Bathymetry of Lake Constance – a High-Resolution Survey in a Large, Deep Lake

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Summary

Within the project "Tiefenschärfe – hochauflösende Vermessung Bodensee" a high-resolution seamless terrain model is created using airborne topobathymetric laserscanning and multibeam echosounder (MBES) techniques. The project visualizes the enormous wealth of features of underwater landscapes of lakes. The combination of hydroacoustic (multibeam echosounder) and laser-optic (topobathymetric laserscanning) methods was used for the first time in a freshwater body of this size. Opportunities, limitations and restrictions of these high-resolution methods are presented.

Zusammenfassung

In dem Projekt „Tiefenschärfe – hochauflösende Vermessung Bodensee" wird mit topobathymetrischem Laserscanning und Fächerecholotaufnahmen ein nahtloses Geländemodell der Seebodenoberfläche hergestellt. Das Projekt zeigt den enormen Formenreichtum der Unterwasserlandschaft von Seen. Die Kombination von hydroakustischen (Fächerecholot) und laseroptischen (topobathymetrisches Laserscanning) Methoden wird erstmals in einem Binnengewässer dieser Größenordnung angewendet. Chancen, Limitierungen und Restriktionen der hochauflösenden Messverfahren werden kurz vorgestellt.

Key words: Lake Constance, Multibeam Echosounder, Airborne Topobathymetry, Bathymetry

1 Introduction

Large institutions handling hydrographic information and companies developing tools in collecting and processing bathymetric data have a strong focus on marine environments. Nevertheless, there is a long tradition in collecting bathymetric information from inland waters, such as (peri-)Alpine Lakes. With this contribution, we present technical details and results of a state-of-the-art bathymetric survey of Lake Constance showing a number of specific aspects relevant for future surveys of other large lakes.

1.1 Lake Constance

Lake Constance (9°30′ E, 47°30′ N) is a large (536 km^2) and deep (254 m) lake with ~50 km^3 of water volume and a theoretical residence time of ca. 4.5 yr. The lake has a catchment area of 11,500 km^2, mainly located in the Alps and its foreland. The main tributary is the Alpine River Rhine (mean annual discharge of 7.66 km^3), which contributes ~64 % of the total average inflow (Gilfedder et al. 2010) and which strongly determines sediment distribution and lake-floor morphology (Wessels 1995). Strong intra-annual variability of the runoff is reflected by mean water-level fluctuations of about 1.5 m.

Politically, the lake is shared between Germany, Austria and Switzerland. Their boundaries were never defined for most parts of the lake (legal term: "condominium"), so that a strong need for cooperation led to the development for a number of trans-boundary organizations that already rose in the late 19th century. As the lake is shared between these countries, different local coordinate systems with different vertical reference levels are in use, which historically refer to Marseille (Switzerland), Trieste (Austria) and Amsterdam (Germany) and result in height differences of 32 cm for the same lake level between the different systems.

Ecologically, eutrophication problems became evident in the 1950's, which then initiated the foundation of the International Commission for the Protection of Lake Constance (IGKB) in 1959 by the member states of Baden-Württemberg, Bavaria, Austria and Switzerland. After a maximum degree of eutrophication in 1980, the lake has recovered and returned to an oligotrophic state with low nutrients and declining fish yields. Today, the lake is regarded as one of the best studied lakes worldwide and supplies drinking water for ca. 5 million people. Independent of this successful re-oligotrophication, Lake Constance remains an ecosystem with multiple stressors and conflicts (e.g. intense leisure activities with about 55,000 boats, a large diving community, a rich archeological history (pile dwellings are UNESCO cultural heritage), use and restoration of shoreline, commercial fisheries, micropollutants, climate change, use of thermal energy, …). These are now the main issues for the IGKB.

1.2 Historical aspects in yielding bathymetric information

Lake Constance may act as an example for the long-term development in measuring bathymetry, as already in 1825/26 "Captain Gasser" from the former kingdom of Baden made a first bathymetric survey to describe the lake. He used a metal wire to measure 333 point depths along 17 profiles crossing the lake. The resulting description of lake-specific data like size and maximum depth was given with today unusual units (e.g. “17.5 hours long”, “964 Fuß deep” (Gasser 1826)). More than 11,000 measurements (20 measures/km^2) using ‘bob plumbing’ were acquired between 1889 and 1891 (Zeppelin 1893, Hörnlimann 1893). The resulting “Zeppelin map” was then used as the basis for intensified research until the 1990’s (Earl Eberhard Zeppelin is the brother of the constructor of the Zeppelin airship).

As in 1900, the mouth of the Rhine river was artificially shifted 12 km to the east to avoid floodings in the alpine Rhine valley (Wessels 1998b), the construction management office for the Rhine River conducted surveys of the Rhine River delta every ten years since 1911. Initially, mechanic bob plumbings were used along horizontally stretched wires, while later on, hydroacoustic systems, theodolites (e.g. Waibel 1971) and GPS were introduced for more recent surveys.

A new basis for modern research was the survey of the entire lake between 1986 and 1990, initiated by the IGKB. In this context, echosounder profiles with a maximum distance of 200 m and photogrammetric analysis of the shallow-water situation resulted in a 40 m grid for the deeper areas and 10 m grid for the shallow waters (Braun and Schärpf 1994). These data already showed large-scale structures of the lake floor (e.g. a meandering canyon resulting from underflows and turbidity currents of the Alpine Rhine River). Between 2008 and 2011, several small-scale surveys used portable multibeam systems (e.g. Wessels et al. 2010) to collect data for high-resolution digital terrain models (DTM) in areas of interest, notably pockmarks (concave depressions) at the lake floor or archeological pile dwellings in the shallow-water zone.

The latest step to achieve basic cartographic information was a survey to minimize height differences when modeling the geoid between Switzerland, Austria and Germany. German authorities (BKG) and the Institute for Lake Research agreed to collect data using a ship-mounted gravimeter (Schäfer et al. 2012).

1.3 Motivation for a new topobathymetric survey

As the pilot multibeam surveys mentioned above showed the potential of modern hydrographic survey systems, the need for a detailed topobathymetric survey was discussed (IGKB 2014, Wessels et al. 2015). A working group assigned by the IGKB identified a number of reasons and demands:

- Basic data to evaluate and review long-term environmental changes (climate change, erosional processes within the shallow-water zone, geological risk analysis, …);
- Documentation of man-made interventions and precise definition of judicial terms (e.g. 25 m line);
- Planning of lake-shore measures, restoration of shorelines, conservation of archeological sites, measures for the prevention of anthropogenic long-term erosion;
- Input data for advanced 3D-modeling (e.g. for the use of thermal energy, intrusion of waste waters);
- Scientific goals (neotectonics, investigation of lake-bottom structures, intrusions of ground water into the lake, subaquatic mass movements, …).

To fulfill these requirements for high-resolution data, the IGKB member states (Baden-Württemberg, Bavaria, Austria and Switzerland) decided to conduct a state-of-the-art multibeam survey, followed by an airborne LiDAR survey of the shallow-water zone. Combining both methods enables the generation of seamless DTM’s from land to the deep areas. Both methods were complemented by an independent quality assurance. The quality of the resulting data should fulfill the specific requirements of the “Special order” of the International Hydrographic Organization (IHO). Maps fulfilling the requirements of the special order guarantee an under-keel clearance, that cubic objects > 1 m should be detectable, and a horizontal uncertainty of less than 2 m. The vertical uncertainty is varying with depth in the form $\pm\sqrt{a^2+(b\times d)^2}$, with a = 0.25 m and b = 0.0075; d = Depth (m). As a high public interest in these data was expected, the whole project was to be accompanied by a professional public relation company.

The EU was approached for co-funding within the INTERREG-IV project, as INTERREG promotes cross-boundary cooperation in the Lake Constance area. A bathymetric survey of such a large inland water with latest technologies is not only a focus for the transboundary scientific community, but also for administrative players (e.g. surveying authorities) around Lake Constance. This complex situation (four surveying authorities in three national states), the size of the project (536 km^2), and the combination of different latest technologies, qualifies our project as a key example in handling these new technologies and huge data volumes in freshwater systems.

Costs for our project – entitled “Tiefenschärfe – hochauflösende Vermessung Bodensee” – amount to 612,000 Euro (shared between IGKB-member states and co-funded by INTERREG) excluding a lot of in-kind contributions (e.g. costs for ship and staff of the project partners from administrations). Preparations for the project began in December 2012, leading to its completion in September 2015.

2 Methods

2.1 The multibeam echosounder (MBES) survey

The bathymetric survey for areas deeper than 5 m was carried out during 76 days from April to August 2013 using a Kongsberg EM2040 multibeam echosounder in a single-head configuration (1° × 1° beam width, 300 kHz standard operating frequency) on R/V Kormoran. The transducers and ancillary sensors (antennas for RTK-GNSS positioning, GPS compass, motion sensor, sound-velocity sensor) were incorporated in a portable, rigid mounting attached to the bow of the ship. Sensor locations within this mounting were measured with a tachymeter; angular offsets of IMU (Inertial Measurement Unit) and compass with respect to the transducers were determined with a patch test after installation. Predefined survey parameters included maximum swath angles and minimum sounding densities, depending on water depth, as well as general mission planning. For all areas below 40 m water depth, double coverage (~110 %) was required in order to achieve a minimum sounding density as well as to obtain two independent coverages of the lake floor. Swath angle was adjusted to the local bathymetry and reduced from 75° on each side in the shallowest areas to 38° on each side in the deepest parts of the lake. Dual-swath mode of the EM2040 was used in order to simultaneously maintain sufficient point density, full lake-floor coverage and a reasonable survey speed.

Data were recorded using Kongsberg's SIS-software. In addition to the depth, we also recorded water-column data in order to detect flares of methane bubbles ascending towards the lake surface (Wessels et al. 2010) and backscatter data, which will be used for sediment classification in upcoming steps. All multibeam data processing was performed in the software package "CARIS HIPS & SIPS".

In total, an area of 460 km^2 was covered by 2,961 survey lines (total length 6,001 km), yielding 7,210,000,000 soundings. Typically achieved sounding densities are 15 m^{-2} in the deepest areas (about 250 m), where swath angles were restricted to ~40° to each side, > 20 m^{-2} at 100 m water depth and about 50 to several hundred soundings per m^2 in the shallowest zones (< 10 m), where the full swath (75° to each side) was used. Standard deviations of sounding depths in overlapping areas of cross lines range between 5 and 20 cm and differ for swath angles and water depths.

High spatial and temporal variability of the thermal stratification of the lake made it challenging to maintain a valid sound-velocity model of the water column. Therefore a large number of individual sound-velocity profiles (602) were taken during the survey, and applying sound-velocity correction turned out to be a crucial step during post-processing. The initial plans to use real-time positioning corrections over a cellular network-based internet connection (which is in theory available for the entire survey area) with NTRIP (Networked transport of Radio Technical Commission for Maritime Services data via Internet Protocol) had to be abandoned due to the insufficient stability of the connection, and post-processed RTK (Real Time Kinematic) positions were used instead.

2.2 Visualization of ship wrecks

Since the new bathymetric data reveals potentially sensitive information (drinking-water intakes, archeological sites), it was decided that these features should be masked in the publicly available data-set. During processing, the relevant soundings were classified and flagged, so that raster data-sets, both including (equivalent of "digital surface model", DSM) and excluding these soundings (equivalent of "digital terrain model", DTM), can be generated from the point data.

Besides the usage of backscatter analysis (water column as well as bottom detection), we evaluated three gridding methods to find the optimum solution for the detection of ship wrecks in the huge bathymetry data-set, which are all provided by the processing software CARIS HIPS & SIPS (Groeneveld 2014). The method "swath angle" uses the swath angle of individual echosounder beams, taking also into account the size of the footprint, to create a grid from the soundings. "Uncertainty" utilizes the total propagated uncertainty of the position and the vertical uncertainty of each data point for the calculation of the individual grid cell based on a weighted mean. "Cube" is the most complex algorithm and calculates different hypotheses for the grid cells, which then are statistically evaluated with hypotheses from neighboring cells (Calder and Mayer 2003). It applies Bayes' Theorem to estimate the depth error. Formerly investigated wrecks, which were investigated either by Sidescan Sonar or diving (a cooperation between the Baden-Württemberg archeological administration and environmental protection agency – Institute for Lake Research) were used to evaluate the results of all three approaches.

2.3 Investigations of the Geoid

The geoid, one of the main research topics in geodesy, corresponds approximately to the mean static sea surface and serves as reference for heights like 'above mean sea level'. Since the lake's static surface corresponds to an equipotential surface of the gravity field, we can infer

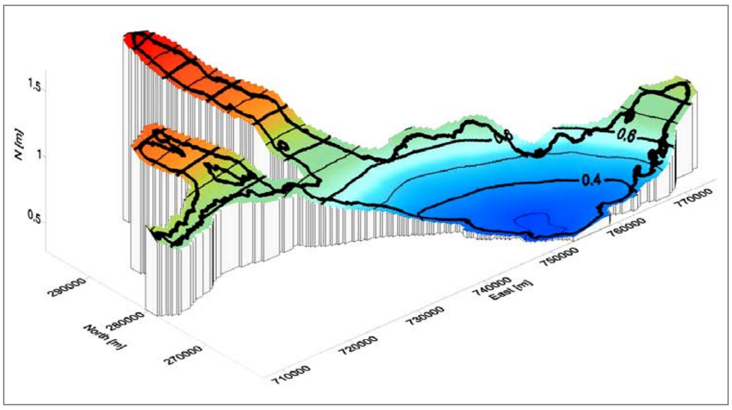

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Fig. 1: The local geoid departs from an ellipsoidal reference (swiss Bessel ellipsoid)

from its three-dimensional geometry the form of the geoid (equipotential surface at mean sea level, Fig. 1) by downward continuation. The three-dimensional geometry of the lake's surface has been determined simultaneously with the bathymetric survey.

A GPS antenna and a downward-looking acoustic ranger were tightly mounted on an outrigger to starboard ahead on the RV 'Kormoran'. The acoustically determined distance from the antenna to the water surface is added to the precise GPS-position of the antenna (Limpach 2009). In doing so, the complete lake's surface has been sampled at about 3 cm precision in mean height, thus enabling a precise determination of the local geoid. Disturbances like waves were removed by filtering, whereas seasonal and meteorologically induced lake-level variations, about 1.7 m during the measuring campaign, have been corrected by gauge data provided by hydrographic institutions around the lake.

2.4 Topobathymetric LiDAR survey

Topobathymetric laser scanning is a new and very effective concept for fast and economic mapping of large areas to collect high-quality, and high-resolution survey data (Fig. 2). We combined a high-resolution spatial view at the lake floor using LiDAR (> 10 points/m²), with high-resolution aerial (< 10 cm/pixel) and thermal images.

The airborne hydromapping survey of Lake Constance was completed within three days using the hydrographic scanner VQ820-G of RIEGL LMS in March and June 2014. As small gaps were identified in the recorded areas during the latest steps of the processing, a final flight using a Riegl VQ880-G was conducted in May 2015.

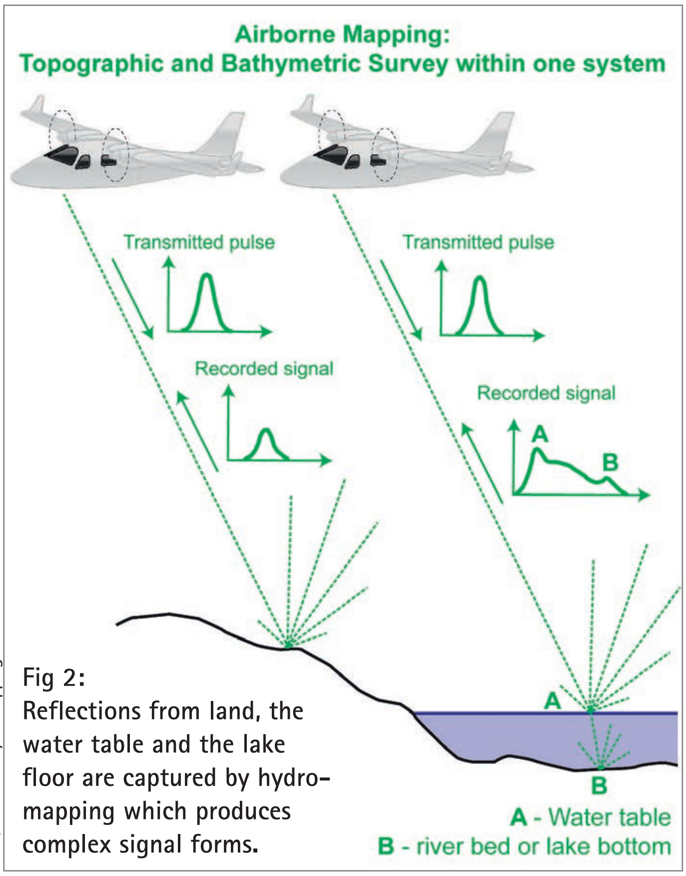

Fig 2: Reflections from land, the water table and the lake floor are captured by hydromapping which produces complex signal forms.

AHM, Airborne Hydromapping

A consistent point cloud was calculated with corrections for the individual scan strips by a strip-adjustment process. The relative accuracy of this procedure ranges between 0.07 m and 0.1 m (given as standard deviation). Then the point cloud was georeferenced to terrestrially measured reference planes, which were distributed around the entire lake (accuracy about 0.08–0.09 m, standard deviation, UTM32N, elliptical heights). The point density after combining all scan strips reaches up to 40–50 points/m² (on land) and about 20–30 points/m² near the shoreline in shallow areas, whereas it decreases to ca. 10–20 points/m² at a depth of 4–5 m. We classified the point cloud into 11 classes (terrain on land/lake, vegetation, etc.) and three classes where remaining gaps had to be interpolated.

In a first step, flaw echoes were automatically filtered. The remaining incorrect points were then identified by visual checks and deleted manually. Within a ca. 50 m wide strip along the shoreline, point classification was done manually to ensure a correct mapping of the water-land-boundary as well as correct classification of complex areas like harbors. The remaining foreland area within a distance of 300 m from the shoreline and the underwater area are classified automatically using algorithms and modules implemented in the software HydroVISH. Runtime and water depth correction were also determined within HydroVISH.

About 22,000 (± 2 %) aerial images were acquired using a mid-format camera (Hasselblad H3DII-39). With these images, a digital orthophotomosaic for the shoreline of Lake Constance is developed. The images are orientated based on an aerotriangulation, and orthorectified using the official DTM (1 × 1 m) of Austria, Switzerland, Bavaria and Baden-Württemberg. About 60 reference points and 20 control points were defined, and their coordinates were extracted from the LiDAR data in order to perform the aerotriangulation. Afterwards, the images are orthorectified and a radiometric correction is applied to homogenize the color distribution of the entire image block. The mosaicking is performed along natural boundaries. Correction of seam lines is carried out only for image boundaries across buildings. The final ground resolution of the orthophotos is about 7 cm with an accuracy better than 1 m.

2.5 Quality Assurance

The project "Tiefenschärfe" is attended by an external quality management from the beginning (preparation for tender to multibeam and LiDAR data acquisition) to processing and finalizing products. To ensure a high-quality digital terrain model (DTM) the measured data are

Tab. 1: Statistical data of the quality assurance of the area shown in Fig. 3 indicate that the requirements of the special order are fulfilled. The beams of a MBES-fan with an opening angle of 60° each side, port- and starbord side were separated into 10°-swaths. They were counted and statistics are computed in meters.

Beam Angle	Count	Max (+)	Min (–)	Mean	Std. Dev.	Special Order (%)
0.0–10.0	161,349	2.624	2.146	–0.098	0.105	100.000
10.0–20.0	174,514	1.184	1.241	–0.091	0.099	100.000
20.0–30.0	207,039	1.343	0.870	–0.090	0.100	100.000
30.0–40.0	257,529	1.019	1.235	–0.090	0.109	100.000
40.0–50.0	368,009	1.335	1.408	–0.086	0.140	100.000
50.0–60.0	623,382	2.774	2.050	–0.065	0.226	100.000

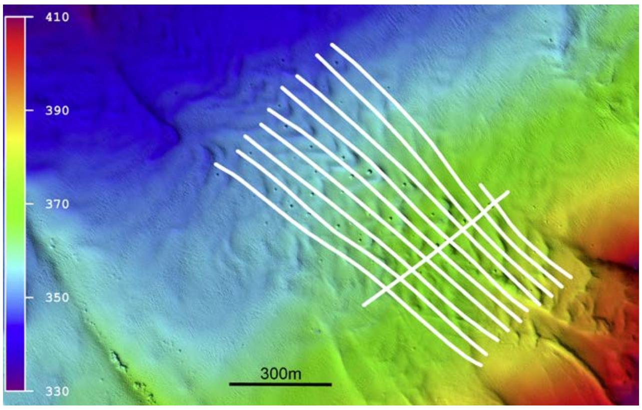

Fig. 3: An area in eastern Lake Constance is used for quality checks. The 2013 grid is compared with survey lines from 2014. Results from quality assurance are given in Tab. 1. The colour bar indicates ellipsoidal heights in meter (GRS80/ETRS89). The lake level is at about 441.8 m.

verified with several methods. An INNOMAR SES2000-light sub bottom profiler (SBP) ran parallel to the MBES measurements. Besides control points and area measurements along subaquatic archeological sites and bankside constructions like nose-piece, the depth traced with the SBP is used, corrected for sound velocity, to validate the MBES and LiDAR measurements. In addition, cross lines and small double surveys are used for MBES data verification in order to assure the requested IHO special order (IHO 2008). Another task for the quality management is to crosscheck the SA*POS*®-based real time kinematic GPS-Height/Tide correction as well as the applied roll/pitch/heave corrections. Previous and recent digital orthophotos and own measurements in the shallow-water zone and on land (roofs, roads) are used to validate the LiDAR surveys made within this project.

For quality checks of the multibeam data, the standard functionality of the software package CARIS HIPS & SIPS was used besides ESRI ArcGis™. Lines from the surveys of 2013 and 2014 cover an area of about 2.5 km^2 in water depths of 60–100 m. The point clouds of the survey-lines as well as the surfaces created with raster-widths of 0.5 m were compared to each other. Standard deviations of 10–23 cm are calculated. In the regions inspected, the multibeam survey fulfilled the requirements of the IHO special order with 100 % (Fig. 3, Tab. 1). Still remaining artifacts (e.g. small offsets resulting from individual ship tracks) will be removed when finalizing for the public.

As topobathymetric laserscanning is a comparably new technique, software packages like CARIS have limited functionality to analyze LiDAR data with respect to classification, or navigation processing. Nevertheless, point densities and comparisons according to IHO (special order) can be made when provided with proper data-sets. We used visual inspections of the accuracy of the classification and statistical approaches (standard deviations, fulfillment of desired data density) and accordance of LiDAR and MBES data-sets.

3 First results of the project "Tiefenschärfe – hochauflösende Vermessung Bodensee"

Numerous fascinating lake-floor features were already detected during the surveys and later refined during processing of data. Only few examples will be presented here as further evaluation will take some time while the final processing of the data is not yet completed. Thus, results and images presented here are still preliminary.

3.1 Morphology in the shallow-water zone

One of the unexpected results is the morphology in the shallow-water zone of Lake Gnadensee, an isolated and somewhat protected basin of Lower Lake Constance.

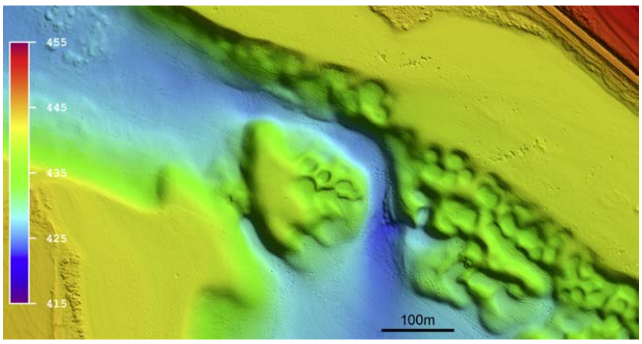

Fig. 4: Shallow areas of Gnadensee, a small isolated and protected basin part of Lower Lake Constance have a hummocky structure, probably a remnant of the retreating Late Glacial Ice sheet. The color bar shows ellipsoidal heights in meter, with respect to GRS80/ETRS89. The lake level is at about 441.8 m.

Here, large portions offshore the coastlines have a hummocky structure or are covered with large but shallow depressions (ca. 10–50 m diameter, 0.2–0.5 m deep, Fig. 4). This was never observed before in any other part of the lake. So far, we speculate, that this protected part of the lake preserved some of the late glacial surface, when the Rhine glacier retreated from the Lake Constance basin. All other shorelines of the lake are much more exposed towards winds and waves, which probably leveled all of these structures at the shoreline. This interpretation is supported by subbottom-profiling data, which show that the morphology of the shallow-water zone in many other parts of the lake has been strongly smoothed since the Late Glacial.

3.2 Indicators for lake-groundwater interactions

In deeper waters (ca. 60–100 m) of Lake Überlingen, the fjord-like northwestern arm of the main basin of Upper Lake Constance, large and irregular depressions with sharp upslope edges and smoother boundaries towards the lake occur (Fig. 5). These depressions lack any hints for rock slides or other mass movements and are currently interpreted to be caused by groundwater discharge into the lake. In a new project, funded by the German Federal Ministry of Education and Research (BMBF), we will investigate if indeed groundwater-sources (e.g. from nearby molasse-rocks) contribute significantly to the water budget of Lake Constance. Even though springs within the molasse are often observed, their contribution to the overall water budget of the lake is unknown. These features are particularly interesting as they may contribute to significant boundary conditions regarding the discussion of fracking-technologies in the vicinity of the lake.

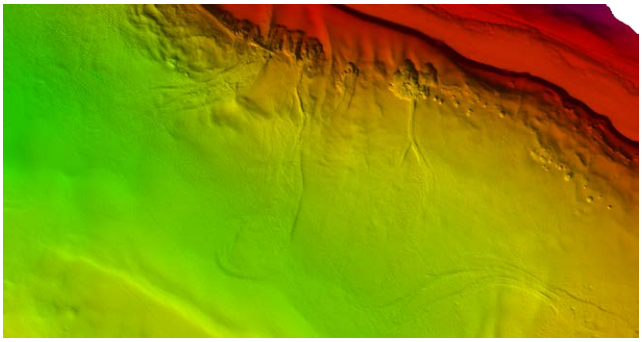

Fig. 5: Depressions along the slope give hints for groundwater intrusions into Lake Überlingen.

3.3 Wreck detection and masking

All methods to detect ship wrecks given by CARIS are successful with a high probability, and only small wrecks, almost buried in the sediment, were not detected (Fig. 6, Groeneveld 2014). As expected, wrecks were less easily detected in deeper waters than in shallow waters. Remaining errors of the bottom detection propagate and lead to a somewhat blurred bottom topography. In shallower waters, even smaller details like the pole and rigging of sailing boats were recognized.

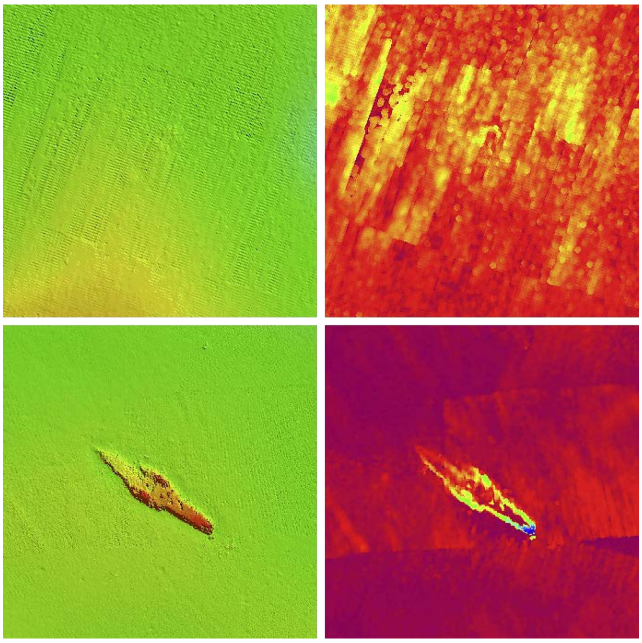

Fig. 6: Digital elevation model of two wrecks (left) and standard deviation (right) of the processed data. An almost buried wreck in deeper water (investigated with a deep towed Sidescan-Sonar, Wessels unpublished data) is not recognizable in the data (upper images) while large wrecks are easily identified with all methods.

Compared with modern Sidescan Sonars, the visualization of wrecks found during the multibeam survey is much less detailed. Modern Sidescan Sonars produce more signals per ping, use multi-frequency techniques with variable ranges (and horizontal resolution) and work with much smaller working distances between sensor and object (usually deep towed).

The backscatter signal (the strength of the reflected echo) of multibeam echosounders often does not give significant additional information for the detection of wrecks compared to the bathymetry, mainly due to the relatively high frequency (300/400 kHz) used. Backscatter data of a lower frequency bear information on physical properties (acoustic impedance and roughness) of the lake floor, so that some wrecks with high acoustic impedance (e.g. steel-hull buried in soft sediment) are detected.

When analyzing the LiDAR data, we found similar results: identification of multiple-part, three-dimensional objects like exposed planking or prehistoric pile fields of the shallow-water zones are difficult to identify due to the spot size of the footprint of the green laser-beam of about 50 cm.

3.4 Topobathymetry in the shallow-water zone

Water levels of Lake Constance usually differ about 1.5 m (max. 3 m) with maximum wave height of up to 2.5 m. This results in a high degree of erosion and accumulation, which is increased by ship waves and which strongly endangers cultural heritage like pile settlings. Despite these forces, which tend to equalize morphology, our new data show a high degree of morphological patterns in the shallow-water zone (e.g. mega ripples near the mouth of the River Rhine, Fig. 7, or stream patterns near Friedrichshafen, Fig. 8). These of course were known (and visible in orthophotos) but with dimensions never investigated in detail in a lake. Thus, the new data will strongly help to understand the functioning of the shallow-water zone in a large lake.

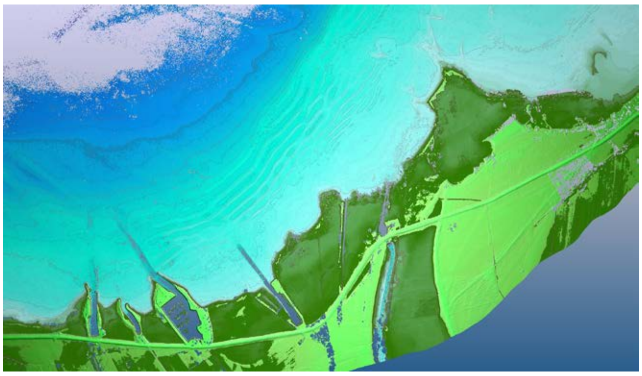

Fig. 7: Airborne LiDAR data of the Rohrspitz impressively show the rich morphology in the shallow-water zone with long mega ripples parallel to the shoreline. The mega ripples have a wavelength of 30 to 40 m, a height of 0.20 to 0.4 m and can be followed for hundreds of meters.

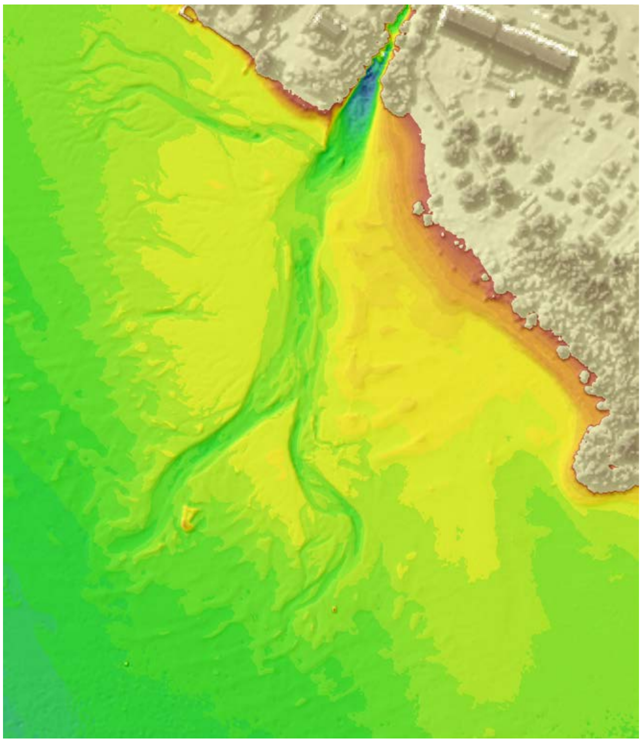

Fig. 8: Lake bottom in front of the Rotach, a small river near Friedrichshafen, showing very detailed structures even in the highly variable shallow-water zone.

Dark surfaces with low reflectance (e.g. dark and muddy sediments within harbors, dense underwater vegetation) prohibited accurate detection of the lake bottom.

3.5 "Flight into the lake"

Besides the above-mentioned basic technologies, a number of existing data-sets have to be handled. To visualize the bathymetry, a virtual flight from the surrounding region into the lake is anticipated, fueling the high degree of enthusiasm of the public for the rich underwater landscape, which eventually will help to protect the entire lake. This flight should visualize the existing data (on land) and the new underwater data (from LiDAR and MBES) for the public. For that flight, digital orthophotos (DOP) with a resolution of up to 20 cm and DTMs with 1 m grid size were transformed from four national grids into a common coordinate system. Errors occurring when combining the data-sets of different origin were corrected manually with software solutions that are able to handle the large image files. Once this product is finished, the visualization is done using two different resolutions: in a first step, DTMs with 10 m resolution will be covered with a 4 m DOP. LiDAR- and Multibeam-data from the lake will then be integrated in a second, high-resolution level, so that, when flying into the lake, the visualization automatically switches into the relevant level.

4 Summary

Our project resulted in a number of lessons and experiences in addition to the lake-floor data. Technically, a project of this size is really difficult to handle, as small freshwater bodies are much more variable compared with fully marine systems. Especially in near-shore regions, properties of water bodies strongly differ spatially and temporally, in particular in spring and early summer, when the lake is rapidly warming. So far, also advanced processing software packages ("CARIS HIPS & SIPS") still lack a proper handling of the high numbers of sound-velocity profiles in a satisfactory way (we measured 602 profiles). Also, possibilities to handle and classify data, which should not be visible in the final products (mainly inlets for drinking water supply and relevant archeological objects), are limited so far.

When processing LiDAR-topobathymetric data, there is no solution to achieve lake-floor data in densely vegetated areas. Further, the methods presented will have limitations when used, e.g. for vegetation studies with submerged macrophytes. Dark areas at the lake floor reflect significant lower signal amplitude compared with light sediments. Thus, this technique does not only depend on the transparency of the water-column but also mirrors properties of the sediments: coarse sediments (gravels, sand, often consisting of light grains like quartz, feldspar, carbonates) are better detected than fine grained sediments with a higher proportion of clay minerals deposited in bays and regions with lower turbulence.

Experiences from our transboundary cooperation of the surveying authorities will help to execute further national surveys, as boundary conditions (e.g. coverage of multibeam swaths) can be well defined and evaluated and data processing and handling can be better planned. In fact, new projects are already anticipated in Switzerland that will also combine topobathymetric LiDAR and multibeam echosounder data.

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