Peer-Reviewed Technical Communication

Ocean Floor Observation and Bathymetry System (OFOBS): A new Towed Camera/Sonar System for Deep-Sea Habitat Surveys

Autun Purser, Yann Marcon, Simon Dreutter, Ulrich Hoge, Burkhard Sablotny, Laura Hehemann, Johannes Lemburg, Boris Dorschel, Harald Biebow, and Antje Boetius

***Abstract*—Towed camera systems are commonly used to collect photo and video images of the deep seafloor for a wide variety of purposes, from pure exploratory research to the development of management plans. Ongoing technological developments are increasing the quantity and quality of data collected from the deep seafloor. Despite these improvements, the area of seafloor, which towed systems can survey, optically remains limited by the rapid attenuation of visible wavelengths within water. We present an overview of a new towed camera platform integrating additional acoustical devices: the ocean floor observation and bathymetry system (OFOBS). The towed system maintains continuous direct communication via fiber optic cable with a support vessel, operational at depths up to 6000 m. In addition to collecting seafloor photo and video data, OFOBS gathers sidescan data over a 100-m swath width. OFOBS functionality is further augmented by a forward looking sonar, used to aid in hazard avoidance and real-time course correction. Data collected during the first field deployments of OFOBS, at a range of seamounts on the Langseth Ridge/Gakkel Ridge intersection (86° N, 61° E) in the high Arctic in September 2016, are presented to demonstrate the functionality of the system. Collected from a location with near continuous ice cover, this explanatory data set highlights the advantages of the system for deep-sea survey work in environments currently difficult to access for the majority of subsurface research platforms.**

***Index Terms*—Acoustic devices, high-resolution imaging, oceanographic techniques, terrain mapping, underwater equipment, underwater technology.**

I. INTRODUCTION

IMAGE data from the deep seafloor have been collected by autonomous time series camera systems [1], [2], towed camera systems [3]–[7], manned submersibles, and remotely operated and autonomous vehicles [8]–[10] for decades. In recent years, digital imaging and illumination technology have reached levels sufficiently high to allow images to be collected, during motion, which allow even features of a few millimeters diameter to be resolved on images of seafloor [11]. Mobile fiber optic tethered platforms such as remote operated vehicles (ROVs) are capable of directly investigating discreet, user defined locations with high-resolution camera systems [12], [13]. The last decade has seen automated underwater vehicles (AUVs) [14]–[16], and hybrid remote operated vehicles (HROVs) [17]–[19] added to the list of vehicles capable of imaging the seafloor.

The spatial and temporal data resolution, which may be achieved, varies considerably between underwater imaging platforms. Deployment costs, (human support, financial cost, and support vessel availability), also varies by platform. Fixed location camera platforms, such as those used to monitor fish behavior [2] even in the extreme deeps of the World Ocean [20] can be reasonably cheap to deploy and generally require little supervision to operate, as well as facilitating data collection over extended periods of time [21], [22], particularly if coupled with cabled power and data infrastructure [23]. However, such systems can only investigate one location during a deployment. Towed systems rely on ship presence, and while suitable for imaging roughly linear transects of seafloor, transect courses are determined by towing vessel movement [24], [25]. Equipped with positioning systems such as Ultrashort baseline (USBL), the seafloor track, and flight height of these towed systems can be determined with a nominal precision of 6–10 m at 3000-m water depth. Although these towed systems image greater areas of seafloor than can be achieved with single location static camera platforms, the width of coverage remains limited by camera and illumination parameters. ROVs are complex, expensive vehicles (both financially and in terms of human support costs), though they can be directly controlled and are capable of imaging regions of deep seafloor over extended areas, commonly with highly accurate positioning. Although ROVs can be equipped with the capacity to conduct large-scale acoustical and photo mapping of seafloor structures [26]–[29], surveys are usually limited in spatial scope for logistical reasons, such as dive and ship-time availabilities. AUVs such as the Autonomous Benthic Explorer [30] and Sentry (WHOI) [31], platforms, which can operate during dives independently of the research vessel, are becoming increasingly adept at collecting spatially extended arrays of seafloor image and sensor data during programed automatic deployments [15], [16], [32]. Commonly, the data collected by AUVs are used to guide subsequent ROV deployments if high- resolution close-up imaging is required [15]. Ongoing developments in real-time optical or acoustical hazard avoidance techniques for AUVs [33], [34] may in the near future allow automated systems to image the seafloor in high detail directly. Current generation AUVs may also mount acoustical systems to allow

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Manuscript received June 6, 2017; revised September 6, 2017; accepted January 10, 2018. This work was supported by the "Managing Impacts of Deep-seA reSource exploitation" project funded by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant 603418. Initial dives of OFOBS were carried out during the PS101 cruise, under Grant AWI_PS101_01, which was a contribution to the ERC AdvG Project Abyss (under Project 294757), and the HGF Infrastructure Program FRAM. *(Corresponding author: Autun Purser.)*

Associate Editor: J. Potter.

A. Purser, S. Dreutter, U. Hoge, B. Sablotny, L. Hehemann, J. Lemburg, and B. Dorschel are with the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven 27570, Germany (e-mail: autun.purser@awi.de; simon.dreutter@awi.de; ulrich.hoge@awi.de; burkhard.sablotny@awi.de; laura.hehemann@awi.de; johannes.lemburg@awi.de; boris.dorschel@awi.de).

Y. Marcon is with the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven 27570, Germany and also with the MARUM Center for Marine Environmental Sciences, Bremen 28359, Germany (e-mail: ymarcon@marum.de).

H. Biebow is with iSiTEC, Bremerhaven 27570, Germany (e-mail: hbohlmann@isitec.de).

A. Boetius is with the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven 27570, Germany, the MARUM Center for Marine Environmental Sciences, Bremen 28359, Germany and also with the Max Planck Institute for Marine Microbiology, Bremen 28359, Germany (e-mail: antje.boetius@awi.de).

Digital Object Identifier 10.1109/JOE.2018.2794095

sidescan and bathymetry data to be concurrently collected with image data during deployments [27], [35].

The cost, complexity, and scarcity of ROV and AUV systems currently available for ocean research limits their use in basic science, such as for the mapping of habitats and spatial analysis of faunal community composition. Such spatial data are important framework data, underlying many aspects of ecosystem research, biogeographical studies, and also with applied applications, such as in impact assessment and habitat management. In addition, technological factors may also limit their use in high risk environments, such as regions with pervasive high swell conditions or under sea ice. To date, surveys of such environments have been predominantly conducted with towed camera systems, though successful AUV scientific deployments under ice are becoming more common [36]–[39] with forthcoming systems undergoing active development [40]. Here, we substantially enhanced the functionality of the existing ocean floor observation system (OFOS) [7], [25], [41], the latest iteration of the towed camera sled for Arctic work used by the Alfred Wegener Institute Deep Sea Ecology and Technology Working Group [25], by adding the capacity to additionally collect bathymetrical data during deployments.

Identifying bathymetric features of the seafloor is important for understanding the distribution of seafloor habitats, with multibeam and sidescan sonar systems commonly used in mapping these. Such systems are commonly mounted on the current generation of oceanographic and industrial survey vessels, and have been highly useful in improving the quantity of spatial data available on global seafloor topography. At time of writing, such ship mounted systems produce seafloor data sets of decreasing spatial resolution and quality with increasing water depth (e.g., 100-m grid resolution in water depths of 4 km is not uncommon). This limits their use in surveying discreet mesoscale habitat features, such as seamounts or ridge systems in the open ocean, rather than for smaller scale habitat mapping, such as determining the distribution of hard substrates, rocky outcrops, drop stones, nodules, and reefs. Recently, an increasing number of AUVs [38]–[41] and ROVs [46], [47] have been equipped with acoustical systems to obtain high-resolution bathymetry of such features, in some cases in combination with simultaneous photo and/or video image collection.

By combining acoustical systems with camera platforms towed in proximity to the seafloor, the volume of water the acoustical beams must traverse is greatly reduced. The image data collected via the platform cameras can then be effectively used to "ground truth" the collected sonar data, and scientific conclusions made from this image data (i.e., on biological distributions, resource abundances, etc.), and extrapolated over the larger areas surveyed by the sonar. Here, an integrated imaging and sidescan sonar towed system, with an additional integrated forward mounted imaging sonar, was developed and tested in the complex topography of the Langseth Ridge (86° 51.84′ N, 061° 30.34′ E). This perennially ice-locked region of the Arctic Ocean hosts one of the most northerly seamount complexes on the Earth [48]. We present an overview of this versatile towed system—the ocean floor observation and bathymetry system (OFOBS)—and additionally show examples of the raw and processed data products collected during the testing research cruise [49], demonstrating the versatility of such an platform for deep sea spatial mapping in highly complex and high risk areas of the world ocean.

II. METHODS

A. Instrument Overview and Deployment

The OFOBS consists of two primary platform components: 1) A topside unit mounted on the support vessel and 2) the subsea unit for deploying to the region of research interest. The topside unit is a ship-mounted rack unit, which supplies power and connectivity via a combined fiber optic/copper coaxial cable to the 6000-m depth-rated subsea unit. From the topside rack unit, two-way communication is also provided to various laptops running the positioning (see Section II-D), imaging (see Section II-E), and acoustical (see Section II-F) devices. These laptops allow the operator(s) to modify the operating parameters of OFOBS in real-time during deployments. The subsea unit consists of a sturdily constructed metal main frame containing the majority of sensors and equipment, with a secondary bathymetric sidescan unit mounted on the rear (see Fig. 1). Weighing 1 T in air, the subsea unit is compact enough to allow deployment either from the A-frame of moderately sized research vessels or alternatively via smaller winch systems. The purpose of the heavy frame is twofold—to ensure a heavy tether weight at the end of the deployment cable, and to allow the OFOBS to be flown without danger of damage in close proximity to rough, steep and solid seafloors, where collisions may occasionally occur. This design strategy was taken to allow regular deployments in regions where hazard avoidance may not be straightforward, or even possible with a winched system. The Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) commonly operate in deep high Arctic areas with ice cover hindering ships mobility and in areas with very steep seafloor relief [36], [49]. By using a robust framed towed system, sudden changes in ice flow direction or steep topographical changes can be borne, even if these changes happen too fast for the winch operator to avoid bottom contact. ROV systems, though equipped with thrusters, navigational aids, etc., may be at greater risk during similar deployments, and generally would have to operate in a more controlled and tentative fashion, surveying a reduced region of seafloor over a comparable deployment time. The robust OFOBS frame allows the deploying vessel to move at a greater speed, or drift with the ice, secure in the knowledge that seafloor contact will not damage the survey device or result in the end of a deployment. The subsea unit does not record data directly or carry its own power reserves, rather, both power and data are transmitted via the fiber optic/coaxial tether cable. Fig. 2 shows the connectivity of the various components of OFOBS, which are discussed in more detail throughout this section.

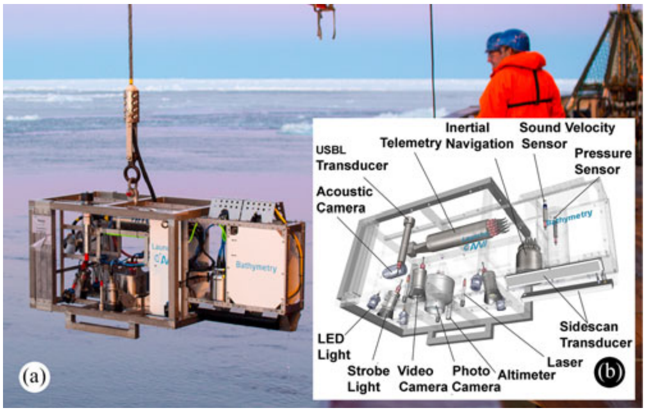


Fig. 1. OFOBS subsea unit. (a) Photographed during PS101 deployment during icy conditions. PHOTO: Frederic Tardeck, FIELAX. (b) Schematic of subsea unit.

B. Power Supply

A 600-V/700-W ac power supply is delivered from the topside unit via tether cable. The topside unit requires a 230-V ac power source

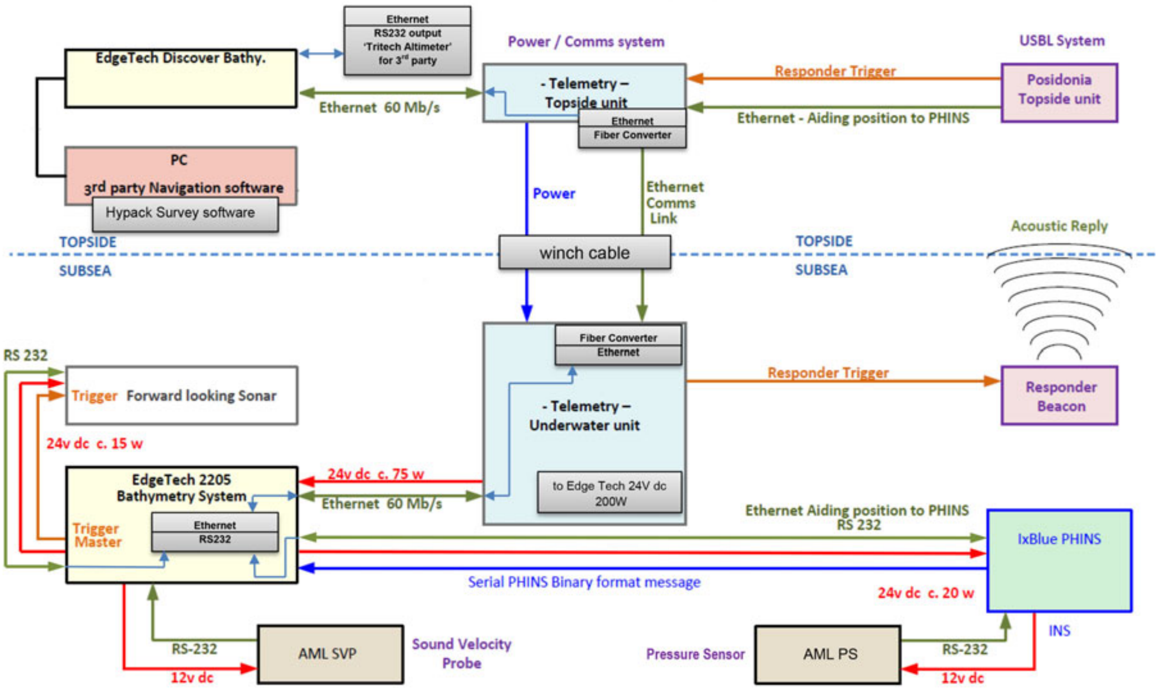


Fig. 2. Data and power diagram for the full OFOBS system, incorporating both the shipboard upper unit and the OFOBS subsea system.

from the support vessel for operation. A cabled power solution allows the power intensive illumination and sonar systems mounted on the OFOBS subsea unit to operate at a higher frequency than can be achieved by many autonomous systems, given the space and weight constraints associated with the design of those platforms.

C. Data and Communication

A bidirectional connectivity is maintained between the topside and subsea units during OFOBS deployments. The system has been tested successfully with several brands of ∼200-kN breaking strength 18-mm fiber optic cables [such as the Rochester Instrumentation and Control Cable (IM0030373PO00) and NSW Fiber Optic Tow Cable (101381)]. No data are stored on the subsea unit, with all collected data transmitted directly via the tether cable to the ship-mounted unit and appropriate instrumentation laptops for direct storage. This approach to data collection has numerous advantages over *in situ* data storage, including the facility for operators to directly inspect all collected optical and acoustical data for quality control upon collection, and to streamline the subsea system design by avoiding the requirement of mounting storage media on the subsea unit. Furthermore, this design solution ensures that following a serious failure/accident and loss of the subsea unit, all previously collected data are already safely stored on board. Further devices can be physically attached to the subsea unit frame, but each will require their own data storage and power solutions (see Section II-G), with live readout of the data from these additional sensors not possible by default.

D. Positioning

A USBL positioning system (iXBlue Posidonia) is used to track the position of the OFOBS subsea unit during deployments. Additional spatial accuracy is given from the output of the iXBlue PHINS inertial navigation system (INS) and AML Micro-X pressure sensor. This gives a stable position with an accuracy of approximately 0.2% of the slant range from the ship to the subsea unit, assuming suitable deployment angles, environmental conditions, etc. For the deployment, as discussed in Section II-J, the USBL position of the OFOBS subsea unit was interrogated and recorded every 3 s during the survey dive.

E. Imaging Systems

OFOBS is equipped with both a high-resolution photo camera (iSiTEC, CANON EOS 5D Mark III) and a high-definition (HD) video camera (iSiTEC, Sony FCB-H11). The cameras are mounted on a steel frame (235 L × 92 W × 105 H cm). Illumination is provided by four downward facing SeaLight sphere 3150 LED lights positioned in the corners of the main OFOBS frame, with two additional strobe lights (iSiTEC UW-Blitz 250, TTL driven). The LED lights provide a constant light source for the HD video camera, with the strobe lights boosting the image quality, which can be achieved with the stills camera under motion. By default, the photo camera records an image every 15 s, to remove observer bias in the data collected and to allow the strobe illumination to charge between images. This camera has additional functionality allowing "hotkey" images to be taken in addition to the timed images. These hotkey images can be triggered to record events, which would otherwise be missed by the timer system—for example, to record a transient fish swimming past OFOBS, or the random occurrence of a point of interest, such as a piece of litter or hydrothermal vent on the seafloor.

From an altitude of 2 m, both cameras image an area of approximately 6.5 m^2 of seafloor (highly dependent on seafloor topography), resulting in an average bottom resolution of 0.5 mm in the orthorectified still images. An increase in flight height increases the area, which can be imaged, though this also reduces acquired image brightness, given the reduced flux of illumination reflected from the more distant seafloor.

F. Sonar Systems

The sidescan bathymetry sonar is an interferometric EdgeTech 2205 AUV/ROV MPES (multiphase echosounder) with two sidescan frequencies (low/LF: 230 kHz and high/HF: 540 kHz) for different range and resolution achievements [50]. The transducers additionally hold bathymetric receive arrays to calculate bathymetric 2.5D data in the range of the 540-kHz sidescan sonar with around 800 data points per ping. A range setting of 100 m for LF and 50 m for HF results in a ping rate of around 3.5 Hz for LF and 7 Hz for HF.

The forward looking sonar is a BlueView M900-130 acoustical camera [51], mounted 5° downward from the horizontal on the front of the OFOS, giving a view angle of 130°. The primary function of the device is to aid in hazard avoidance via real-time modification of the ships heading, particularly on modern research vessels equipped with dynamic positioning systems. However, it may also provide scientific output during some deployments, such as for the detection of gas bubbles in the water column in cold seep areas, or give some indications on the geology of steep slopes in canyon or seamount areas. The acoustical camera takes a new image approximately every half second.

The main aim of equipping the existing OFOS with the acoustical systems was to increase the survey range of the platform to augment the seafloor photograph data with lateral swathes of acoustical habitat data provided by the sidescan sonar. While the cameras capture an area with a diameter of approximately 1.5 times the flight height, the sidescan sonar ensonifies the surrounding area with ranges of 50 m (HF) and 100 m (LF) on both sides of the vehicle. With flight heights of between 1.5–3 m, this coverage is frequently disturbed by shadow effects of higher objects such as rock formations as well as steep slopes. Fig. 3 shows a schematic of the data coverages, which can be expected from the OFOBS optical and acoustical systems during a typical deployment.

G. *Auxiliary Sensors*

Aside from the camera and acoustical systems, real-time depth information is available from the integrated USBL system (see Section II-D). Additional sensors, such as conductivity, temperature, and depth sensors, miniaturized temperature loggers, and miniaturized autonomous plume recorders [25] may be mounted on the OFOBS subsea frame to record and monitor various physical and chemical parameters (temperature, pressure, conductivity, turbidity, and redox potential), depending on the research or monitoring interests of the deploying team. Timestamped data collected by these sensors may be combined postdeployment with the real-time data collected by the camera and sonar systems, to determine whether changes in measured parameters within the water column are correlated with changes in seafloor relief, feature occurrences (e.g., vents or pockmarks), or seafloor community structure.

H. *Concept of Operations (CONOPS)*

The OFOBS may be operated near continuously from the research vessel, given the data and power connectivity provided to the subsea unit via the umbilical cable. To do so requires the availability of a suitable operational team.

1) Operational Team: For 12-hr deployments, a team of four is optimal for the OFOBS device, plus a winch operator:

a) *Overall systems engineer:* A dedicated systems engineer is required to ensure the full suite of OFOBS subsea systems and sensors are operating and communicating with the topside unit correctly.

b) *Acoustical engineer/technician/scientist:* An engineer, appropriate technician, or well-trained scientist is required to operate the acoustical systems correctly. Interpretation of acoustical data can be challenging, particularly when exploring unknown regions, where little is known of the acoustical properties of the seafloor. Potentially, a generalist OFOBS scientist can be supported by the overall systems engineer in interpreting the collected data, if they are not fully experienced and adept in interpreting acoustical data. During the test cruise (see Section II-J) an experienced bathymetric technician was employed to ensure accurate acoustical data were collected during deployments. In regions of steep seafloor relief, the acoustical team member can keep an eye on the forward imaging sonar system to ensure the winch operator is warned of any approaching steep rises.

c) *Imaging scientist/engineer:* The third member of the team oversees the imaging data collected by the subsea unit. This member makes sure all video data and timed image data are collected and recorded in a standardized fashion, that it is in focus and taken from an appropriate altitude. Commonly, the imaging team member is in near continuous communication with the winch operator, advising on height corrections required to maximize the usefulness of collected data and to aid in hazard avoidance.

d) *Navigator (optional, deployment specific):* A fourth member of the team may be required to monitor and record the position of the subsea unit within a geographic information system (GIS) framework in real time, and to communicate with the bridge to request modifications to the course headings in response to weather conditions, ice conditions (if applicable), or changing research requirements. During dives, a digital log is maintained by this team member, noting observations of interest made by the rest of the team, for rapid re-evaluation after dive completion. This forth team member is not essential for most deployments, where any occasional required changes in direction can be requested of the bridge by other team members, but in areas with complex poorly surveyed seafloor or challenging surface conditions, their presence can greatly support a deployment.

e) *Winch operator:* A winch operator from the vessel crew is required to raise and lower the OFOBS subsea unit through the water. The winch operator should ideally be able to see the live video and image stream from the subsea unit, but as a minimum the altimeter from the device should be visible. The operational crew should be able to communicate directly with the winch operator to ensure a suitable flight height is maintained.

2) OFOBS Deployment and Operation: Setting up OFOBS for a research cruise is a reasonably straightforward process. At the start of a cruise, the topside unit is mounted and connected to laptops running the various onboard imaging and acoustical systems. These laptops should ideally be positioned in a location where the operating OFOBS team can communicate with the ships winch operator directly, as the nature of the collected data can allow the scientists to assist the winch operator in: 1) avoiding obstacles and 2) prepare changes in flight height to best investigate the approaching terrain.

After setup of the topside unit and instrumentation laptops, the topside unit is connected to the winch cable and the OFOBS subsea frame. At this point, any auxiliary, mission specific sensors may be mounted onto the frame and primed for use (see Section II-G). Live powered connection to the subsea unit is not started until the OFOBS is winched off the deck and into the surface waters—a safety protocol maintained due to the high system power load.

Once in the surface waters, the full OFOBS system is powered up and the various instrumentation turned on, with each checked for reading stability and data quality. This process usually takes 5–10 min, after which the subsea unit is lowered through the water column to the required operational height. Traditionally, the AWI-OFOS system has

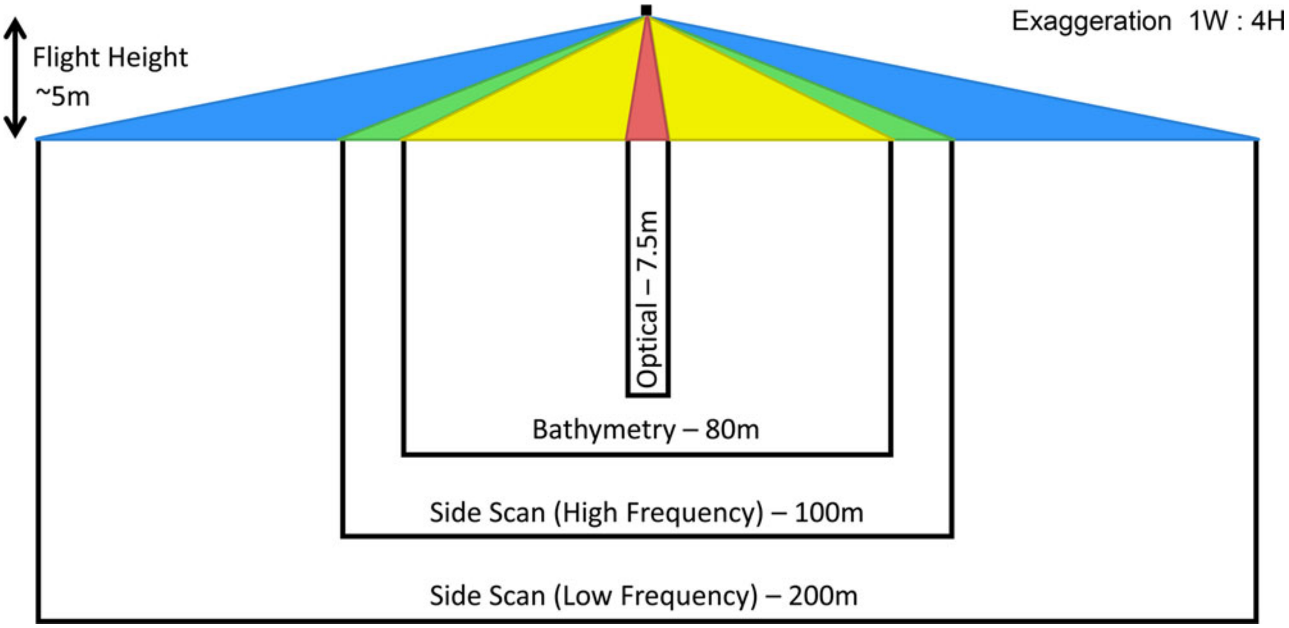


Fig. 3. Schematic diagram of the OFOBS subsea unit optical and sidescan data collection swath widths achievable from a flight height of 5 m.

been used to image the seafloor from a height of 1.5–2 m to achieve a resolution suitable for the identification of fauna of 1.5-cm diameter in clear waters [7], [25]. The OFOBS can also be used to image the seafloor with less light intensity from heights up to 8-m above seafloor, though with a progressively reduced ability to delineate features, fauna, and points of interest. However, this higher deployment height does allow the sidescan sonar system to increase survey coverage. During deployments, the height of the system can be manually controlled by the winch operator, to avoid obstacles, follow gradient changes in the seafloor, or to modify the sidescan/image coverage as appropriate for the research topic.

Throughout the process of lowering of the subsea unit, the USBL positioning system (see Section II-D) allows direct import of its position into an "on the fly" position display solution. GIS software is used for this, mapping in real time the position of the OFOBS subsea unit, the survey vessel, and other transponders in the vicinity (i.e., deployed Landers, AUVs, etc.,) directly onto a base bathymetry map.

Upon reaching the operational depth, the various instrumentation laptops are triggered to commence recording data and the towing vessel is issued with instructions on how to proceed with the survey plan. Both vessel heading and speed can be modified as desired, in response to research interests (e.g., to reduce speed and therefore carry out a more detailed survey in a particular area of interest), for safety (lower speeds more appropriate in areas of complex topography) or for operational reasons (e.g., to maintain a navigable course and speed under unfavorable weather conditions).

I. *Data Analysis Workflow*

Following the completion of a survey, the collected data sets are processed on the appropriate laptops and backed up to a permanent storage server also carried on board. The subsea unit is then returned to the surface for cleaning, inspection, and stowage until next required for deployment.

Analysis of still image data can be done with any image analysis software, such as ImageJ [52] or BIIGLE [53]. For the initial test cruise deployments, PAPARA(ZZ)I version 2.5 [54] was used to log geological and biological features throughout the collected images. Video data were labeled manually using the online MARVIDLIB system [55], with frames extracted from the video for use in the production of georeferenced photomosaic maps of areas of interest using the LAPM mosaicking tool [29] and the Agisoft PhotoScan software application [56]. Sidescan sonar data are initially inspected in the EdgeTech "Discover Bathymetric" software application, with bathymetry postprocessing being carried out in "Hypack," "Caris HIPS and SIPS," or any similar application. The mosaicked video frame data and postprocessed sonar data may be combined within any GIS system.

J. *Langseth Ridge Deployment*

The first research cruise for the new OFOBS was the PS101 cruise with *RV POLARSTERN* to the Langseth Ridge (86° N, 61° E) and the adjacent regions of the Gakkel Ridge in the high Arctic (see Fig. 4), September 8–October 23, 2016. The primary objective of the OFOBS deployments was to determine the high resolution morphology and structure of a number of northerly seamounts, and of various other locations of interest on the Langseth Ridge and within the surrounding area. Like many seamounts, those of the Langseth Ridge are characterized by steep and complex flanks (comprising of both gentle slopes and vertical terraces of 10 s of meters height) and flat, level summits—an ideal mix of topographies to test the OFOBS. A site of particular interest was the Central Mount, (723-m depth, 86.47° N, 61.8° E) separated from a more southerly peak by a saddle feature, with a maximum depth of ∼1300 m (see Fig. 4). The *RV POLARSTERN*, though at time of writing in excess of 30 years old, is a well maintained and regularly refitted research ship. During cruise PS101, it was fitted with an integrated 8000-m fiber optic cable suitable for deploying a range of ROVs and cabled systems such as OFOBS. To demonstrate the versatility of the OFOBS system for use on other research vessels, a self-contained 6000-m fiber optic winch system, which can be mounted on any reasonably sized vessel, was additionally brought on the PS101 cruise.

Within this paper, we present data collected during part of the PS101/169-01 OFOBS deployment to survey this peak, conducted dur-

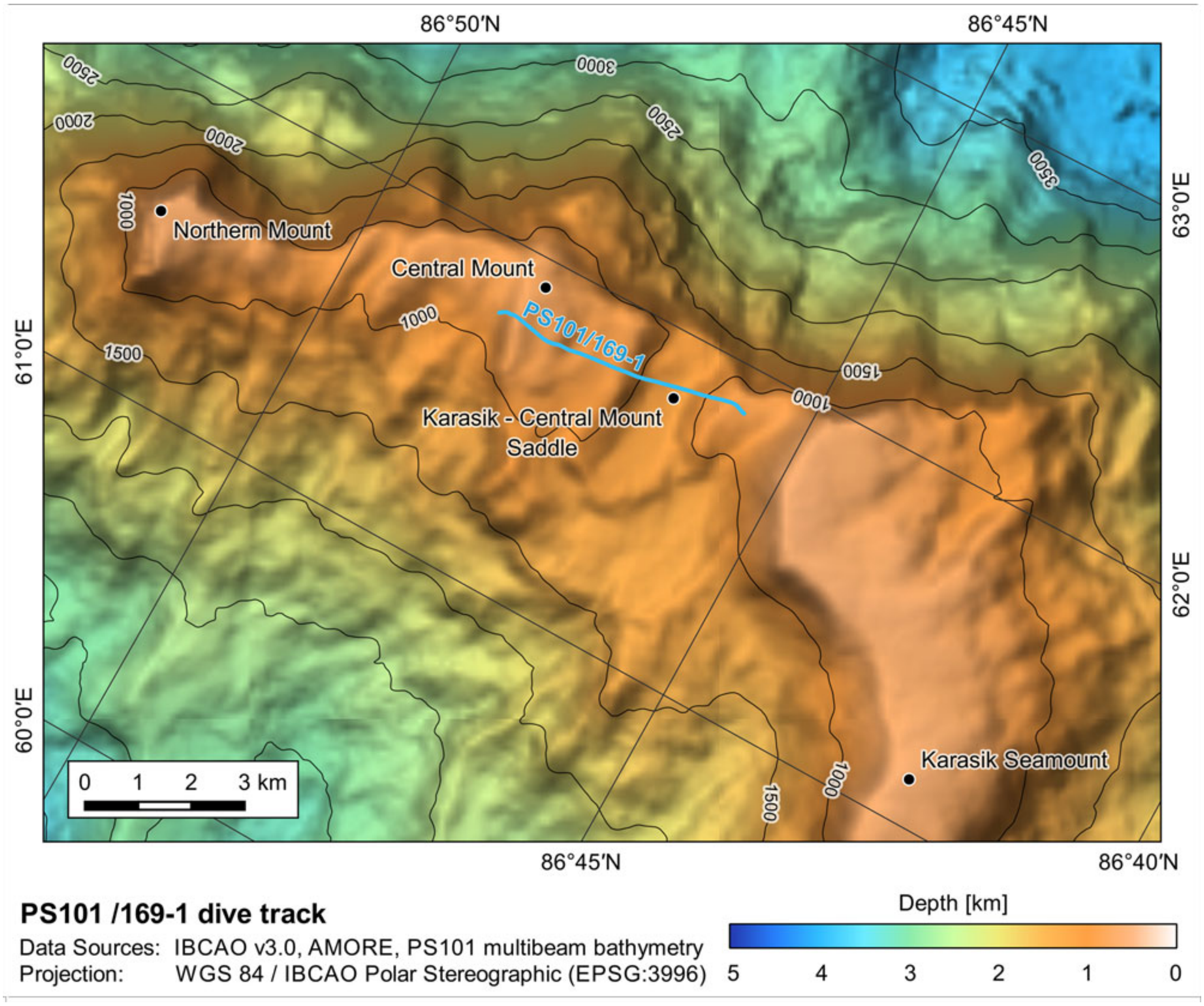


Fig. 4. Three seamount peaks surveyed with OFOBS on the Langseth Ridge, high Arctic, during cruise PS101 in 2016. Dive 169 covered one sponge covered seamount peak ("Central Mount") and a saddle feature separating this from a more southerly peak ("Karasik Seamount"). Examples presented throughout this paper originate from this dive. Bathymetry is from the International Bathymetric Chart of the Arctic (IBCAO, Version 3.0) [57], higher resolution multibeam bathymetry was conducted during AMORE [58] and PS101 [59].

ing September 30–October 1, 2016. Example data collected from all instruments, together with data processing products, are given in the results section. All dive track navigation data are available directly from PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.871545).

III. Demonstration Deployment Results and Discussion

During the PS101 cruise, OFOBS was successfully deployed 15 times. Details of all deployments, and links to collected data, can be found in the open access cruise report [49]. In total 15 deployments were made using both the integrated *RV POLARSTERN* winch system and a 4000-m standalone 18-mm fiber optic winch system. The main A-frame of the ship, as well as the secondary side crane were used in deployments, as a function of ice coverage and the particular dive plan intended. The majority of the 15 deployments were made with the RV POLARSTEN actively under power, either following leads in the ice or during the breakage of thin ice. Several deployments were made with the ship primarily in drift mode, locked in the ice, with only minimal ship engine use. During all deployments no significant vertical displacement associated with sea state or sudden ice movements was experienced, so the importance of an integrated heave compensation system in determining collected data quality was not fully tested. OFOBS PS101/169-01, a typical exploratory deployment conducted under 0.1 kt power, cut across the Central Mount and the saddle feature separating this from the southerly Karasik Seamount, collecting data from a range of terrains and from various faunal communities. Data from the visual and acoustical systems are presented here to show the versatility of OFOBS, and present an approach to processing the collected data.

A. Still Image Data

The PS101/169-01 OFOBS deployment collected 1002 still images of the saddle. From a height of ~3 m the OFOBS still image camera could be used to distinguish fauna and features of >1 cm size. The

1002 images covered a total area of ∼20 000 m^2 (roughly 20 m^2 each). For a description of the image annotation process and fauna of the region, see Section III-G. The full raw image data set is available on PANGAEA: (https://doi.pangaea.de/10.1594/PANGAEA.871545)

B. Video Image Data

HD video data were collected for the entire length of the dive and uploaded to the MARVIDLIB video data depository (www.marvidlib.de). In addition to visually recording, every seafloor feature and all fauna from the OFOBS field of view for the entirety of each deployment, frames were extracted from the video data to augment the data set collected with the still image camera. These additional frames can be used for mosaicking and photogrammetry (see Section III-E).

C. Sidescan Sonar Data

The raw data from the EdgeTech sidescan sonar system were recorded throughout the entire survey, covering a region of 500 000 m^2 (200 m × 2500 m). These data were not visualized or georeferenced on acquisition (rather they were displayed as "waterfall" lines of data, with each horizontal line of data representing a measurement, regardless of the speed of movement of the subsea unit, see Fig. 5). Sidescan sonar data represent acoustical seafloor reflectance amplitude over time (range). The "leading edges" or facing sides of hard features appear as bright linear features in the data. Areas where no reflecting surface is present, such as the central regions of the fissures in Fig. 5, appear as darker areas in the waterfall display. Behind distinct objects on the seafloor, an acoustical shadow is present that gives additional information on size and shape of the ensonified object, such as the large feature on the right of the sidescan waterfall in Fig. 5. All raw acoustical data from this deployment are available on PANGAEA at doi: 10.1594/PANGAEA.873046.

D. Forward Looking Sonar Data

All forward looking sonar data were recorded throughout the PS101 survey dives successfully, although the primary use of the system was for aiding in the real-time avoidance of approaching obstacles rather than for testing a scientific hypothesis. These data were not further processed for this deployment, though such oblique sonar data may also be integrated into the production of improved bathymetric products, particularly in areas with steep relief. As with the sidescan acoustical data displayed in the real-time waterfall displays, features of interest can be readily seen in the live output of the front sonar system, such as the fissures in Fig. 5.

E. Image Mosaicking, Photogrammetry, and Image Notation

The high-resolution quality of the image and video data collected via the OFOBS system allow the images and frames to be readily imported into commercial image alignment systems and extended mosaics of the transect imagery produced. In Fig. 6, photographs and video frames collected above a region of the Central Peak abundant in sponges have been mosaicked using the Agisoft PhotoScan software application. As the position of the OFOBS is accurately known from the INS, these submillimeter resolution mosaics can be georeferenced. The uniform angle from which the seafloor is photographed and filmed (from directly above) and the high amount of imaging overlap between subsequently collected video frames allow local subcentimeter three-dimensional (3-D) models and microbathymetry grids of the imaged seafloor using Structure from Motion techniques in Agisoft PhotoScan.

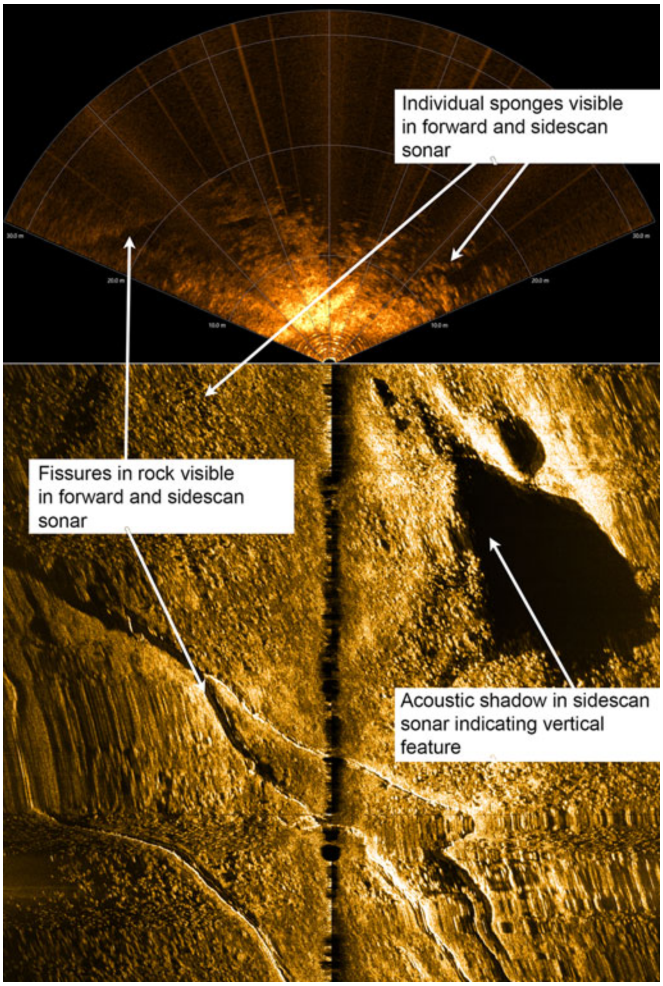


Fig. 5. Raw acoustical data collected via OFOBS from the seamounts of the Langseth Ridge. (a) Output from the forward looking sonar and (b) the sidescan sonar "waterfall" of reflectance data, with each line of data collected at a user defined frequency, timestamped on collection for later combination with positioning data from the USBL/INS systems.

In Fig. 7, the various stages of this workflow within PhotoScan are demonstrated. In Fig. 7(a), a "point cloud" of distinct seafloor features identifiable from across a number of subsequent images is generated in 3-D. From these points, a 3-D model can be derived, triangulating the surfaces between points [see Fig. 7(b)]. Finally, the orthorectified image mosaic (see Fig. 6) can be accurately draped over this model. As with the 2-D mosaic, if position of the OFOBS at time of image collection was well known, this 3-D model can also be georeferenced. There are numerous applications for such models, with these data products allowing the spatial relationships between seafloor features (fauna, vents, lava flows, drop stones, etc.,) and topographical variables such as rugosity, aspect, curvature, etc., to be investigated using ecological niche factor analysis or similar statistical approaches on a very local scale [60], [61].

In Fig. 8, the upper surface of a sponge from the area mosaicked in Fig. 6 is shown as such a model. This model presents much more information than a 2-D equivalent: The upper surface of the sponge is now seen to be clearly concave—information not apparent from the initial image data or the 2-D mosaic product. Further, a shrimp can be seen in relief within this concave sponge top. This high-resolution 3-D spatial data can be coregistered to the bathymetry provided by the acoustical

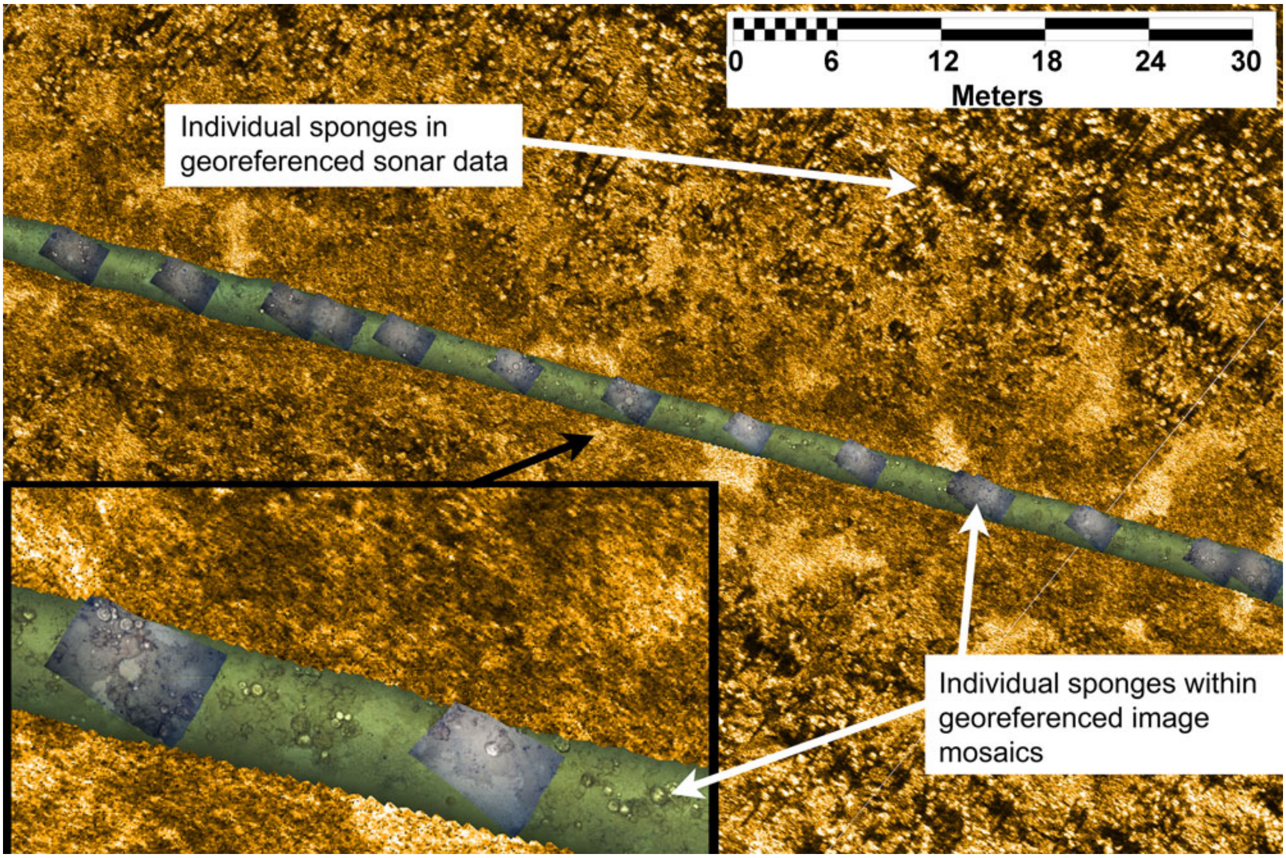


Fig. 6. Example of sidescan sonar data georeferenced and integrated into a photomosaic derived from the still image and video data frames collected throughout each survey dive. Here, individual sponges of some 5–35-cm diameter can be identified directly in both the image and sonar data.

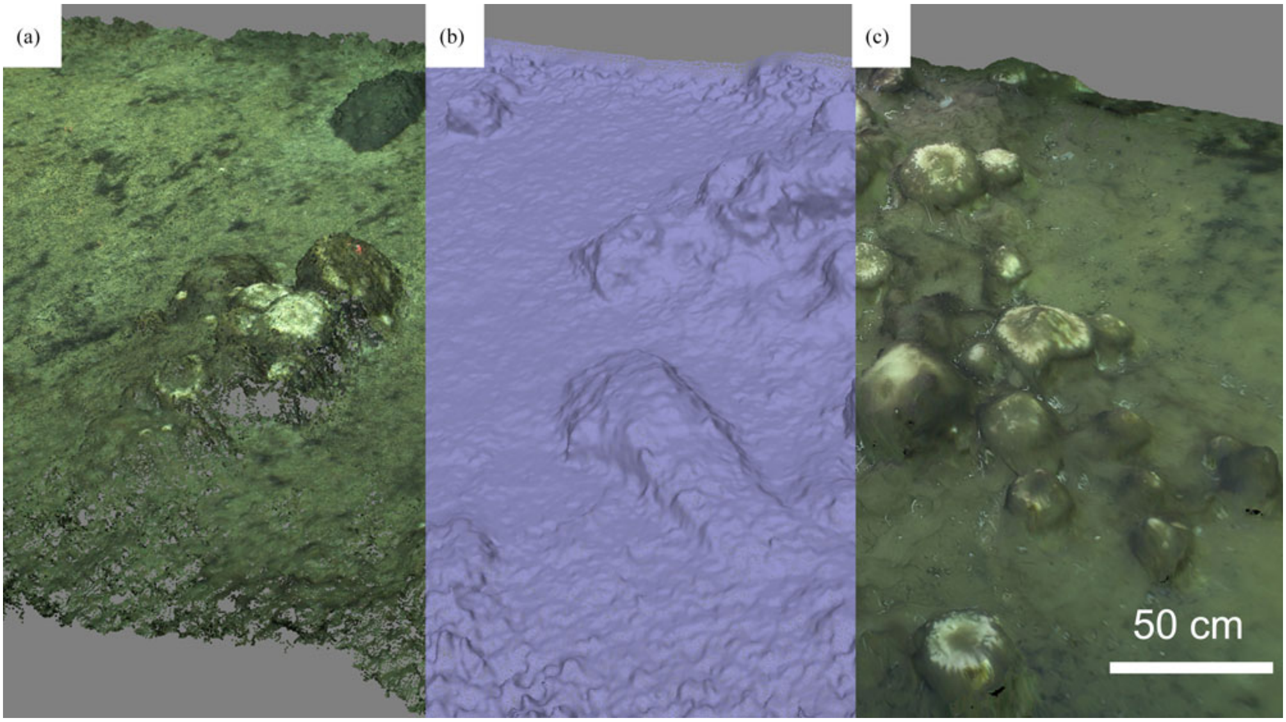


Fig. 7. High resolution, spatially referenced 3-D models can be derived from the still and video image frames collected during a dive. Processing of these frames can be conducted using the Agisoft PhotoScan software application. (a) Point cloud of distinct seafloor points identifiable in sequential images is initially determined. (b) From this point cloud, a 3-D model of the seafloor is produced. (c) Image mosaic is then draped over this 3-D model.

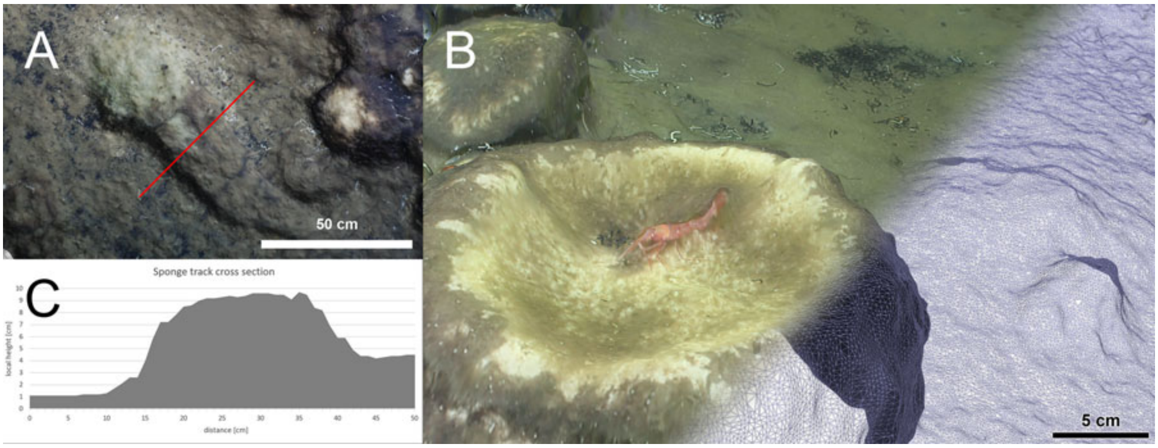


Fig. 8. Three-dimensional models can be used to elucidate various aspects of ecosystem functioning and development. (a) Sponge has died on the seafloor after moving some distance over time by the extrusion of numerous spicules. This movement has resulted in a significant 3-D trail feature on the seafloor, as can be seen in the cross section. (b) These spicules have left a ridged structure on the seafloor, still present after the death of the producing organism, resulting in a local alteration of hydrodynamic and seafloor physical condition. (c) On the Langseth Ridge a range of sponge morphologies are present. In this image, a barrel-like demosponge with a concave upper surface is providing a useful niche for the occupation of a shrimp. The 3-D model makes the concave nature of the sponge surface much more apparent, as well as also showing clearly that the shrimp is directly in contact with the sponge, rather than swimming above it.

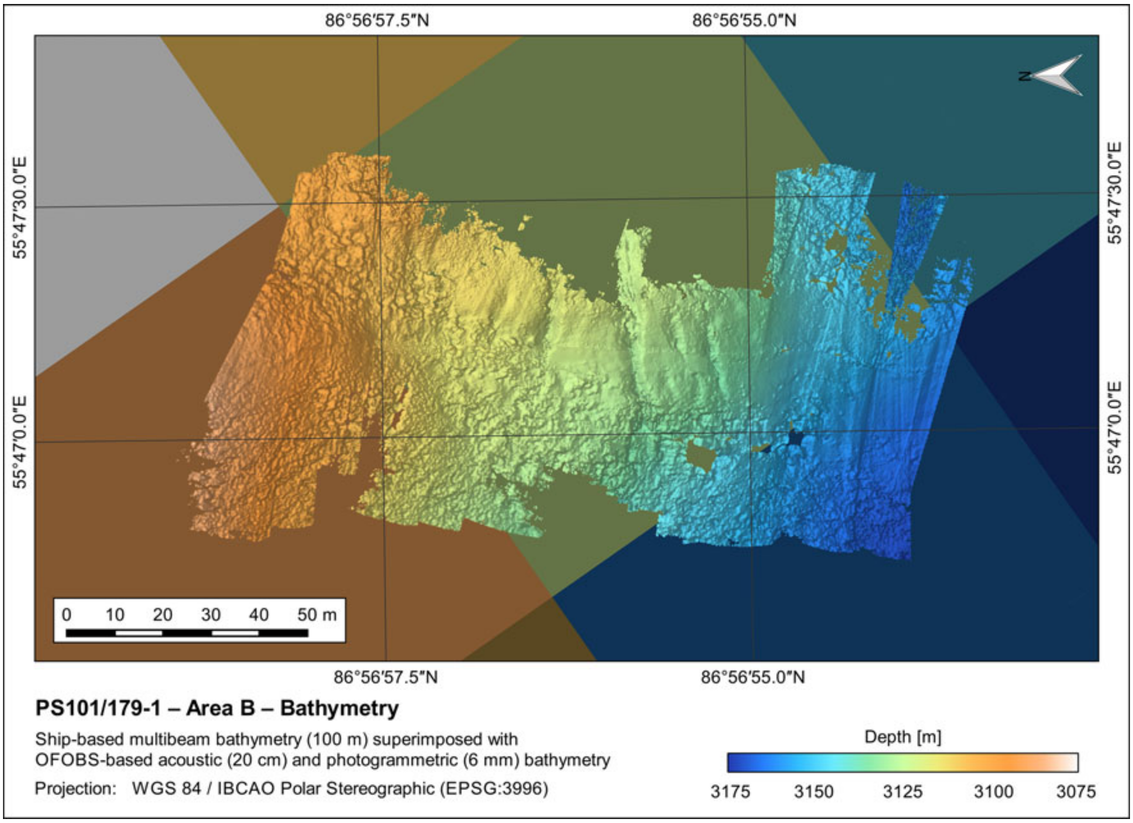
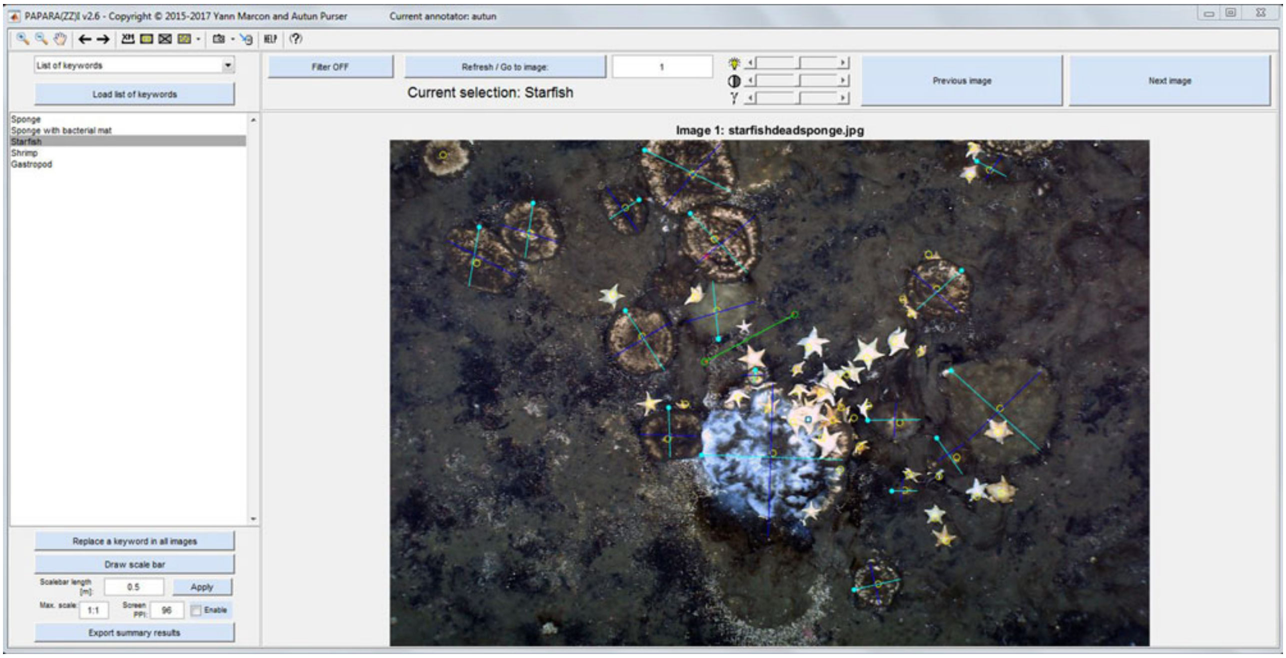


Fig. 9. Bathymetry generated from ship mounted systems, OFOBS sidescan, and photogrammetry based on OFOBS still image and video data for the PS101-169 OFOBS deployment.

system. By making such 3-D photogrammetric models from the data collected throughout a surveyed region, questions such as whether such concave topped sponges are preferentially favored by shrimp as sites of refuge or rest can be investigated. The photogrammetric model can also be imported into a GIS system and integrated with the coarser bathymetry generated by shipbourne and OFOBS acoustical data (see Fig. 9).

F. Processed Bathymetry Data

In addition to the sidescan sonar waterfall data being useful for real-time monitoring during deployments, postprocessing of the data allows the sidescan bathymetry to be spatially mapped using the Hypack, Caris HIPS and SIPS, or similar software packages, providing accurate positioning data for the OFOBS at time of collection is available.



PAPARA(ZZ)I v2.6 - Copyright © 2015-2017 Yann Marcon and Autun Purser

Current annotator: autun

Current selection: Starfish

Image 1: starfishdeadsponge.jpg

Refresh / Go to image: 1

Scalebar length [m]: 0.5

Max. scale: 1:1

Screen PPI: 96

☐ Enable

Fig. 10. Typical still image collected via the OFOBS system of a region of sponge covered seamount peak of the "Central Peak" of the Langseth Ridge, as viewed in the PAPARA(ZZ)I v2.6 annotation software GUI. The green line joins two red laser points of known spacing (50 cm), allowing the seafloor features and fauna to be scaled automatically.

In Fig. 6, the processed sidescan mosaic collected from the saddle collected during PS101/169-01 can be seen, overlaid by the photomosaic produced from the image data collected in parallel. By combining seafloor bathymetry information with observations made in the simultaneously collected image and video data (such as fauna, or geological features, Section III-G), the acoustical system can spatially map these features of $\sim$>10-cm diameter across the whole of the width of the acoustically surveyed swath. In Fig. 6, individual sponges identified in the imaging data can also be identified in the sidescan data. These sponges are so well defined in the acoustical data that the ground truthing provided by the imaging systems allows this fauna to be accurately mapped with confidence in interpretation across an extended area of the seafloor; the width of the acoustical swath.

G. *Feature Quantification in Image and Acoustical Data*

For the quantification of features of interest an image annotation stage is required, either prior or after georeferenced mosaics have been produced from the collected data. For the PS101/169-01 dive survey, the PAPARA(ZZ)I 2.5 software application was used for annotation of fauna and features of interest [62]. Within Fig. 10, a still image of seafloor taken on the Langseth Ridge with OFOBS, various sponges can be seen in the PAPARA(ZZ)I GUI. The three lasers mounted on the OFOBS allow the scaling of images, with the green line annotated via the software and representing the 50-cm spacing between two of these laser points. Various sponges are marked within the image, with the pairs of light blue and dark blue lines manually entered to quantify the maximum and minimum diameters of these oblate spheroid forms. Numerous starfish have also been marked as point features. A feature of interest within the image is the large (>50-cm diameter) central sponge, on which a bacterial mat can be seen. This sponge appears to be the loci of attraction for the starfish arrayed around it. Within PAPARA(ZZ)I, every label is identified by pixel coordinates within the image, and given the scaling of the image provided by the laser, the relationship between labeled features can then be analyzed using any spatial statistics appropriate for a particular research question. For this image, and for the others collected during the survey transect, hypotheses which might be investigated using OFOBS and the workflow discussed within this paper could include "Starfishes on the surveyed seamount are preferentially found within a proximity of *x* m from bacterial mat supporting sponges," "sponges on the surveyed seamount exhibit a convex upper surface on reaching an average diameter of *x* m," "individual sponges maintain an average spacing from neighbors of *x* m although they form loose clusters of *x* m average diameter." Further approaches for the spatial analysis of features within the raw and mosaicked image products are possible, with a geostatistical approach feasible given the high accuracy of the OFOBS position data collected during deployments.

IV. SUMMARY

The data collected at the seamounts surveyed on the Langseth Ridge during PS101 clearly indicate that the new OFOBS offers for a range of research questions, advantages over other current deep-sea survey technologies, though there are also some limitations on the usefulness of the system. The current OFOBS presented here has two major advantages when compared with noncabled imaging and survey solutions. The first being that output from the full sensor payload can be viewed in real time, a functionality facilitated by the continuous power supply and two-way data connectivity provided by the tethered design. Power supply is a particularly important consideration limiting the deployment durations of AUV and HROV systems [63]. The second advantage of the OFOBS is that a lower number of specialized technicians and operators are required to operate it than are commonly required for HROV, ROV, or AUV systems. At a minimum, one dedicated engineer can ensure the system is operating correctly, with members of the research vessel deck crew placed in charge of maintaining the flight height of the OFOBS during deployments via a standard winch setup, though the full CONOPS team (as outlined in Section II-H2) are recommended for best quality data acquisition. Decades of towed system benthic deployments have demonstrated the ability of research vessel crew members to carry out the winching tasks associated with deployment and operation, without the extensive additional training required to operate complex free-swimming systems [3], [6], [7]. The opportunity to take detailed images and video of the seafloor directly below the subsea unit, while simultaneously recording acoustical responses of the port and starboard seafloor greatly increases the area, which can be surveyed and ground truthed during a single tow. How accurately the features imaged in the visual systems can be scaled up to reflect distribution across the larger region imaged acoustically depends in part on the characteristics of the seafloor surveyed and the research questions of interest. Results from surveys of ecosystems with high structural complexity, such as Norwegian cold-water coral reefs [64], would likely be substantially improved (i.e., greater areas of coral coverage accurately mapped) by using OFOBS rather than more traditional towed cameras coupled with ship-bourne acoustical systems. Areas of the deep seafloor with small structural features of interest, on scales of a few meters diameter, such as hydrothermal vent chimneys or cold seep pockmarks, could also be located efficiently with OFOBS. By conducting such exploratory surveys with OFOBS, potential acoustical candidates for these discreet features could be located, for resurveying with ROVs or HROVs, or to guide the deployment of lander systems.

The OFOBS presented within this paper is comprised of predominantly "off the shelf" components, a design strategy which keeps costs low and allows for the rapid production of identical systems. The availability of such replicate OFOBS units strengthens their use for monitoring seafloor locations over time. AUVs deployed with sonar systems for microbathymetric studies have shown how even small seafloor anthropogenic disturbances, on the scale of meters, can be delineated from heights of 10 s of meters in the water column [65]. Being able to gauge such disturbances over sizable areas with towed camera/acoustic systems cheaply and with a high degree of reproducibility provides cost effective opportunities for improving the monitoring requirements of regions of the deep sea seafloor, requirements which may be imposed in the future on deep sea mineral mining operators [66], [67], oil and gas exploitation endeavors or deep sea fishing activities [68], [69].

ACKNOWLEDGMENT

The OFOBS frame was developed based on the OFOS-Launcher system (HGF Alliance ROBEX). A. Purser wrote the manuscript with input from all other authors. S. Dreutter and B. Dorschel developed the acoustical and processing procedures. S. Dreutter and Y. Marcon developed the image mosaicking and georeferencing techniques. A. Purser, S. Dreutter, L. Hehemann, H. Biebow, and A. Boetius ran the initial cruise deployments. B. Sablotny, J. Lemburg, and U. Hoge designed and constructed OFOBS. A. Boetius conceived of and oversaw the development of OFOBS.

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Autun Purser received the B.Sc. degree in geology from Brunel University, U.K., in 1993, the M.Sc. degree in environmental protection and management from Lincoln Unversity, U.K., in 1999, the M.Sc. degree in oceanography from the University of Southampton, U.K., in 2006, and the Ph.D. degree in geosciences from Jacobs University Bremen in 2010.

He is a Senior Scientist with the Alfred Wegener Institute, Bremerhaven, Germany. He is the AWI point of contact for groups wishing to use the OFOBS system in collaborative research. He has spent a decade conducting deep sea ecosystem research within a host of European projects. He was been involved with early attempts to automate underwater image analysis and has a keen interest in monitoring the effects of anthropogenic activity in the deep sea.

Yann Marcon received the M.S. degree in hydrogeology from the University of Montpellier, Montpellier, France, in 2006 and the Ph.D. degree in marine geosciences from the University of Bremen, Bremen, Germany, in 2013.

Before his Ph.D., he was a Consultant with the Management Of Water Resources, U.K., from 2007 to 2010. From 2014 to 2017, he was a Research Scientist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, and is currently a Research Scientist and the Project Manager at the University of Bremen and MARUM Center for Marine Environmental Research, Bremen, Germany. He developed the data workflow for the OFOBS system. His research interests include the development and application of software and technology for deep-sea exploration, mapping and monitoring, as well as for management and processing of scientific imagery data. His research work focuses on the dynamics of natural hydrocarbon seepage and deep-sea ecosystems in a wide range of settings.

Simon Dreutter received the B.Sc. degree in cartography and geomedia and the M.Sc. degree in cartography and geodesy from Beuth University of Applied Sciences, Berlin, Germany, in 2010 and 2012, respectively, and the M.Sc. degree in geomatics/hydrography from HafenCity University Hamburg, Germany, in 2017.

He is currently the Data Manager at the Department of Bathymetry, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany. He operated the acoustical systems of the OFOBS during the testing period and during the PS101 cruise. His main research interests include high-resolution multisensor habitat mapping in deep sea environments.

Ulrich Hoge received the Diploma degree in engineering from the University of Applied Science, Bremen, Germany, in 2000.

He is currently a member of the Deep Sea Research Group, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany. He is also an Electronic Engineer at the University of Applied Science. He is currently the Lead Engineer on the OFOBS system at AWI. He has been the in charge of autonomous underwater vehicles since 2003, and specialized in hardware and software engineering for submersible devices.

Burkhard Sablotny has been an Engineer in Electronics, working in marine technology since 1988. He integrated the camera and lighting systems into the OFOBS.

Laura Hehemann received a Diploma in environmental technology from Camosun College, Victoria, Canada, in 2008 and the B.S. degree in environmental science from Royal Roads University, Victoria, Canada, in 2015.

She is a Geoinformation Specialist at the AlfredWagner Institute, Bremerhaven, Germany. From 2008 to 2013 she worked as a Geographic Information System (GIS) analyst at CloverPoint, Victoria, Canada and has coauthored in Geomorphology, 2010, (formerly Colquhoun) determining controls to debris flow mobility. She was responsible for integrating the optical and acoustical data into GIS products, as well as for dive progress monitoring and optimization, during PS101.

Johannes Lemburg received the Dipl.Ing. and Ph.D. degrees in mechanical engineering from the RWTH Aachen University, Aachen, Germany, in 2002 and 2009, respectively.

Until 2008, he was a Research Assistant for the Chair and Institute for Engineering Design and focussed his research to the development of a methodology for embodiment design. From 2008 to 2014, he joined the German Research Center for Artificial Intelligence as a Senior Researcher to develop systems in the field of service and underwater robotics. Since 2014, he designs and implements scientific instrumentation with the HGF-MPG Research Group on Deep Sea Ecology and Technology, Alfred Wegener Institute for Marine and Polar Research, Bremerhaven, Germany. He made significant design decisions in developing the OFOBS.

Boris Dorschel received the Ph.D. degree from the University of Bremen, Bremen, Germany, in 2003, with dissertation titled "Late Quaternary Development of a Deep-Water Carbonate Mound in the Northeast Atlantic."

Following his Ph.D., he continued cold-water coral carbonate mound research with a two-year postdoctoral position with the Zentrum für Marine Umweltwissenschaften, University of Bremen. In 2005, he received a fellowship from the Irish Research Council for Science, Engineering, and Technology and moved to the University College Cork (UCC), Cork, Ireland, where he stayed until 2012, and commenced working on cold-water corals in the scope of various Irish and European projects. Over the years, in addition to the work on cold-water corals, his research included increasingly geographic information systems and bathymetry components until these components became the main focus of his research. Consequently, in 2012, he started his current employment as the Head of the Bathymetry Working Group, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, where he researches the bathymetry and seafloor morphology of the high latitudes. He oversaw the integration of the acoustical systems into the OFOBS.

Harald Biebow is currently a Technician with ISITEC GmbH, Bremerhaven, Germany, with several decades of ocean going experience and an active involvement in the development of new marine equipment. He oversaw the technical integration of the acoustical systems into the OFOBS platform.

Antje Boetius received the Ph.D. degree from the University of Bremen, Bremen, Germany, in 1996.

She is currently a Deep Sea Researcher and a Professor of Geomicrobiology with MARUM, University Bremen, Bremen, Germany, and the Director with the Helmholtz Center for Polar and Marine Research, Alfred Wegener Institute, Bremerhaven, Germany. Her current studies focus on Arctic deep-sea life under the ice, and the long-term observation of the effects of global warming on polar and ocean ecosystems. She developed the concept for the OFOBS system and was chief scientist on the initial PS101 test cruise of the completed system.