Bathymetry of Lake Constance

State-of-the-art in surveying a large lake

An article by MARTIN WESSELS and FLAVIO ANSELMETTI[1], ROBERTO ARTUSO[2], RAMONA BARAN[3], GERHARD DAUT[4], ALAIN GEIGER[5], STEFAN GESSLER[6], MICHAEL HILBE[1], KARIN MÖST[7], BERTHOLD KLAUSER[8], STEFFEN NIEMANN[1], ROBERT ROSCHLAUB[7], FRANK STEINBACHER[3], PAUL WINTERSTELLER[9], ERNST ZAHN[10]

In 2014 the by far largest German lake has been newly surveyed. The transnational project is funded by the European Union and delivers a detailed 3D-model of the lake-floor. The German project name is »Tiefenschärfe – Hochauflösende Vermessung Bodensee«, which in English roughly means: high-resolution survey of Lake Constance. The German term »Tiefenschärfe« (in optics and photography: depth of field) plays with the meanings of »Tiefe« (depth) and »Schärfe« (sharpness). The result of the survey shall be a clear and sharp image of the deep and shallow lake-floor. At present the LiDAR and multibeam data are still processed, but first results are presented in this article.

Lake Constance | Tiefenschärfe | IGKB | lake level | geoid | groundwater intrusions | megaripples | pockmarks

Authors

Dr. Martin Wessels is head of the department »Sedimentology and Lake Physics« at the Institute for Lake Research in Langenargen which is part of the Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW)

martin.wessels@lubw.bwl.de

[1] Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern
[2] Bundesamt für Landestopografie swisstopo, Wabern
[3] AirborneHydroMapping GmbH, Innsbruck
[4] FSU Jena – Institute of Geography, Physical Geography
[5] Geodesy and Geodynamics Lab., Institute of Geodesy and Photogrammetry, Zurich
[6] Lorth Gessler Mittelstaedt GmbH, Konstanz
[7] Landesamt für Digitalisierung, Breitband und Vermessung, München
[8] Landesamt für Geoinformation und Landentwicklung, Karlsruhe
[9] Marum, Bremen
[10] BEV - Bundesamt für Eich- und Vermessungswesen, Wien

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 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.

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 approximately 4.5 years. 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 ca 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 there rose the need for cooperation and the development for a number of trans-boundary organisations already in the late 19th century. As the lake is shared between these countries, different local coordinate systems with different lake levels are in use, which refer to Marseille (Switzerland), Triest (Austria) and Amsterdam (Germany) and which result in height differences of 32 cm for the same lake level between the grids.

Ecologically, eutrophication problems became aware in the 1950s, 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 about five million people. Independent of this successful re-oligotrophication, Lake Constance remains an ecosystem with multiple stressors and conflicts (e.g. intense leisure activities, ca 55,000 boats, a large diving community, rich archeological history (pile dwellings are UNESCO cultural heritage), use and restoration of shore lines, commercial fisheries, micropollutants, use of thermal energy, etc.), which now are the main tasks for the IGKB.

Historical aspects in yielding bathymetric information

Lake Constance may act as an example for the long term development in bathymetric data, as already in 1825/26 Captain Gasser from the kingdom of Baden made a first bathymetric survey to describe the lake. He used a metal wire to measure 17 profiles crossing the lake. More than 11,000 measurements (20 measures/km^2) using ›bob plumbing‹ then were acquired between 1889 and 1891 (Zeppelin 1893, Hörnlimann 1893). The resulting »Zeppelin-map« was thereafter used as the basis for intensified research (Earl Eberhard Zeppelin is the brother of the constructor of the 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 1998), the construction management office for the Rhine River conducted a survey of the Rhine River delta since 1911 every ten years. Initially, mechanic bob plumbings were used along horizontally stretched wires, while later on, hydroacoustic systems, theodolites (e.g. Waibel 1971) and GPS were introduced when available.

A new basis for modern research was the survey of the entire lake between 1986 and 1990, initiated by the IGKB. In this context, echo sounder profiles with a maximum distance of 200 m and photogrammetric analyses of the shallow-water situation resulted in a 40 m grid for the deeper areas, and 10 m grid for the shallow-water zone (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 surveys used portable multibeam systems (e.g. Böder and Wessels 2009, Wessels et al. 2010) to collect data for high-resolution digital terrain models (DTM) to investigate 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 minimise height differences when modelling 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).

Intention for a new topobathymetric survey

As the pilot multibeam surveys mentioned above showed the potential of modern hydrographic survey systems, the needs for a detailed topobathymetric survey were discussed. A working group assigned by the IGKB identified a number of reasons and needs:

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

To fulfil 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, it is possible to generate seamless DTMs from land into the deep areas. Both methods were complemented by an independent quality management. As a high public interest in these data was expected, the whole project should 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 cooperations in the Lake Constance area. A bathymetric survey of such a large inland water with latest technologies is not only a focus for the trans-boundary 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.

Costs for our project – entitled »Tiefenschärfe – hochauflösende Vermessung Bodensee« – amount to 612,000 euros (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 the middle of 2015.

Methods

The multibeam echo sounder survey

The bathymetric survey for areas deeper than 5 m was carried out during 76 days from April to August 2013 using a Kongsberg EM 2040 multibeam echo sounder in a single-head configuration (1° × 1° beam width, 300 kHz standard operating frequency) on RV »Kormoran«. The transducers and ancillary sensors (antennas for RTK-GNSS positioning, GPS compass, motion sensor, sound velocity probe) were incorporated in a portable, rigid mounting attached to the bow of the ship. 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 optimum data quality. Dual swath mode of the EM 2040 was used in order to maintain a reasonable survey speed while keeping sufficient point density and full lake-floor coverage.

In total, an area of 460.6 km^2 was covered by 2961 survey lines (total length 6,001 km), yielding 7,210,007,325 soundings. Typical achieved sounding densities are in average about 15 m^{-2} in the deepest areas (250 m), where swath angles were restricted to ~40° to each side, >20 m^{-2} at 100 m water depth with a swath width of 120° and about 50 to several hundred soundings a m^{-2} in the shallowest zones (<10 m), where the full swath (75° to each side) was used.

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

TIEFEN SCHÄRFE

Hochauflösende Vermessung Bodensee

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positioning corrections over a cellular network-based Internet connection (which is in theory available for the entire survey area) with NTRIP had to be abandoned due to the insufficient stability of the connection, and post-processed RTK positions were used instead.

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.

Investigations of the geoid

The geoid, one of the main research topics in geodesy, corresponds approximately to the mean sea surface topography and serves as the reference for height indications like ›above mean sea level‹. The three-dimensional geometry of the lake's surface has been determined simultaneously with the bathymetric survey.

A GPS-antenna and a down-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. 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 (Fig. 1). Disturbances like waves were removed by filtering whereas seasonal and meteorologically induced sea level variations, about 1.7 m during the measuring campaign, have been corrected by gauge data provided by hydrological institutions around the lake.

Topobathymetric LiDAR survey

Airborne 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. We combined a high-resolution spatial view at the lake-floor using LiDAR (>10 points/m^2), with high-resolution aerial (<10 cm/pixel) and thermal images.

The airborne hydromapping survey of Lake Constance (Fig. 2) was completed within three days using the hydrographic scanner VQ820-G of Riegl LMS in March and June 2014. 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 geo-referenced to terrestrially measured reference planes, which were distributed around the entire lake (accuracy about 0.08 to 0.09 m, standard deviation). The point density after combining all scan strips reaches up to 40 to 50 points/m^2 and about 20 to 30 points/m^2 near the shoreline in shallow areas, whereas it decreases to ca 10 to 20 points/m^2 at a depth of 4 to 5 m. We classified the point cloud into eleven 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 and the remaining was then corrected manually. Within an approximately 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 harbours. The remaining foreland area with 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 pictures were acquired using a mid-format camera (Hasselblad H3DII-39). With these pictures, 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 aerotriangu-

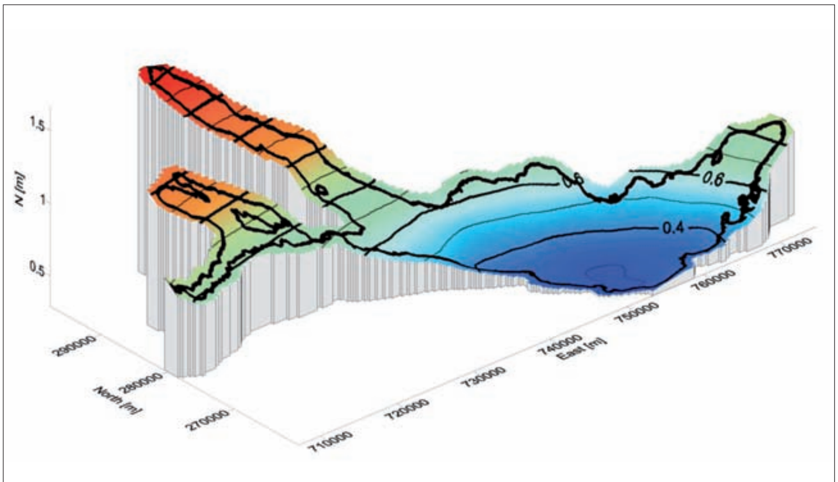

Fig. 1: Lake's surface departs from an ideal ellipsoidal reference and runs approximately parallel to the geoid. It reflects directly the form of the gravitational field (Geodesy and Photogrammetry, ETH Zurich)

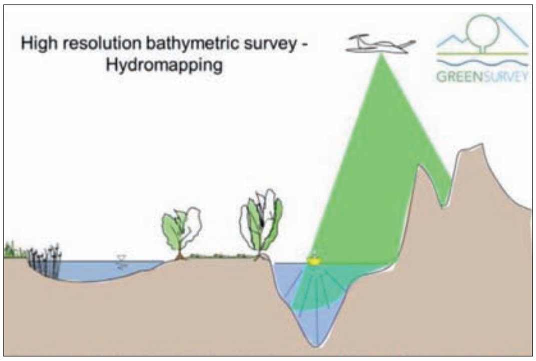

Fig 2: Shallow areas captured by hydromapping, deeper areas captured by echo sounder

lation. Afterwards, the pictures are orthorectified, and a radiometric correction is applied to homogenise the colour distribution of the entire image block. The mosaicking is performed along natural boundaries. Correction of seamlines is carried out only for image boundaries across buildings. The final ground resolution of the orthophotos is about 7 cm with an accuracy of less than 1 m (CE90).

Quality management

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 finalising products. To ensure a high-quality digital terrain model (DTM) the measured data are verified with several methods. An Innomar SES-2000 light sub-bottom profiler (SBP) run parallel to the multibeam measurements. Besides control points and area measurements along sub-aquatic archeological sites and bankside constructions like nose-piece, the depth traced with the sub-bottom profiler is used, once sound velocity profile corrected, to validate the multibeam and LiDAR measurements. In addition, cross lines and small double surveys are used for multibeam data verification in order to assure the requested IHO special order. Another task for the quality management is to cross-check the SAPOS-based real time kinematic GPS-height/tide correction as well as the applied roll/pitch/heave corrections. Previous and recent digital orthophotos and especially ground control point measurements are used to validate the LiDAR surveys made within this project.

Public relations activities

Within our public relation activities, a logo and a corporate design was designed by an advertising agency Lorth Gessler Mittelstaedt located in Konstanz. These products were already prepared for the kick-off meeting, which was accompanied by a press conference. Journalists had on board of the RV »Kormoran« the opportunity to observe the capacity of the online-visualisation of the multibeam acquisition software. Later on, a website, a brochure and a small exhibition in a public place in the village of Langenargen were realised. Two further press conferences and several appointments with journalists produced an outcome of more than 200 contributions in newspapers, websites, radio and TV in four countries.

First results of project »Tiefenschärfe«

A lot of fascinating lake-floor features were already recognised during the surveys and later on refined during processing of data. Only few examples will be presented here as further evaluation will take

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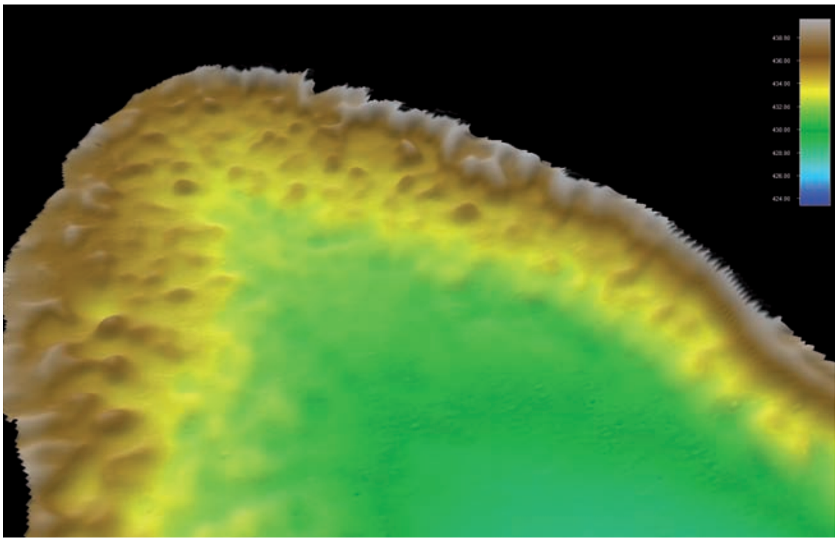


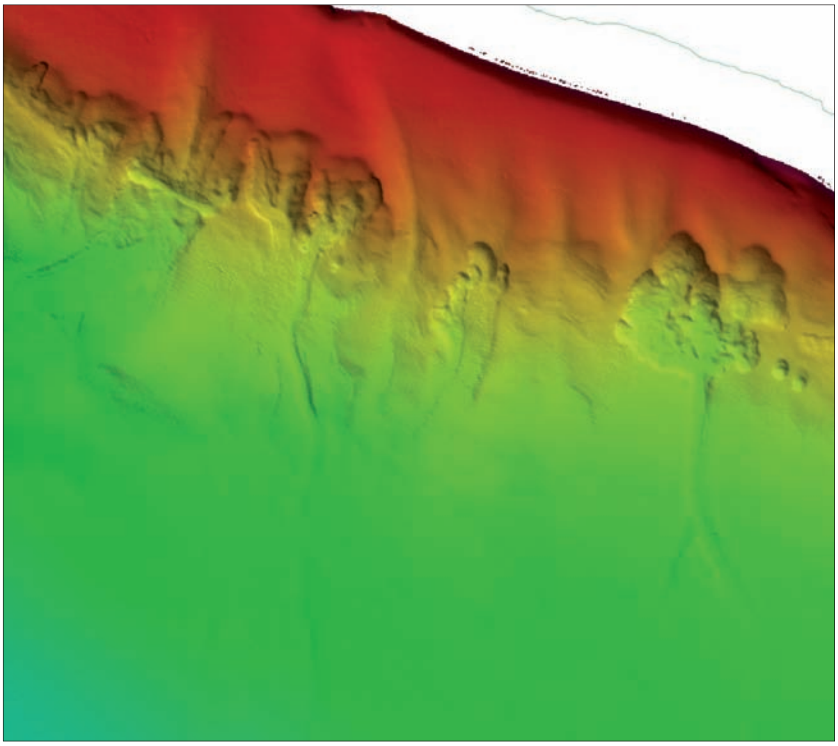
Fig. 3: Shallow areas of Gnadensee, a small isolated and protected basin part of Lower Lake Constance have a hummocky structure, probably a remnant of the retreating Late Glacial ice sheet

some while and final processing of the data is not yet completed. Thus, results and images presented here are still preliminary.

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. Here, large portions offshore the shorelines have a hummocky structure or are covered with large but shallow depressions (ca 10 to 50 m diameter, 0.2 to 0.5 m deep, Fig. 3). 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 levelled all of these structures at the shoreline. This interpretation is supported by sub-bottom profiling data that show in other parts of the lake the morphology of the shallow-water zone being strongly homogenised since the Late Glacial.

Fig. 4: Depressions along the slope give hints for groundwater intrusions into Lake Überlingen



Indicators for lake-groundwater interactions

In deeper waters (about 80 to 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 lake ward boundaries occur (Fig. 4). These depressions lack any hints for rock slides or mass movements and are currently interpreted as caused by groundwater discharge into the lake. In a new project, we will investigate if indeed groundwater-sources (e.g. from nearby molasse-rocks) may contribute 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 in particular interesting as they may contribute to significant boundary conditions regarding the discussion of fracking technologies in the vicinity of the lake.

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 strongly endangering cultural heritage like pile settlings. Despite these forces which tend to equalise morphology, our new data show a high degree of morphological patterns in the shallow-water zone (e.g. megaripples near the mouth of the River Rhine, Fig. 5). 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.

Flight into the lake

Besides the above mentioned basic technologies, a number of existing data sets have to be handled. To visualise the bathymetry, a virtual flight from the surrounding region into the lake is anticipated, fuelling 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 visualise the existing data (on land) and the new underwater data (from LiDAR and multibeam) 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 unique 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 visualisation is done using two different resolutions: in a first step, DTMs with 10 cm 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 visualisation automatically switches into the relevant level.

Experiences and challenges

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 nearshore regions, 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 and SIPS) still lacks 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 vegetational studies with submerged macrophytes.

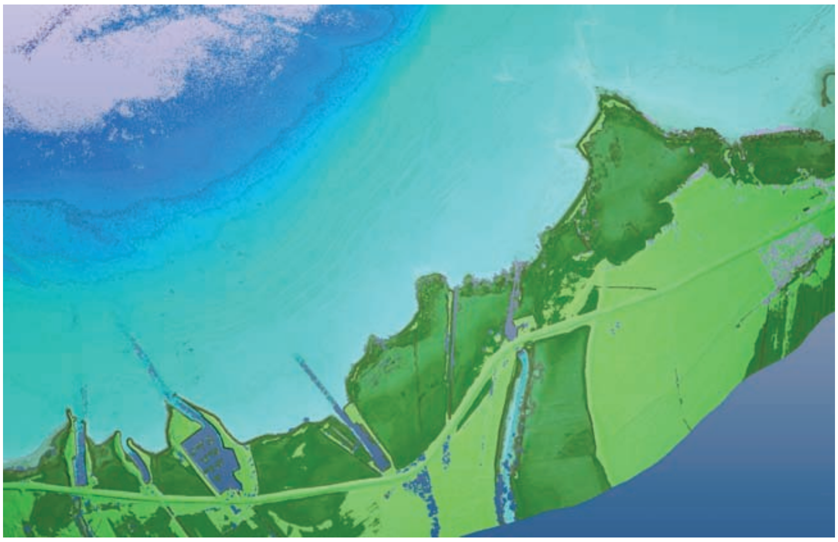


Fig. 5: Airborne LiDAR data of the Rohrspitz impressively show the rich morphology in the shallow-water zone with long megaripples parallel to the shoreline

Experiences from our trans-boundary 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 echo sounder data. ⚓