demand, have the same height datum as altimetry (ellipsoidal heights optionally corrected with a geoid model) and their accuracy (around 1–3 cm) is usually adequate for calibration (Bonnefond et al., 2011, 2013). In order to overcome the problem of upscaling from point to area measurements, or to obtain high-resolution local geoid models for height transfer from shore to ocean, the use of ship-mounted GNSS receivers has been established for mapping sea surface heights across larger areas (Bouin et al., 2009). This method allows sufficient area coverage and spatial resolution, but accuracy may be problematic (STD between 22 cm for a large ship (Bouin et al., 2009) and 2.7 cm for a wave-riding catamaran (Bonnefond et al., 2003a), bias 1.9 cm compared to tide gauges). Also, the time needed to cover the area of at least a single footprint with a ship-mounted sensor may be long enough for dynamic water surface height changes to influence the measurement.

Remote sensing techniques can provide rapidly collected, area-covering, high resolution, point-based elevation measurements. These could be an alternative or complementary data source to shore gauges or GNSS floats, provided they can deliver comparable accuracies in height independent from (but linked to) shore heights in the same reference frame as satellite altimetry measurements. Airborne Laser Scanning (also known as airborne LIDAR or ALS) is gaining ground as a technology for surveying terrestrial topography, with centimeter-scale ranging accuracies for the individual measurement points. National or regional scans often cover water bodies that are of interest for altimetry, and dedicated scans at planned locations and times are also affordable as the technology is now mainstream (Heritage and Large, 2009). With the onset of bathymetric ALS, coastal zones and lakes are also directly scanned (Pastol, 2011).

Oceanography is moving towards higher resolution and (Melville et al., 2016) suggest that ALS measurements of waves and sea surface height can be used in the calibration and validation of satellite altimeter missions. They synchronized an ALS acquisition with a Jason-1 overpass over the Gulf of Mexico, with time lags below 1 h. The common track length is about 1.75° of latitude. Sea surface height and sea surface height anomaly were computed from the satellite radar altimeter and the airborne LIDAR data, with LIDAR averaged across the swath and along track. The RMS of differences was "a few centimeters". Significant wave height computed from both sensors also fits together in the order of 0.1 m.

The utility of airborne LIDAR to measure water surface elevations accurately has been proven by additional studies (Carter et al., 2001; Zlinszky et al., 2014; Marmorino et al., 2015; Mandlburger et al., 2015). Expected error budgets are within 10 cm for individual measurement points and in the same range for global georeferencing (Zlinszky et al., 2014), which can be improved by using ground reference data (Kager, 2004). Based on this high accuracy, further enhanced by the statistical redundancy offered by high measurement densities, LIDAR is expected to have potential for calibration and validation of satellite altimetry. Connor et al. (2009) have compared airborne LIDAR with Envisat altimetry over sea ice areas, and conclude that under favourable conditions (re-frozen lead surfaces with little snow cover) the two datasets match with mean differences around 1 cm. However, this setup did not involve in-situ water height measurement (GPS buoys or gauges) and to our best knowledge, no systematic three-way comparison of LIDAR water surface altimetry to satellite altimetry and water gauge heights was carried out yet.

Our objective was to develop and test a methodology for processing airborne LIDAR data as a basis for comparison with satellite radar altimetry, and to assess accuracies of both LIDAR and altimetry-derived heights with respect to near-synchronous water gauge measurements linked to a terrestrial levelling network. Based on the outcome of this comparison, we aim to establish airborne LIDAR as a sensor for calibrating high-resolution satellite water surface altimetry.

2. Data and methods

Satellite altimetry relies on emitting a short pulse of electromagnetic radiation in the nadir direction, measuring its travel time, and calculating the target elevation from this travel time and the position of the satellite platform (Fu and Cazenave, 2000). Airborne Laser Scanning works with the same principle at a different emitted wavelength (Wagner, 2010). However, due to higher pulse repetition rates, lower beam divergence and slower platform speed, instead of a single track at nadir, a wide swath can be covered by deflecting the laser pulse perpendicular to the flight direction in a systematic scan pattern. As a result, a near-equidistant point cloud of measurement footprints is created within the swath, with point densities typically in the range of 0.5 to 10 points/m^2 (Wehr and Lohr, 1999).

2.1. LIDAR data processing

For this study, we used ALS point clouds collected during a scan of Lake Balaton, Hungary on the 26th August 2010 (Zlinszky et al., 2011). The data were collected using a Leica ALS50-II sensor operating at 1064 nm wavelength, 4 ns pulse length, 0.2 mrad beam divergence and 40° scan angle using an Applanix POS AV positioning system, collecting GNSS positions every second and inertial navigation system (INS) readings at 200 Hz. Over the open water, the data were collected as a by-product of airborne hyperspectral measurements targeting the lake water quality in N–S swaths (flying height 4500 m, point density 1 pt /5 m^2, footprint diameter 1 m, pulse repetition frequency 29 kHz, scan rate 58 Hz). The coastal zone was covered in a dedicated campaign with an irregular pattern following the shoreline (flying height 1400 m, point density 1 pt/m^2, footprint diameter 0.22 m, pulse repetition frequency 83.1 kHz, scan rate 45.1 Hz). The accuracy of individual