Airborne Laser Bathymetry for Monitoring the German Baltic Sea Coast

J. NIEMEYER[1], T. KOGUT[1,2] & C. HEIPKE[1]

ABSTRACT: Periodic monitoring of the sea bed is one of the most important tasks of the public maritime and hydrographic authorities. The corresponding measurements, which guarantee the safe navigation of ships, have been carried out by ship-based echo sounding in the past, but this method is rather expensive. A project called 'Investigation on the use of airborne laser bathymetry in hydrographic surveying' studies the opportunities of airborne laser bathymetry for monitoring of the sea bed in the Baltic Sea. This paper summarizes the goals of the project and presents results of the first data acquisition campaign. In a test site with heterogeneous water depths the point densities, coverage and depth accuracy are evaluated. As expected, good results for shallow water areas up to one Secchi-depth are observed. For deeper areas points are detected only very rarely. A comparison to echo sounding data shows only small differences in the depths values of both data sets.

1 Introduction

Measurements of the underwater topography (bathymetry) are one of the most important tasks of hydrographic authorities worldwide. Periodic monitoring of the sea bed, which guarantees safe navigation of ships, is currently carried out by echo sounding, a rather expensive and time consuming ship-based method. Due to international agreements and a steadily growing maritime traffic relying on high precision navigation systems the demand for periodic monitoring campaigns has increased.

Shallow water regions between depths of 0 m and 1-2 m are particularly difficult to measure, because these areas are not accessible for vessels in many cases. Thus, data of these regions are often not very accurate and sometimes missing, although they are needed for many applications such as a reliable determination of the coast line, coastal protection and coastal zone management.

Airborne laser bathymetry (ALB) is a promising technique of sea bed measurement, which became more and more important in recent years thanks to improved hardware and better processing software. Such devices use a green laser which can penetrate the water column, often in addition to an infrared laser, which is reflected at the water surface. The depth is determined from the two-way runtime between the water surface and reflections from the solid ground underneath. Especially the pulse repetition rate and thus the point density have been significantly increased for state-of-the-art sensors, with good results under optimal conditions (IRISH ET AL.

1 Institute of Photogrammetry and GeoInformation, Leibniz Universität Hannover, D-30167 Hannover, Germany; E-Mail: (niemeyer, kogut, heipke)@ipi.uni-hannover.de

2 Department of Geoinformatics, Koszalin University of Technology, 75-453 Koszalin, Poland

1999, STEINBACHER ET AL. 2012). However, there are many limiting factors, in particular water turbidity. Some other issues are wind, sea state, and reflectance of the sea bed.
This paper introduces the aims of the project 'Investigation on the use of airborne laser bathymetry in hydrographic surveying', which is a cooperation of BSH (Federal Maritime and Hydrographic Agency of Germany) and IPI (Institute of Photogrammetry and GeoInformation, Leibniz University Hannover). The project studies the opportunities of airborne laser bathymetry for monitoring the sea bed in the Baltic Sea in comparison to traditional ship-based echo sounding. Several flight campaigns in representative test areas will be carried out in order to analyze the reachable depths, the accuracies of the acquired points, and the detection of obstacles depending on different conditions (e.g. water turbidity). In this investigation, we report results of the first campaign that took place in autumn 2012.

2 Laser bathymetry

Conventional bathymetry of water bodies is performed by echo sounding systems mounted on vessels, but particularly in shallow water (for example close to the coast) these vessels cannot access some areas due to the draft. A relatively new method to obtain 3D information of near-shore shallow water regions is ALB. Using this technique a three dimensional description of the ground is obtained including sea and river beds. In contrast to topographic laser scanners operating with near infrared laser, bathymetric sensors make use of a green laser of 532 nm wavelength. These pulses are able to penetrate the water column and thus may reach the sea bed. The measuring depth is limited due to attenuation of the laser energy by absorption, scattering, and refraction effects while the laser pulse is traveling through the water column. Most sensors work with a combination of a near infrared and a green laser. In this case the infrared signal is reflected from the water surface, whereas the green laser measures the ground. The water depth is the difference of both levels. Recent work investigates for example the accuracy of the surface points determined by a green laser solely in comparison to a reference near infrared laser signal (MANDLBURGER ET AL, 2013).
The first systems were introduced in the 1960th for military tasks such as the detection of submarines. HICKMAN AND HOGG (1969) proposed to use an airborne laser for bathymetric surveying. In the next decades several prototypes of ALB sensors were developed, for example by NASA and the U.S. Navy. The Royal Australian Navy constructed the first operational system called LADS in 1986 (LILLYCROP ET AL., 2002). As a strong green laser pulse is necessary in order to reach deeper areas in the ocean, the pulse repetition rate of the sensor was limited considerably. This led to low point densities on the sea bed. GUENTHER ET AL. (2000) reported basic technical requirements for laser bathymetry; different available sensors are summarized by MALLET AND BRETAR (2009). By increasing the pulse repetition rate, some systems of the newest generation, such as the Riegl VQ-820-G sensor (RIEGL, 2013, STEINBACHER ET AL., 2012) or Chiroptera (AIRBORNE HYDROGRAPHY A.B., 2013), reach higher point densities in shallow water of about one Secchi depth (the Secchi depth is the maximum depth at which the human eye can detect a specific disk in the water). However, these sensors are not suitable for deeper water because the pulse energy is too low for a longer travel through the water column.
Many of the published civil applications of laser bathymetry obtained promising results and measurements of up to 60 m (IRISH AND LILLYCROP, 1999) were reached in test studies with clear

water. In COSTA ET AL. (2009) it was shown that laser bathymetry was 6.6% cheaper and took only 2 hours instead of 42 hours for mapping the entire study area, albeit with the drawback of lower spatial resolution compared to multi-beam sonar for a coral reef mapping project with water deeper than 50 m. In the case of Germany there are strong tidal effects at the North Sea coast leading to a turbidity of the water due to the whirled sediments. In contrast the water of the Baltic Sea coast is much clearer, although it is still not optimal for laser bathymetry. This is the reason why the work of the presented project focuses on the Baltic Sea coast.

3 Project description

3.1 Goals and requirements

In 2011 BSH decided to launch a 3 year project in order to evaluate the potential of laser bathymetry in the area of the German Baltic Sea coast in more detail. A focus of the project lies on the quality of the data, another one on economic aspects compared to conventional echo sounding. The most important question is: Can laser bathymetry be used as an alternative for at least a subset of BSH's tasks and is ALB economic for operational application? In order to answer these questions, three surveying flights (one per year) are planned. Additionally to the laser flights, reference measurements with conventional ship-borne bathymetry will be conducted. In the project the geometric accuracy of the laser data will be validated, and the potential of full waveform information detecting obstacles such as stones will be evaluated. Of special interest are also shallow water areas and the transition zone to shore. Taken as a whole all environmental influences such as water turbidity, weather, strength of the waves etc. need to be considered to determine the limitations of the technique.
Concerning the quality of the data, laser bathymetry must meet the constraints of the IHO Standards for Hydrographic Surveys (S-44) (INTERNATIONAL HYDROGRAPHIC ORGANIZATION, 2008), Order 1a specifications to partly substitute ship-based bathymetry. These standards require full sea floor coverage during surveying. Moreover, it must be possible to detect cubic obstacles of a size of larger than 2 m in depths up to 40 m. The maximum allowable total horizontal uncertainty (THU) is defined by

$$THU_{max} = 5\,m + 5\%\ \text{depth} \quad , \tag{1}$$

whereas the total vertical uncertainty is computed by

$$TVU_{max} = \sqrt{(0.5\,m)^2 + (0.013 * depth)^2} \quad . \tag{2}$$

For both parameters a 95% confidence level must be fulfilled.

3.2 Study Area, 1st campaign

For the first data acquisition campaign four test sites situated near the island of Poel, Germany were chosen. The data acquisition was conducted by Milan Geoservice GmbH in early November 2012 with a Cessna C207 and a Piper Seneca PA34 carrier and a Riegl VQ-820-G sensor, which works with a green laser (λ=532 nm) solely. For this survey the pulse repetition rate was set to 120 kHz. The typical measurement range is one Secchi depth (RIEGL, 2013). A scan pattern of an elliptical arc segment aimed ahead of the aircraft ensured a nearly constant incident angle. This is helpful for the correction of refraction occurring at the water surface. In order to assess the quality of the results and its dependence on different influences, the data was acquired in different flying heights above ground. An overview illustrating the extent of the test areas is given in Fig. 1.

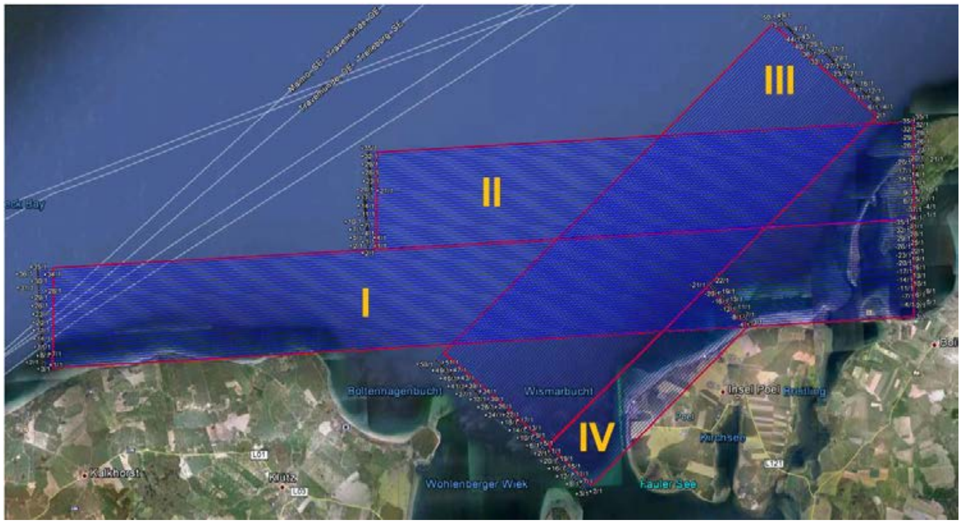

Fig. 1: Overview of the four test areas situated close to the island of Poel in the Germany Baltic Sea (© GoogleEarth)

Area 1 reaches from west to east and is the largest test site with 136 km^2. It touches the coast, but mainly consists of water regions. The water depth reaches up to approx. 25 m, but also includes a shallow water region of a depth with 3-4 m called Hannibal and some larger stones, which may be an obstacle for ships. Area 2 is also orientated in west-east direction; the area of 84 km^2 lies in the north of Area 1. It comprises water of the depth of 10 to 15 m in the main part, but also covers an island in the east. The other two areas reach from south-west to north-east. Area 3 has a size of 104 km^2 and is completely located in water. The maximum depth is up to 21 m, but the area also comprises the shallow water region Hannibal. In contrast, Area 4 covers the coast of Poel. In the 21 km^2 region, some parts are onshore. A large variation of the water depth can be observed here; it reaches from very shallow water at the beach to 15 m. Orthophotos were provided for this area additionally, the date of image acquisition was one month before the laser survey. The results of Area 4 are already presented in NIEMEYER AND SOERGEL (2013). In this work we focus on the combined evaluation of Area 1 and 2, which are more challenging due to deeper water levels in the test sites. The analyzed data sets were acquired with an altitude of 500 m.

4 Evaluation of Area 1 and 2

4.1 Description of the data

The delivery of the data comprises the point coordinates with the attributes concerning the echo return number, intensity values as well as a classification in one of the six object classes for each laser point: *onshore*, *water surface*, *sea bed*, *underwater vegetation*, *underwater obstacles*, and *noise*. The processed point cloud was corrected to account for the angle of refraction at the water surface. Moreover, the speed of light is reduced in water compared to the propagation in the air.

This difference in velocity must also be corrected. In addition to the processed point cloud the original waveform information was delivered for further research, too. A 2D-profile view of a subset of the laser point cloud showing the *water surface* and the *sea bed* points is depicted in Fig. 2. The statistics of the point clouds of Areas 1 and 2 are given in Table 1; they are based on the classification performed by Milan Geoservice. The numbers of *sea bed* points (39.3 %) and points classified as *onshore* (38.3 %) are nearly the same, although the land area is significantly smaller than the area covered by water. Additionally, it is notable that the amount of *water surface* points (22.1 %) is smaller than the number of *sea bed* points. This effect is already described in MANDLBURGER ET AL. (2013) for a river test site. There are no points assigned to the class *underwater obstacles* in our areas, and only very few are (0.03 %) classified as *underwater vegetation*.

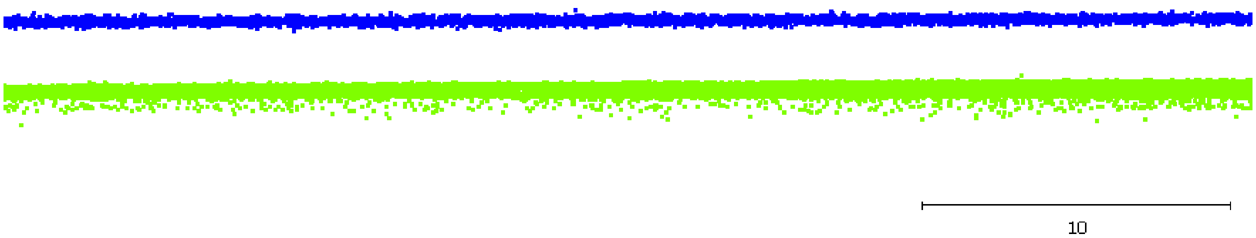

Fig. 2: Profile of point cloud showing *water surface* (blue) and *sea bed* points (green) with a depth of approximately 2 m.

Tab. 1: Distribution of classes in Areas 1 and 2 with 500 m altitude

# of points	**181,876,581**	
Size [km^2]	220	
Noise	0,31 %	568,358
Water surface	22,08 %	40,159,065
Sea bed	39,29 %	71,460,309
Underwater vegetation	0,03 %	45,566
Onshore	38,30 %	69,643,282

4.2 Analysis of the sea bed points

In particular the points classified as *sea bed* are of interest for hydrographic applications. This is the reason why this paper investigates these points in more detail in terms of number and density per depth level, depth accuracy, and actual area coverage in relation to the echo sounding data. The analysis is carried out in depth levels of 0.5 m and 1 m intervals, respectively.

4.2.1 Point depths

Analyzing solely the points classified as *sea bed* a depth of about one Secchi depth, which was approximately 6 m, can be observed; this result was to be expected (the Secchi depths were measured by vessels in the same time of the laser data acquisition). The depths of the *sea bed* points are plotted in Fig. 3. The two orange polygons mark the test areas, and *sea bed* points were obtained only in the colored regions (the point coverage is analyzed in Section 4.2.4). The diagram in Fig. 4 additionally shows the distribution of points in different depth levels. 43% of the points lie between 0 and 1 m. With increasing water depth the number of points decreases. 6% of the points are measured at a level from 4 m to 5 m and only less than 1% of all *sea bed* points have a depth larger than 5 m. Of course, this distribution can be partly explained by the topography of the sea ground in this area, on the one hand, and by inhomogeneous point densities, on the other hand. This is for example notable at the depth level of 3-4 m, which exhibits a small local maximum in the graph. The reason might be that the reference area in this depth level is larger compared to the shallower depths (c.f. Fig. 8). Thus the probability of obtaining values in this depth level is larger. In order to minimize the effects due to the topography, the histogram in Fig. 5 is normalized by the actually covered area of *sea bed* points (red bars in Fig. 8) based on a binary cover mask, as explained in Section 4.2.4. As expected the function now decreases nearly monotonically. Further investigations will focus on a more detailed analysis of this issue.

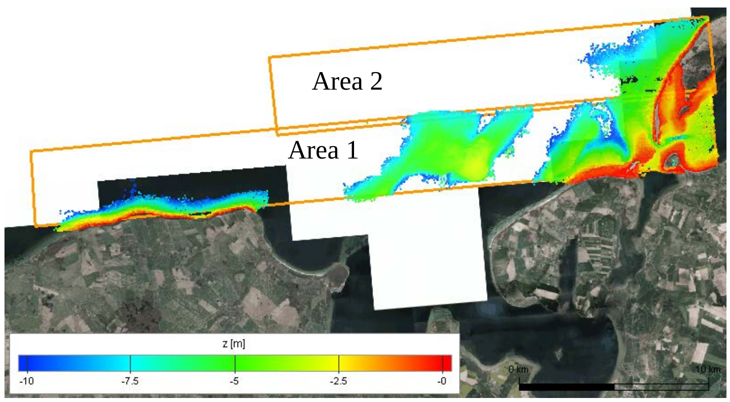

Fig. 3: Depth of sea bed points in Areas 1 and 2. (orthophotos ©GeoBasis-DE/M-V)

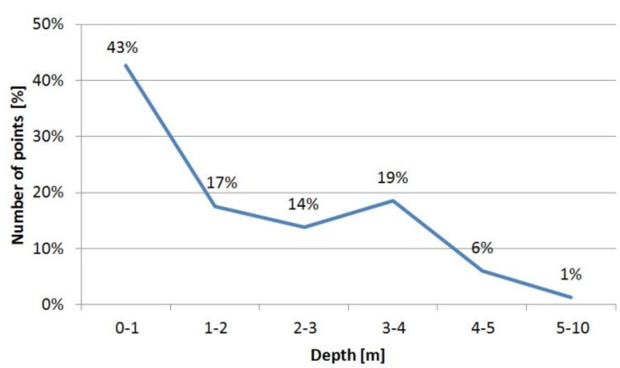

Fig. 4: Number of *sea bed* points per depth level

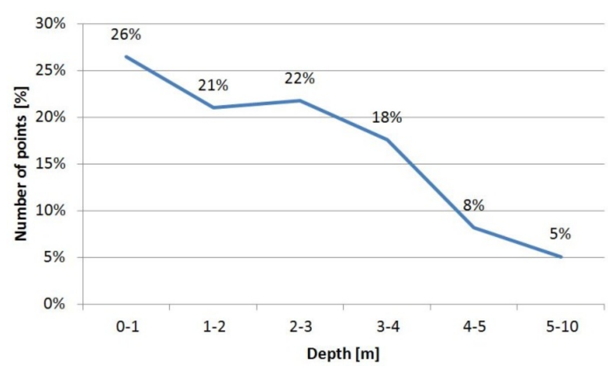

Fig. 5: Number of *sea bed* points normalized by the actually covered area per depth level

4.2.2 Point density

A similar behavior can be observed for the point densities (Fig. 6).The result reveals that a high point density was achieved in the shallow water areas. Between 0 and 1 m the average point density is about 6 pts/m^2. It decreases to approx. 5 pts/m^2 (from 1 to 3.5 m depth) and then quickly goes down to around 2 pts/m^2 at 4.5 m level. For deeper regions it is 1 pt/m^2. However, these are only single points and an extensive coverage of the sea bed in not achieved. In accordance to the number of points in the different elevation levels, the standard deviation of the point densities, represented by bars in Fig. 6, also decreases. Note that these values correspond to the observations made in Area 4 (NIEMEYER AND SOERGEL, 2013). A further investigation of the data will show if the LiDAR point cloud meets the IHO S-44, Order 1a specifications.

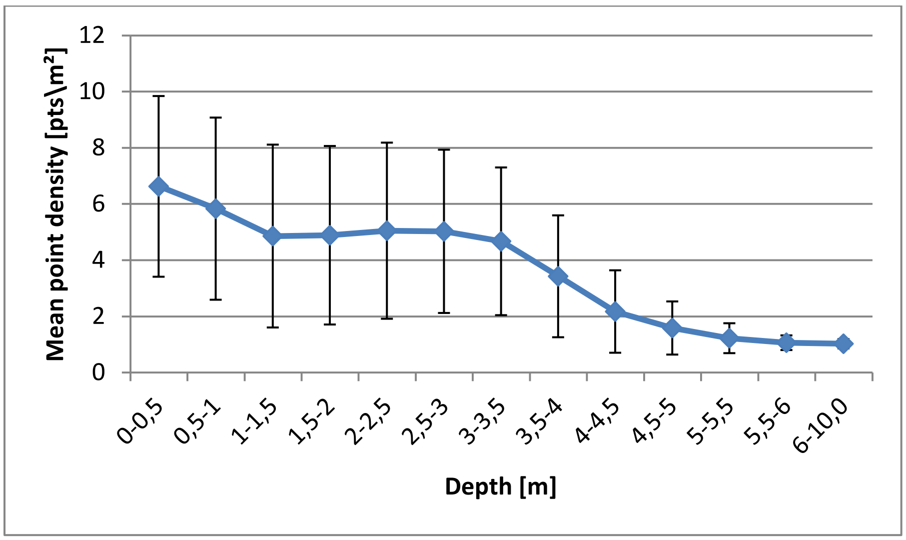

Fig. 6. Mean point density of sea bed points per depth level

4.2.3 Depth accuracy

The depth accuracy of the collected data is a very important question in our investigation. The ALB data are compared with echo sounding data, which were acquired by BSH over the last twenty years. A number of recent ship-based measurements, carried out in a few areas, verified that in general the morphology from echo-sounding is still up-to-date. This enables us to use these older echo sounding data as reference in order to obtain an approximation of the ALB accuracy. For further analysis a reference DTM with a grid size of 1 m was generated from the echo sounding data using nearest-neighbor-interpolation.

The results of the differences between the reference DTM and the laser point cloud, shown in Fig. 7, reveal that both techniques, ALB and echo sounding, lead to comparable results. The majority (89 %) of the laser points exhibits only a small difference of ±0.5 m. A further 9.5 % of the points are observed at a difference from ±0.5 m to ± 1 m. In particular, in the shallow regions (for example in the eastern part of the test site), the differences are very small. Larger differences of about 1 m can be observed at the slopes to deeper areas. This may be caused by morphological movements between the two epochs. However, in general the present study demonstrates that the depth of the points acquired by ALB give promising results. This finding will be investigated in more detail in future work.

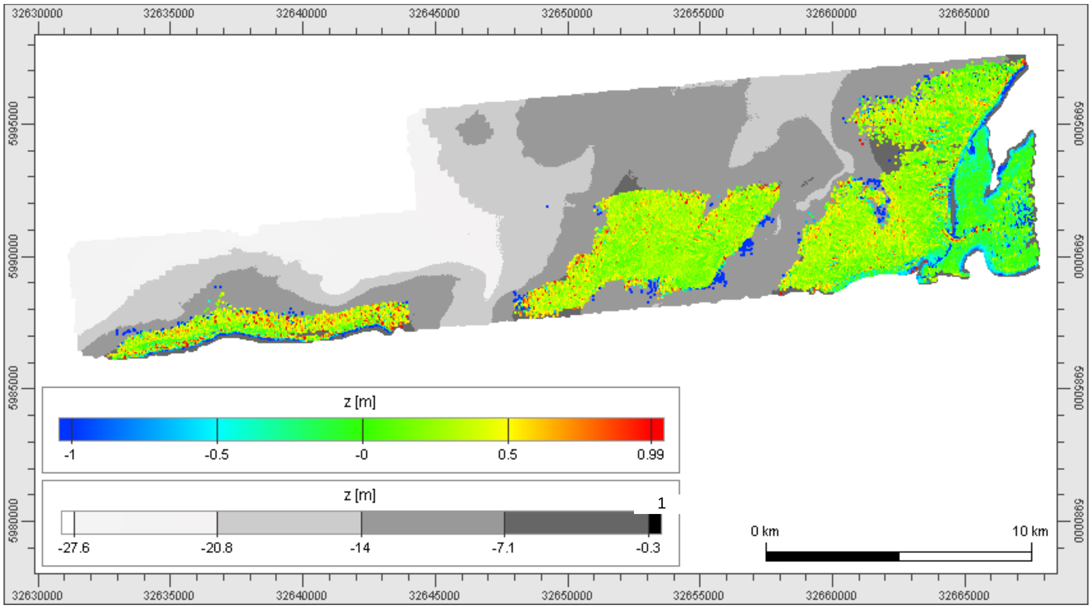

Fig. 7. Difference of depths (echo sounding DTM (heights grey-scaled) - ALB points). The color of the ALB points indicates the difference in depth.

4.2.4 Area coverage per depth level

The goal of the last experiment is to obtain an idea of the sea bed area, which is actually covered by ALB points in comparison to the (available) reference area. We use the echo sounding based DTM as approximation of the reference areas. Again, the analysis is performed in several depth levels. Each pixel in the DTM corresponds to an area of 1 m² in the respective depth level. By counting the pixels in a certain depth interval of 0.5 m the reference area in this depth level can be obtained.

For the ALB data a binary mask with a 1 m grid resolution is generated. Gaps in the data are not interpolated. At each grid cell the mask is set to 1 if the cell contains least one ALB *sea bed* point, otherwise the grid cell is set to 0. An approximation of the area per depth level covered by the ALB data is then determined by counting the grid cells containing a “1” that correspond to the pixels of a particular depth level in DTM.

In this way the diagram in Fig. 8 can be obtained. The blue bars represent the reference area in certain depth levels. Compared to that, the red bars show the area actually covered by ALB. A special case is the very shallow water between 0 and 0.5 m. In these regions no echo sounding data could be acquired, because they were not accessible for the vessels. This is the reason why no reference area is available in this depth level. In all other depth levels up to 5 m less than half of the reference area was covered by ALB; coverage decreases significantly for the deeper regions. At a level of 0.5 to 1 m at least 46 % of the approximated area is covered (note, that since we are only interested in analyzing the coverage in this section, the diagram only considers one (gridded) ALB point per m², although in particular the shallow water regions have much higher point densities with >5 points per m²).

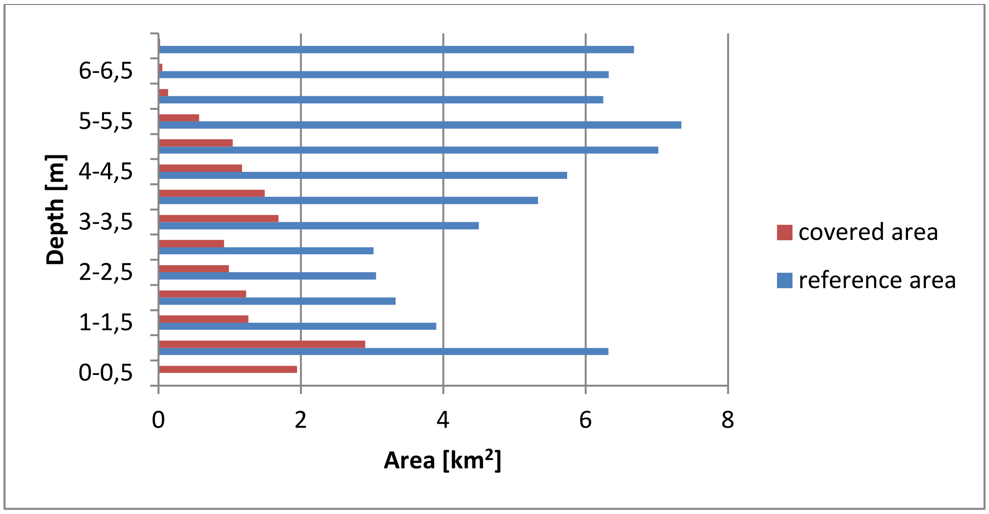

Fig. 8. Area actually covered by ALB data (red) in comparison to reference area (blue) per depth level

5 Conclusions

This paper presents results of the project 'Investigation on the use of airborne laser bathymetry in hydrographic surveying', carried out by the German Federal Maritime and Hydrographic Agency (BSH) in cooperation with the Institute of Photogrammetry and GeoInformation, Leibniz Universität Hannover, Germany. The goal is to assess the potential of airborne laser bathymetry (ALB). One task is to determine the limitations of this technique and investigate potentially suitable areas for which ALB is more economical than ship-borne echo sounding. At the current state of the project we processed data from the first of three acquisition campaigns and evaluated the point clouds. A Riegl VQ-820-G sensor was used for the first campaign, which is designed for shallow water areas up to the Secchi depth. As expected, the point densities are higher in the shallow areas that in deeper ones, notably in regions lower than 5 m. We also show that 89 % of the acquired points have depth differences of less than 0.5 m compared to an echo sounding DTM indicating a satisfying coincidence. *Sea bed* points are obtained by laser bathymetry even in very shallow water regions, which are not accessible for vessels, as long as the two echoes from water surface and sea bed can be separated (this minimum depth difference is related to the pulse duration). ALB may therefore be very helpful for applications such as coastal protection or the determination of the coast line.

In further work we want to concentrate on the analysis of the full waveforms in the very shallow transition zone between land and water to investigate whether these echoes can be separated. Also, we will strive to determine why only a low number of echoes were found on the water surface in comparison to the *sea bed* points. Moreover, the data from the next campaigns will be evaluated. The second campaign was flown in September 2013 with a combination of a Chiroptera sensor, which has comparable properties to the Riegl device, and a HawkEye II sensor, which is designed for the acquisition of deeper areas up to 3x Secchi depths. Data analysis is currently ongoing.

Acknowledgement

Funding of this project comes from BSH under project number 10019311, the support is gratefully acknowledged. The authors would also like to thank Dr. Wilfried Ellmer, Annett Büttner and Wolfgang Sent from BSH Rostock for the data and many productive discussions.

References

AIRBORNE HYDROGRAPHY AB, 2013: Chiroptera – Technical Specification. http://www.airbornehydro.com/chiroptera-technical-specification.

COSTA, B., BATTISTA, T. & PITTMAN, S., 2009: Comparative evaluation of airborne lidar and ship-based multibeam sonar bathymetry and intensity for mapping coral reef ecosystems. Remote Sensing of Environment **113**(5), pp. 1082–1100.

GUENTHER, G. C.; CUNNINGHAM, A. G.; LAROCQUE, P. E. & REID, D. J., 2000: Meeting the accuracy challenge in airborne lidar bathymetry. In: Proceedings of the 20^{th} EARSeL Symposium: Workshop on LIDAR Remote Sensing of Land and Sea, Dresden, Germany, pp. 1–28.

HICKMAN, G. D. & HOGG, J. E., 1969: Application of an airborne pulsed laser for near shore bathymetric measurements. Remote Sensing of Environment **1**(1), pp. 47–58.

INTERNATIONAL HYDROGRAPHIC ORGANIZATION, 2008: IHO Standards for Hydrographic Surveys. Special Publication N 44, 5^{th} Edition. www.iho.int/iho_pubs/standard/S-44_5E.pdf.

IRISH, J. L. & LILLYCROP, W. J., 1999: Scanning laser mapping of the coastal zone: the shoals system. ISPRS Journal of Photogrammetry and Remote Sensing **54**(2), pp. 123–129.

LILLYCROP, W. J.; WOZENCRAFT, J. M. & POPE, R. W., 2002: Airborne LIDAR Hydrography: a Vision for Tomorrow. Sea Technology **43**(6), pp. 27–34.

MALLET, C. & BRETAR, F., 2009: Full-waveform topographic lidar: State-of-the-art. ISPRS Journal of Photogrammetry and Remote Sensing **64**(1), pp. 1–16.

MANDLBURGER, G.; PFENNIGBAUER, M. & PFEIFER, N., 2013: Analyzing Near Water Surface Penetration in Laser Bathymetry – a Case Study at the River Pielach. In: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. II-5/W2, ISPRS Workshop Laser Scanning 2013, 11 – 13 November 2013, Antalya, Turkey, pp. 175-180.

NIEMEYER, J. & SOERGEL, U., 2013: Opportunities of Airborne Laser Bathymetry for the Monitoring of the Sea Bed on the Baltic Sea Coast. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W2, 2013, ISPRS2013-SSG, 11 – 17 November 2013, Antalya, Turkey, pp. 179-184.

RIEGL, 2013: Datasheet RIEGL VQ-820-G. Riegl Measurement Systems, http://www.riegl.com/uploads/tx_pxpriegldownloads/10_DataSheet_VQ-820-G_10-06-2013.pdf.

STEINBACHER, F.; PFENNIGBAUER, M.; AUFLEGER, M. & ULLRICH, A., 2012: High resolution airborne shallow water mapping. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Proceedings of the XXII ISPRS Congress, Vol. XXXIX-B1, Melbourne, Australia, pp. 55–60.