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Multisensor microbathymetric habitat mapping with a deep-towed Ocean Floor Observation and Bathymetry System

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To describe the seafloor topography, a number of different bathymetric methods can be applied which show major differences in coverage, resolution and topographic uncertainty. In order to conduct high-resolution habitat mapping in the deep sea, subsea survey methods need to be utilised. One of those methods is the use of deep-towed sensors. This work presents the newly developed Ocean Floor Observation and Bathymetry System (OFOBS), a sensor frame with optical, acoustic and navigational sensors. With a developed processing workflow, different products are gained from post processing the collected data sets, namely submetre acoustic bathymetry, subdecimetre side-scan mosaics, subcentimetre photogrammetric microbathymetry and geometrically corrected, georeferenced submillimetre photo mosaics. The data was collected during the RV *Polarstern* expedition PS101 in the extreme environment of the volcanic seamounts along the Langseth Ridge in the high Arctic (87°N, 60°E).

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1 Introduction

When Fridtjof Nansen produced the first chart of the Arctic Ocean in the beginning of the last century, it showed a single basin with little to no distinct seafloor features. Large-scale gravimetry and radar altimetry reveal a large abundance of features, such as ridges and seamounts. To increase the level of detail on the knowledge of the seafloor, ship-based acoustic survey methods can be applied. Yet, in research related to smaller scale features, higher-resolution techniques need to be utilised.

One of those methods is the use of towed systems to bring sensors closer to the seabed. The here presented system is the newly developed Ocean Floor Observation and Bathymetry System (OFOBS), a deep-towed frame, equipped with a sensor suite for close-range, high-resolution habitat mapping. It was first used to conduct surveys during the RV *Polarstern* research cruise PS101 in the Central Arctic in 2016. The following text will summarise the setup of the system, the data collected during the PS101 dives and the workflow developed to post-process the data in order to achieve a variety of microbathymetric results.

2 Ocean Floor Observation and Bathymetry System

The OFOBS setup consists of two primary components, the topside unit with power supply, network facility and control/logging computer, as well as the subsea unit. The latter is towed on a fibre-optic tether cable to enable real-time data transmission.

The original setup of the OFOBS was equipped with a set of cameras, lights, flashes, scaling lasers and a USBL transponder, and was meant for visual exploration from 1.5 to 5 m above the seabed (Purser et al. 2018). To extend the survey coverage and to augment the original camera setup, the OFOBS was later equipped with a bathymetric side-scan sonar for lateral measurements, a forward-looking sonar and some auxiliary sensors needed for bathymetric data collection (Fig. 1).

The navigation setup is built up by an iXBlue PHINS 6000 INS, an iXBlue Posidonia transponder and an AML Micro-X pressure sensor. With its internal fibre-optic gyros and accelerometers, as well as the external inputs, the INS outputs a Kalman filtered navigation solution and creates a time reference for all other subsystems.

With regards to optical sensors, the OFOBS is equipped with a downward facing Canon EOS 5D Mark III stills camera with a 24 mm fixed lens and a Sony FCB-H11 high-definition camera for continuous video recording. Continuous LED illumination assures constant lighting conditions on the video stream while additional strobe lights aid the stills

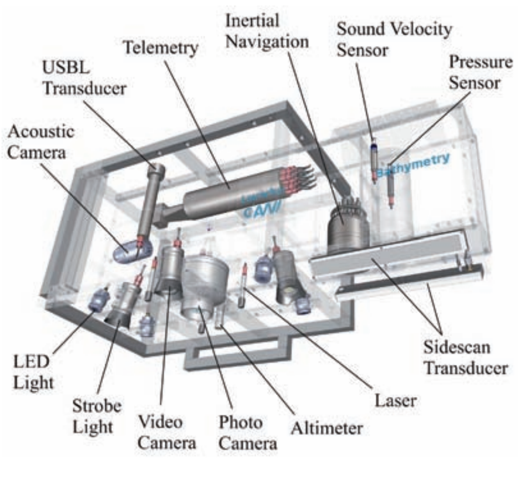

Fig. 1: Schematic view of the OFOBS instruments (Purser et al. 2018)

camera for sharper images (Purser et al. 2018). Three parallel lasers are positioned in a triangle around the stills camera with a distance of 50 cm between each laser.

Two acoustic surveying systems are installed on the OFOBS: an EdgeTech 2205 multiphase echo-sounder (MPES) and a BlueView M900-130 forward-looking sonar (FLS). Both are aided by an AML Micro-X sound velocity (SV) probe. The MPES is based on side-scan sonar (SSS) technology, operating on 230 kHz and 540 kHz (chirped) and brings the advantage of a wide swath whilst simultaneously collecting side-scan and bathymetry data. The transducers hold an additional bathymetric receive array of ten vertically stacked staves to infer nine phase-difference measurements, which allows for statistical filtering, resulting in a relatively clean data set (Brisson and Hiller 2015). The FLS on the other hand is a pure imaging sonar, operating on 900 kHz, that creates a 2D image wedge (130°) on the front of the OFOBS with a radius of up to 100 m. It is used mainly for hazard avoidance in habitats with rough topography.

During PS101, the OFOBS was mainly launched over the A-frame of RV *Polarstern* to allow in-ice surveys with some level of manoeuvrability. During decent of the subsea unit, all systems are powered up and the INS starts the alignment process for self-calibration. Once the seafloor is visible, all subsystems start recording and the dive commences. Flight height can be adjusted in communication with the winch operator and in clear water, altitudes can range from 1.5 m to approximately 10 m.

3 Study area

The research aim of PS101 was to investigate geophysical, geological, geochemical and biological processes at seamounts in the ultra-slow oceanic spreading zone Gakkel Ridge (Boetius 2016). The main research area was located on the Langseth Ridge, one of the axis-perpendicular smaller ridges of the Gakkel Ridge, as well as adjacent regions in the Gakkel Ridge rift valley (Fig. 2).

The Langseth Ridge rises from the Nansen Basin at 85°55'N, extends over the Gakkel Ridge and descends into the Amundsen basin at 87°40'N. The highest elevation to the surroundings basin is reached at the Karasik Seamount with 585 m below mean sea level, which marks the shallowest feature in the Eurasian Basin (Boetius and Purser 2017). The flats of the summit are almost entirely covered by mats of living sponges, sponge spicules and dead tubeworm tubes with occasional stretches of sand (Fig. 3a+b). The steep slopes show less biology, but are built up by basalt formations and rock-faced cliffs (Fig. 3c). The investigated mound in the rift valley shows steep aggregations of pillow basalts (Fig. 3d) with sedimented fields on the flatter parts of the slope. On some locations smaller hydrothermal vents and precipitates protrude the sand and gravel (Fig. 3e+f). The foot of the mound is entirely covered with volcanic talus.

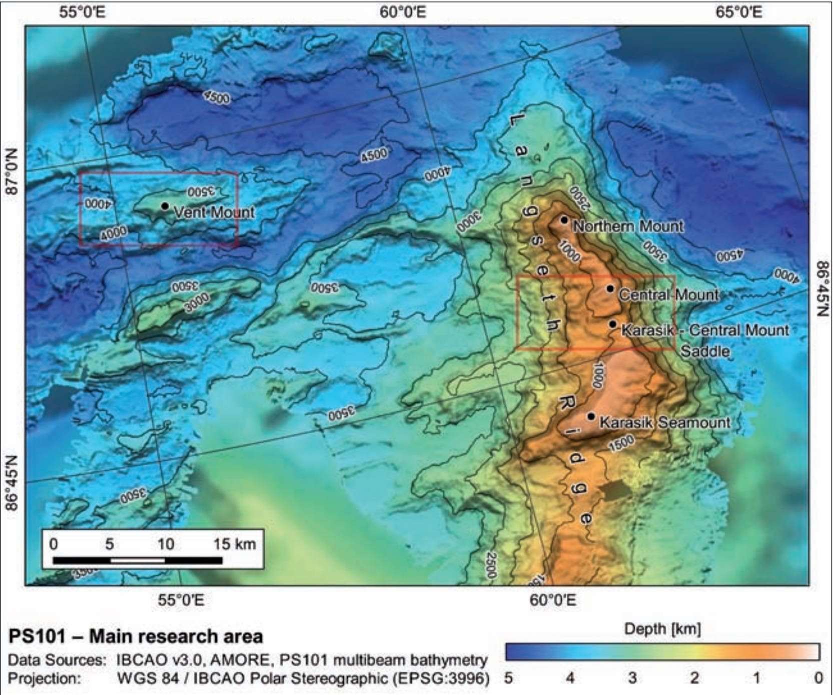

Fig. 2: Main research area on the Langseth Ridge. Red rectangles mark dive locations of presented datasets. Background bathymetry is from IBCAO, AMORE and PS101

The steep terrain caused a number of survey challenges. Operating close-range vehicles in such terrain is a demanding task and successful hazard detection is key during the dives. Additionally, the quality of the USBL deteriorates due to multipath effects and acoustic shadowing. Yet another challenge for the dives was located much closer to the operators. At 86°40'N and higher, the research area is situated below full ice cover throughout most of the year (Fig. 4). Conducting the individual dives required detailed planning along with observations of ice drift and direction as manoeuvrability was limited, even for the icebreaker *Polarstern*.

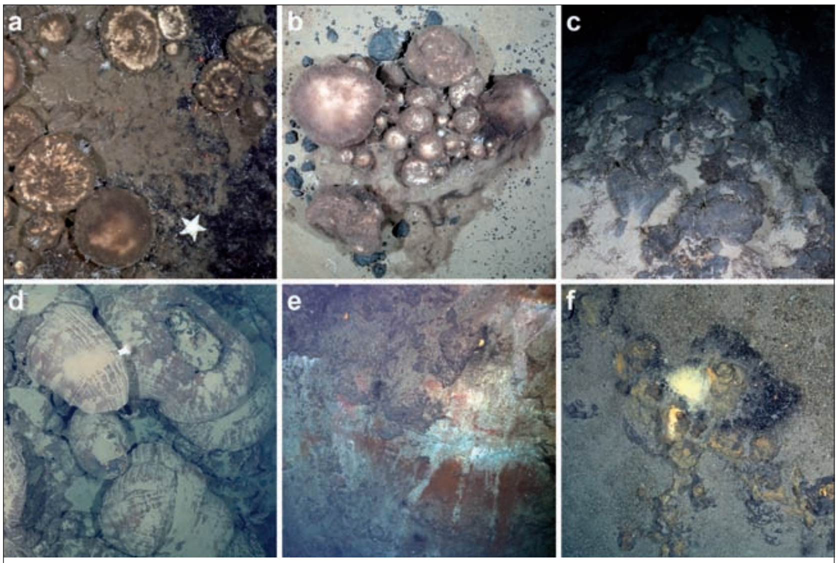

Fig. 3: Seafloor photographs from the research area. **a:** Sponge cover on the Karasik Seamount summit. **b:** Solitary sponges on the Karasik – Central Mount saddle flats. **c:** Rock-faced cliffs on the Northern Mount slopes. **d:** pillow basalt aggregates on the Vent Mount summit. **e+f:** hydrothermal structures on the Vent Mount slopes (Purser et al. 2017)

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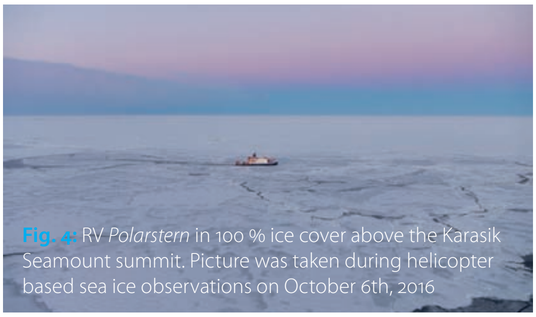

Fig. 4: RV *Polarstern* in 100 % ice cover above the Karasik Seamount summit. Picture was taken during helicopter based sea ice observations on October 6th, 2016

4 Raw data

During the OFOBS dives, a number of different raw data sets were collected as a basis for further processing. Navigation data was logged from the INS including high-precision attitude measurements. Still images were automatically triggered every 20 seconds as well as manually triggered on notable events. The video was recorded with 25 fps. The MPES data set contains dual frequency side-scan imagery with swath widths of 100 m (high frequency, 7 Hz) and 200 m (low frequency, 3.5 Hz), as well as binned bathymetry with 80 m swath width. Fig. 5 shows a schematic view of the OFOBS survey coverages. Still images and acoustic data sets are available in the scientific data warehouse PANGAEA (Dreutter et al. 2017; Purser et al. 2017).

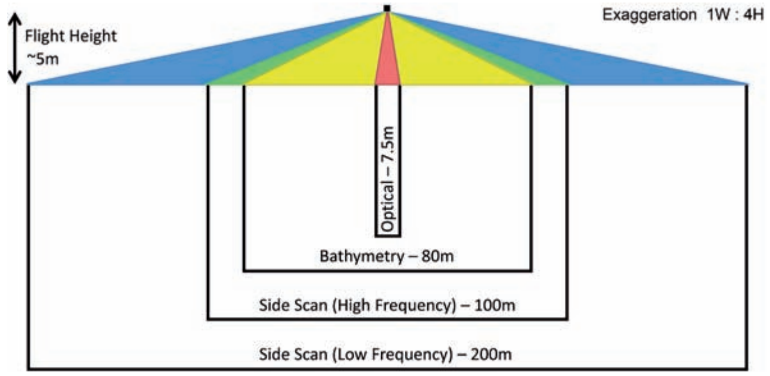

Fig. 5: Schematic coverages of the OFOBS sensors. Flight height is exaggerated by a factor of four with respect to the swath width. The coverage for the camera is only an approximation as it is highly dependent on the topography below the frame. The ranges of the acoustic systems are not altitude dependent and can actually be increased further. Yet, for the here described survey, the shown ranges have proven to be useful for a balance between range, data quality and temporal resolution of the soundings

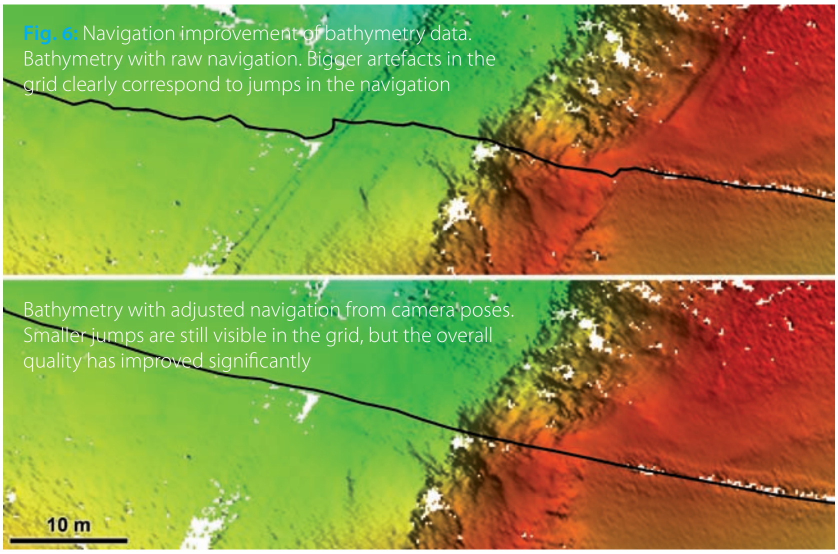

Fig. 6: Navigation improvement of bathymetry data. Bathymetry with raw navigation. Bigger artefacts in the grid clearly correspond to jumps in the navigation

Bathymetry with adjusted navigation from camera poses. Smaller jumps are still visible in the grid, but the overall quality has improved significantly

5 Data processing workflow

Originally, the OFOBS was intended to conduct bathymetric surveys with its onboard sonar systems, while the optical data was meant for visual interpretation and statistical mapping. However, throughout the experimental phase of the project, the optical data sets proved to be very valuable. Structure from Motion (SfM) techniques were investigated to align and georeference the imagery and to reconstruct 3D models of the captured seafloor. Combined processing approaches were incorporated in order to match the different data sets and to improve overall results.

5.1 Photogrammetric reconstruction

The reconstruction was performed with the SfM software Agisoft PhotoScan Professional, a program mainly developed for aerial photogrammetry that has already been used in underwater applications (e.g. Kwasnitschka et al. 2013). PhotoScan offers an integrated toolset for reconstruction, georeferencing and 3D modelling of the data. As input, the software takes both still images and extracted video frames as well as the navigation and attitude data from the INS, corrected for lever arms and angular bias.

The initial step is the alignment of the individual images by detecting matching points in multiple images. During this process, intrinsic camera parameters and camera poses are estimated and adjusted. The detected tie points form a sparse point cloud that can be filtered and manually cleaned for outliers, followed by further optimisation of the alignment. Once done, the adjusted camera poses can be exported for later use in the acoustic processing.

From dense stereo reconstruction PhotoScan can now compute a coloured dense cloud that gives a detailed representation of the scene. After further cleaning, this point cloud is used for creating digital elevation models (DEM) or for mesh triangulation to achieve a more coherent digital representation.

5.2 Side-scan and bathymetry

The acoustic data was processed in Caris HIPS and SIPS. Bathymetry was manually cleaned for erroneous soundings and side-scan data was corrected for slant range and beam pattern and additionally despeckled and normalised.

Yet, with the raw INS navigation the results showed unfortunate jumps in the bathymetry where navigation was obstructed by continuous false USBL readings. As mentioned above, part of the SfM process is the adjustment (improvement) of the imported camera poses along the alignment. As the exported camera poses are timestamped, they can be transformed back to the INS position and parsed onto the navigation records in the acoustic data set. This resulted in a significant improvement on the bathymetry and side-scan grids (Fig. 6).

6 Results

The acoustic bathymetry was sufficient to produce 20 cm cell sized raster DEMs (Fig. 7a) and the side-scan data could be mosaicked with 3 cm grid spacing for both frequency channels (Fig. 7b). For the optical data, microbathymetric grids were computed from the dense cloud (Fig. 7c). The cell size of the photogrammetry grids depends in the density of the point cloud, and for the processed scenes it came out between 2 and 6 mm. From the dense cloud a triangulated mesh was created for the digital representation (Fig. 7e) and for orthorectification of the images to achieve orthomosaics with cell sizes between 0.5 and 1 mm (Fig. 7d).

7 Discussion

7.1 Consideration of uncertainties

In land-based photogrammetry Ground Control Points (GCP) are often used to evaluate the reconstruction results. While it is theoretically possible to place GCPs under water, it is not feasible to do so in Arctic deep-sea environments. Hence, estimating the global uncertainties for the OFOBS survey results is a rather impossible task. One could calculate a total propagated uncertainty by relying on the theoretical measurement errors of the different systems. Yet, due to quality deterioration by the effects of e.g. sea ice and the missing position correction for the ships GNSS, position accuracy is very likely to be significantly lower than theoretically achievable.

Fortunately, the errors can be divided into global position errors and local errors in the results. While the global position errors have to be accepted as is, the multisensor data of the OFOBS and the described workflow offer additional possibilities to reduce the local errors and improve the relative results. Indicators for local uncertainties are, for example, the estimation of the intrinsic camera parameters, the estimation of attitude, as well as visual interpretation of the resulting products.

The cameras of the OFOBS were never intended to be used for photogrammetry and therefore never properly calibrated. Yet, camera calibration models are created within the SfM process and gave consistent results for all processed areas with only little variations. Another indicator is the distance of the laser dots in the orthomosaics. Measuring those on randomly distributed locations showed distance values within the calibration uncertainty of the position and placement angles of the lasers (49 to 54 cm).

Part of the reconstruction is the estimation of camera poses and the deviations from the initial attitude input. These can be exported and compared to the INS measurements. As the input accuracy for attitude was set to 2° in PhotoScan, reconstruction uncertainties of any kind can easily be loaded on to the attitude error. Sections with larger attitude deviations usually correspond to rapid vertical acceleration of the subsea unit or areas with higher flight height, hence, worse image quality. Yet, when looking at the errors plot (Fig. 8), the overall estimation can be considered very successful.

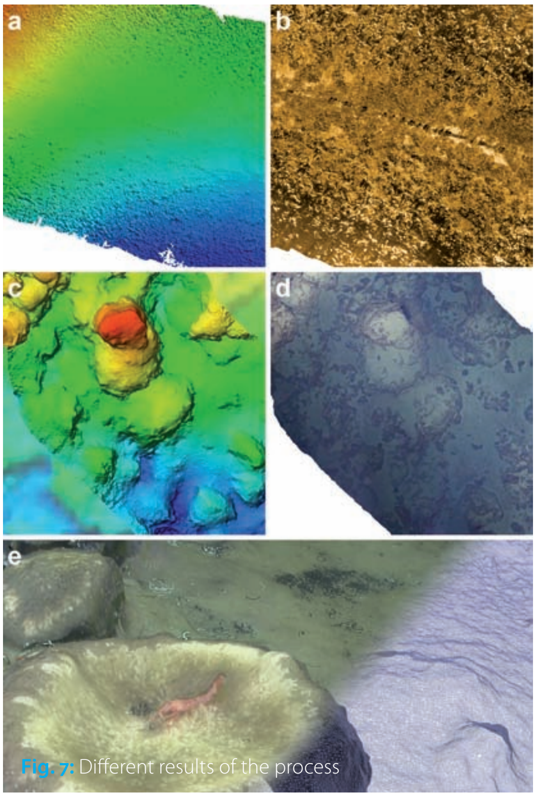

Fig. 7: Different results of the process

From the video it becomes clear that the OFOBS travels in a very smooth fashion without sudden movements to either sides of the track. Reconstructed navigation compared to INS measurements tends to give a more realistic view on those travel characteristics (Fig. 9). This can additionally be verified by visual inspection of side scan and bathymetry grids (Fig. 6), as navigation errors are often visible as image distortions and sudden jumps in topography.

7.2. Evaluation of the survey method

While concepts of deep-towed acoustic and optical sensors and the simultaneous collection of both have been around for some time (e.g. Dorschel et al. 2009; Kwasnitschka et al. 2016; Caress and Barr 2017), the OFOBS is a novel approach for high-resolution microbathymetry habitat mapping in deep-sea environments. As navigating deep-towed sensors is comparatively complicated, it has

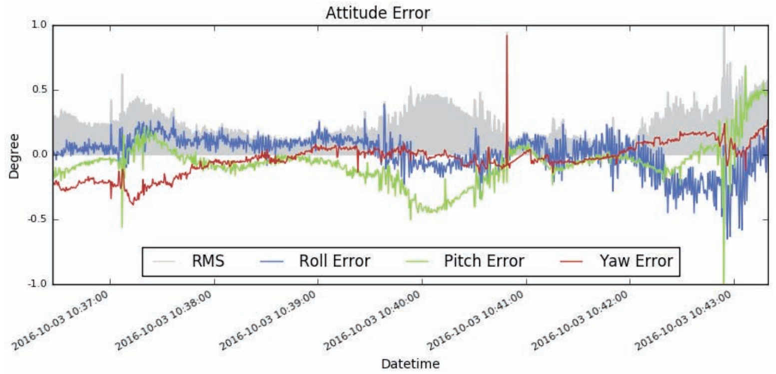

Fig. 8: Attitude error plot of reconstructed sample scene

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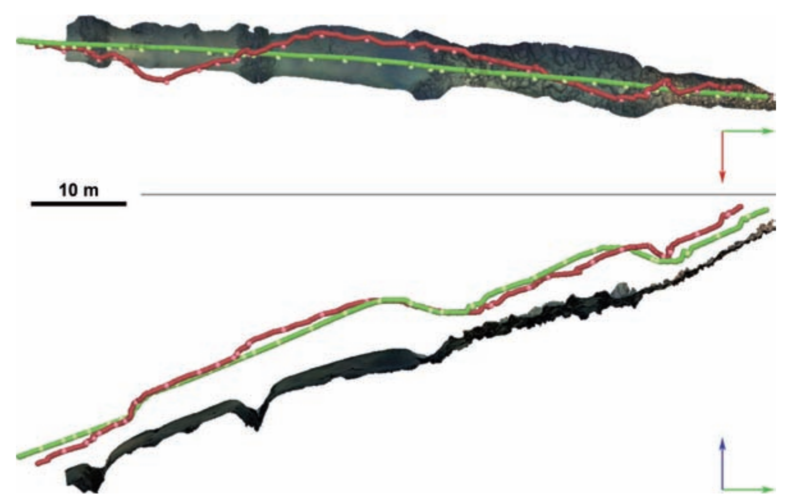

Fig. 9: Navigation adjustment in one of the sample scenes. Top view (upper) and side view on the model (lower). Red spheres mark camera positions imported from the INS log, green spheres mark bundle adjusted camera positions after alignment and optimisation. Lighter coloured spheres represent still images, darker coloured spheres video frames

a disadvantage regarding precision and coverage efficiency. Yet, compared to AUVs, the OFOBS has the capability to be operated in any kind of topography. Fin-steered AUVs often have a minimum speed required for manoeuvring, which limits the intensity of topographic variability of the seafloor in which the vehicle can keep a constant low flight height to avoid collision and vehicle loss. ROVs on the other hand are capable of harsh environment as well and have the additional upside of instant data feedback due to the tethered connection.

However, ROVs and AUVs tend to have high deployment costs, both in hardware and in terms of support/personnel. The OFOBS on the other hand needs a minimum of two engineers in addition to the ship's crew, and launch and recovery do not require specialised installation. The simplicity of the system keeps pre-dive preparation and post-dive maintenance to a minimum.

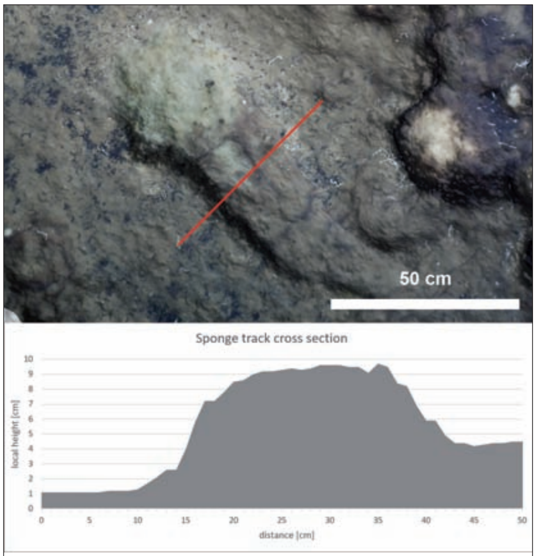

Fig. 10: Cross section of a track of spicules behind a dead sponge colony. The orthorectified still image is draped over the shaded bathymetry to enhance relief in the imagery. The red line represents the location of the 2D cross section

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The data used was collected during RV *Polarstern* cruise PS101, Grant No. AWI_PS101_01, a contribution to the FRAM project.

The sensor payload is highly customisable and at its current state very capable for the job at hand. The ability of the bathymetric side-scan sonar to keep a wide swath at low altitudes ensures high-quality optical data that can be used for instant ground truthing of acoustic results. This offers suitable data sets for a wide range of scientific analyses without the necessity of further investigation.

7.3 Contribution to related research and outlook

Benthic megafaunal populations are often very sensitive to slight geomorphological variations. Subjective observations made from the OFOBS video data showed that, for example, the settling behaviour of large Geodia sponge communities highly depends on the slope inclination of the terrain. With the high-resolution OFOBS bathymetry, it is possible to resolve very fine topographic variations, which allows a high number of habitat characterising analyses like rugosity, aspect, curvature, slope inclination, bathymetric position index, etc. These results can be combined with geostatistical observations made in the image mosaics to perform ecological niche factor analysis or similar statistical analyses.

The combination of bathymetry and imagery makes small-scale, three-dimensional shapes of features visible that can otherwise not be determined in the imagery alone. Fig. 10 shows an example for merging the two results for more advanced interpretation. The 3D models can additionally be used for volume calculations of geological features or biomass estimation by model subtraction.

8 Conclusion

This work has introduced the deep-towed Ocean Floor Observation and Bathymetry System as a novel survey tool for close-range, high-resolution, wide-swath habitat mapping in extreme environments of the deep sea. Throughout the project, the acquired data sets showed immense capabilities for a variety of analyses and high-resolution habitat investigation in post-dive digital fieldwork.

Despite the comparatively large overall position uncertainty of the results, the local offset between optical and acoustic data is not affected by this error as both data sets can be co-registered in post processing. In addition to the advantage of having multiple data sets for a larger number of potential analyses, the multisensor approach proved to be very beneficial for local corrections within the different processing steps and significant improvements in the overall results.

As the system is newly developed, a number of issues were identified during processing of the data sets. These issues were addressed in the thesis along with recommendations for the further improvement of the system and optimum setup of existing components for future surveys, with a particular focus on the optical data sets and the vehicle navigation scheme. After all, good scientific survey practice requires constant optimisation of the used instruments to the surveyor's best knowledge.