ALKOR-Berichte

Autonomous Robotic Network to Resolve Coastal Oxygen Dynamics

Cruise No. AL547

20.10. – 31.10.2020
Kiel – Kiel
ARCODYN

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1 Cruise Summary

1.1 Summary in English

The ALKOR cruise AL547 represents a concluding milestone of the Helmholtz innovation project ARCHES (Autonomous Robotic Networks to Help Modern Societies). The aim was to implement a heterogeneous robotic sensing network to simultaneously monitor changes in the water column and at the seafloor. The network has been developed by a consortium of partners from AWI, DLR, GEOMAR and the University of Kiel. The participating sensing platforms allow for real-time data transfer and the entire network shall be able to autonomously respond to environmental changes in the ocean. The network comprised seven different mobile and stationary platforms. Tests were conducted at the Mittelgrund working area in the entrance of the Eckernförde Bay (western Baltic Sea). During 47 stations the various sensing platforms were deployed and recovered for maintenance. A total of 87853 messages were sent using hydro-acoustics, of which 71734 messages contained O_2 data, 15177 were status messages, 926 messages were commands to trigger a change of the measurement behavior of a platform and 16 messages represented broadcasts about the environmental status. We synoptically recorded short-term O_2 time series on the different platforms, which were placed along a depth gradient in the working area. As the Eckernförde Bay is known for sporadic fish kills by anoxia we hope to contribute to a better understanding of the O_2 dynamics in coastal areas.

1.2 Zusammenfassung

Die ALKOR Forschungsfahrt AL547 repräsentiert den Abschluss des Helmholtz Innvations Projekt ARCHES (Autonomous Robotic Networks to Help Modern Societies). Die Zielsetzung war die Errichtung eines heterogenen, robotischen Messnetzes zur gleichzeitigen Erfassung von Umweltänderungen in der Wassersäule und am Meeresboden. Das Messnetz wurde von einem Konsortium, das von den Helmholtz-Zentren AWI, DLR und GEOMAR sowie der Universität Kiel gebildet wurde, entwickelt. Die teilnehmenden Messplattformen erlauben den Datentransfer in Echtzeit, während das gesamte Netzwerk in der Lage sein sollte autonom auf Umweltänderungen zu reagieren. Das Netzwerk umfasste sieben verschiedene mobile und stationäre Messplattformen. Die Tests wurden bei Mittelgrund im Eingang der Eckernförder Bucht (westliche Ostsee) durchgeführt, wobei als wissenschaftliche Fallstudie die kurzfristige Sauerstoffdynamik in der Eckernförder Bucht im Zusammenhang mit Wetteränderungen beobachtet werden sollte. Innerhalb von 47 Stationseinsätzen wurden die verschiedenen Messplattformen für Messungen und Wartungsarbeiten eingesetzt und wieder geborgen. Während der Tests wurden mittels Hydroakustik 87853 Nachrichten verschickt, davon enthielten 71734 Nachrichten O_2 Daten, 15177 repräsentierten Statusmeldungen, 926 dienten als Befehle zum Ändern des Messverhaltens einer Plattform, 16 Meldungen waren Broadcasts an alle Teilnehmer über den Umweltzustand. Gleichzeitig wurden kurze O_2 Zeitserien von den verschiedenen Plattformen, die entlang eines Tiefengradienten im Arbeitsgebiet platziert wurden, erfasst. Die Eckernförder Bucht ist für sporadisch auftretende Fischsterben bekannt, die auf anoxische Bedingungen zurückzuführen sind. Wir hoffen mit den hier erhobenen Daten zu einem besseren Verständnis der O_2 Dynamik und Verfügbarkeit in Küstengewässern beizutragen.

2 Participants

2.1 Prinicpal Investigators

Name	Institution
Sommer, Stefan, Dr.	GEOMAR
Flögel, Sascha, Dr.	GEOMAR
Walter, Michael, Dr.	DLR
Wenzhöfer, Frank, Dr.	AWI

2.2 Scientific Party

Name	Discipline	Institution
Sommer, Stefan, Dr.	PI, BIGO, OFOS	GEOMAR
Barbie, Alexander	Informatician, ROS	GEOMAR/AWI
Busse, Marc	Electr. Eng., MANSIO, VIATOR	GEOMAR
Flögel, Sascha, Dr.+	MANSIO, VIATOR	GEOMAR
Nordhausen, Axel*	Electr. Eng., FLUX, CRAWLER SIM	AWI/MPI
Pech, Niklas	Informatician, MANSIO VIATOR, ROS	GEOMAR
Türk, Matthias*	Electr. Eng., BIGO/OFOS	GEOMAR
Walter, Michael, Dr.+	Hydroacoustic recorder	DLR
Wenzhöfer, Frank, Dr.	FLUX Lander, CRAWLER SIM	AWI

* participants left RV ALKOR at the 23rd, + participants boarded RV ALKOR at the 23rd

2.3 Participating Institutions

GEOMAR	Helmholtz-Zentrum für Ozeanforschung Kiel
AWI	Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung Bremerhaven
DLR	Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen-Wessling
MPI	Max-Planck-Institut für Marine Mikrobiologie, Bremen

3 Research Program

3.1 Description of the Work Area

Two test-series were conducted at the entrance of the Eckernförde Bay (German Baltic Sea) at the north-eastern slope of Mittelgrund in the working area A1, Figure 3.1.1. In this region, the terrain was gently sloping towards northeast, encompassing water depths of 17 to 23 m. The seafloor in water depths greater than 19 m was muddy whereas sediments in shallower water depths were rather sandy. In greater water depths black colored sediments were covered with extended whitish microbial mats, which tentatively were identified as filamentous sulfide oxidizing bacteria *Beggiatoa*. Shallower sediment surfaces were oxidized as indicated by their light-brownish coloration.

Typically, sluggish ventilation paired with strong stratification of the water column during summer minimizing vertical fluxes causes many parts of the Belt Sea deep waters to become O_2 depleted (Karstensen et al. 2014). Deep layers of the Belt Sea are mainly influenced by the inflow of warmer and saltier water from the North Sea, which during rare major inflow events depending on specific wind conditions have the potential to ventilate the deeper water layers (Karstensen et al. 2014). Apart from these rare inflow events specific processes have been suggested to govern local O_2 availability in the Eckernförde Bay (Dietze and Löptien, 2021; see section 5.3). The physical properties (density, temperature, salinity, turbidity, sound velocity profiles in the water column as well as the distribution of O_2 and nitrate are described in detail in section 5.3. Briefly, throughout the cruise the water column was stably stratified. At the beginning of the cruise at the 23rd a pronounced pycnocline was located in a water depth of 22 m but became progressively shifted towards 12 m at the 30th Oct. Below the pycnoline the O_2 level declined from about 316 µmol l^{-1} to 12 µmol l^{-1} (OFOS track #4) representing severe hypoxic conditions.

Due to bad weather conditions, a third test was performed in working area A2 in the inner part of the Eckernförde Bay, Figure 3.1.1.

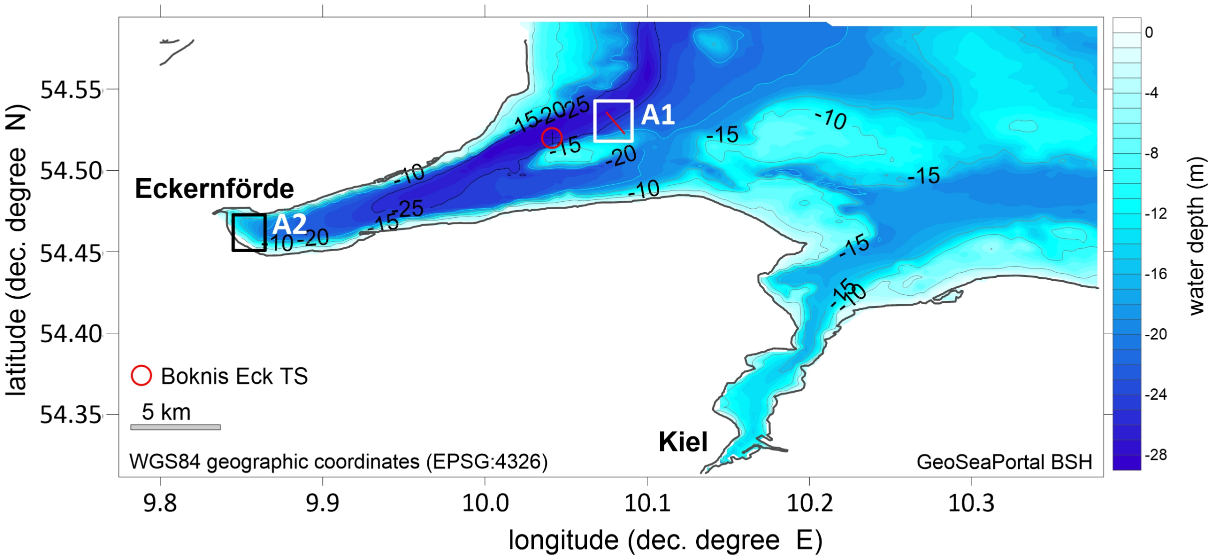

Fig. 3.1.1 Bathymetrical map of the Eckernförde Bay and the Kiel fjord. The working area is indicated by the rectangle A1. The red line inside A1 indicates the section along which measurements with the OFOS and the CTD were performed. The red circle indicates the Boknis Eck time series station. A2 marks the working area in the inner part of the Eckernförde Bay.

3.2 Aims of the Cruise

The ALKOR cruise AL547 represents a concluding milestone of the Helmholtz innovation project ARCHES (Autonomous Robotic Networks to Help Modern Societies). One overall aim of ARCHES has been to implement a heterogeneous robotic sensing network to simultaneously monitor changes in the water column and at the seafloor. The network has been developed by a consortium of partners from AWI (Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany), DLR (German Aerospace Center, Oberpfaffenhofen, Germany) and the GEOMAR (Helmholtz Centre for Ocean Research Kiel, Germany). For the development of the network software cooperation exists with the Kiel University within the framework of a PhD thesis. The participating sensing platforms shall allow for real-time data transfer and the entire network shall be able to autonomously respond to environmental changes in the environment by adopting its measurement strategy. Beside data generated by the network itself, the network shall include data from external sources (e.g. weather data, Kiel Lighthouse). The network partly includes measurement platforms developed within the HGF funded project ROBEX (Robotic Exploration of Extreme Environments, Wedler et al. 2018 Wenzhöfer et al. 2016).

The tests performed during cruise AL547 aimed to demonstrate the functionality of the network under field conditions. Due to Corona restrictions, the network could not be deployed as originally planned. The tested network comprised 7 different mobile and stationary platforms (for details see section 5.1) and was used to observe short-term fluctuations of O_2 in the Eckernförde Bay in relation to atmospheric forcing.

As a science case progressing O_2 loss in coastal waters was addressed. O_2 concentrations in both the open ocean and coastal waters have been declining since at least the middle of the 20th century. O_2 loss is one of the most important changes occurring in the oceans and coastal waters increasingly modified by human activities that have raised temperatures, CO_2 levels, and nutrient inputs and have altered the abundances and distributions of marine species (e.g. Breitburg et al. 2018). Whereas deoxygenation in the open ocean is considered to be induced by global warming caused by increased greenhouse gas emissions, O_2 loss in estuaries and other coastal environments often is induced by extensive agricultural use of their catchment areas and massive loadings of nutrients (nitrogen and phosphorous) causing severe eutrophication and spread of hypoxia.

3.3 Agenda of the Cruise

As outlined in the cruise proposal the above objectives were approached by implementing an underwater sensing network in the Eckernförde Bay. The network consisted of seven different mobile and stationary platforms that are described in detail in section 5.1. During the time course of AL547 all platforms were simultaneously deployed during three deployment series to perform detailed tests of platform interaction, hydro-acoustic communication for the transfer of data and commands as well as for positioning, and environmental measurements.

Overall, we conducted 6 OFOS sections, and several deployments of the different sensing platforms described in section 5.1. During the night from the 26th to the 27th of Oct. the surface buoy, which is required for the recovery of BIGO, was lost. For its recovery at the 29th of Oct. the diving team Submaris was engaged. Generally, the deployments and recoveries of the different gears took place during the daytime hours. During the evening hours, the network was tested and VIATOR was operated. Overall, during 47 stations the various sensing platforms were deployed and recovered for maintenance and battery change (6 x OFOS, 5 x MANSIO, 3 x VIATOR, 5 x BIGO, 4 x FLUX lander, 2 x CRAWLER SIM and one SLM lander). Scientifically relevant data regarding the dynamic of O_2 in the working area were recorded during different short-term time series.

Apart from minor changes the measurement and test campaign was conducted as outlined in the cruise proposal despite only 7 instead of 12 scientists participated in the cruise due to restrictions caused by the Corona pandemic.

According to the ship time proposal, we successfully conducted measurements at all planned stations. We followed the DFG regulations summarized in the „Erklärung zu einer verantwortungsvollen Meeresforschung“ and the (OSPAR) Code „Code of Conduct for Responsible Marine Research in the Deep Seas and High Seas of the OSPAR Maritime Area” to avoid unnecessary environmental and ecosystem disturbances. The impact of the conducted work to the environment can be considered as very minor. All instruments were recovered at the end of the cruise. There were no activities, which could lead to substantial physical, chemical, biological or geological changes or damage of marine habitats. Care was taken to avoid activities, which could disturb the experiments and observations of other scientists. We made use of the most environmentally-friendly and appropriate study methods, which are presently available. Sediment or water samples were not taken.

4 Narrative of the Cruise

At Tuesday 20th of October, a team of seven scientists from GEOMAR, AWI and MPI boarded RV ALKOR in Kiel harbor (east-shore) after successfully having passed the required Covid-PCR-tests. Laboratories were established for the operation of the interactive underwater sensing network. In the afternoon after a short transit, we started station work in the working area A1 at the entrance of the Eckernförde Bay close to the Boknis Eck time series station using the OFOS. The OFOS was towed along a section across the working area starting in water depths of 27 m and ending at 14 m. Visibility at the deepest sites was strongly reduced due to an increased particle load.

At the 21st of October, our activities focused on establishing a stable hydro-acoustic communication between the MANSIO and the shipboard USBL Modem mounted in the moon pool of RV ALKOR. The experiments were conducted to determine the maximum distance with still reasonable signal quality for reliable communication.

At the 22nd of October, we recovered the MANSIO lander, finished station work and headed towards Kiel (GEOMAR west shore pier) due to a sick crew member, who was transferred to a hospital in Kiel. Staying overnight in Kiel for the exchange of scientists, station work was continued at the 23rd of October, where MANSIO, BIGO, FLUX Lander, and the Crawler SIM were deployed for further network tests. The station work at this day further comprised the deployment of the SLM lander, which was moored at the seafloor for the entire duration of the cruise to record the current regime and other physical parameters.

Saturday 24th of October - the station work started with the deployment of the FLUX lander and the VIATOR and concluded with an extended OFOS deployment, which was towed along the depth section across the working area A1.

At the 25th of October, all instruments except the SLM lander were recovered back on board of RV ALKOR. Subsequently, we headed towards Eckernförde, where we stayed overnight to collect in the morning of the 26th of October electronical spare parts for the repair of the WLAN antenna of the WLAN catamaran. We left Eckernförde at about 08:00 and continued station work to establish the underwater network at slightly shallower water depths around the pycnocline. Prior to the deployment of the different sensing platforms an OFOS-section was conducted (OFOS-4) to record O_2, nitrate and physical properties the water column. The measurement revealed that since the start of the cruise the pycnocline became lifted upwards from 20 to 18 water depth. Subsequent to the OFOS-section, the FLUX Lander, BIGO, MANSIO and CRAWLER SIM were deployed. From all platforms positions and status were safely received.

During the evening the BIGO was successfully controlled via underwater communication and the network operation software. O_2 values from inside the flux chambers and from the O_2 sensor monitoring the bottom water O_2 levels were reliably received. Typically, the measurements of BIGO were conducted according to a defined protocol, which was programmed prior to its deployment and the data became only available after the retrieval of the lander system. This BIGO deployment was the first time, we were able to perform controlled underwater experiments with real-time data access.

In the morning of Tuesday 27th of October BIGO was prepared for its retrieval back on deck by closing the shutter beneath the flux chamber and getting the chamber out of the sediment. However, during the night the surface buoy required for its retrieval was lost. As we were under control of the BIGO position via hydro-acoustics, we decided to proceed with the station program and deployed the crawler VIATOR.

At Wednesday the 28th of October, all platforms except BIGO were recovered. Subsequently, we prepared the recovery of BIGO using dragging device, which was mounted beneath the OFOS as well as three additional dragging devices, which were attached to the OFOS steel frame. Soon after the first trials failed and due to the strongly reduced visibility, we decided not to continue in order to prevent damage of the BIGO and the OFOS and ordered the professional diving team Submaris (Kiel) for recovery. In the afternoon, we repeated the OFOS transect to characterize the physical and biogeochemical variability of the water column. Distinct differences with regard to the location of the pycnocline and turbidity as well as the O_2 and possibly the sulfide distribution were observed. In the evening hours, we headed towards Eckernförde harbor to pick up the diving team.

At the 29th of October, the diving team boarded after conducting a Covid-test. Arriving at the BIGO position, we had strong winds and wave height was up to one meter. Nevertheless, the divers successfully located the lander and enabled its rapid retrieval.

Due to the weather conditions and the need to disembark the diving team, we decided to conduct our station program more inshore the Eckernförde Bay (working area A2). At around noon, all platforms except the Crawler Sim, which had electronical problems, were deployed. The diving team filmed the deployment of VIATOR and MANSIO and performed a camera calibration using a checkboard. Afterwards, the diving team was shuttled to the harbor of Eckernförde. During the evening, further tests of the network were successfully conducted.

In the morning hours of Friday 30th of October the platforms were recovered and cleaned. Subsequently, we moved towards Mittelgrund, to deploy the OFOS for concluding 4 depth profiles along the previous OFOS-section and to recover the SLM lander.

Afterwards we went back to Kiel. After cleaning the laboratory and having the scientific equipment packed, five scientific crew members left the ship in the evening hours. Michael Walter and Frank Wenzhöfer stayed onboard and left at Saturday 31st of October.

5 Preliminary Results

5.1 Description of the ARCHES Network

The ARCHES network consisted of seven mobile and stationary platforms, which were supplied from AWI and GEOMAR, Figure 5.1.1. To enable navigation and communication, each of this platform was equipped with an USBL Modem (EVOLOGICS, 7-17 kHz). Another modem was placed in the moon pool of the RV ALKOR to enable communication between the network and the ship. In addition to platform specific sensors, each platform was equipped with sensors (AANDERAA / PYROSCIENCE) to measure O_2, which represented a network overarching basic environmental parameter.

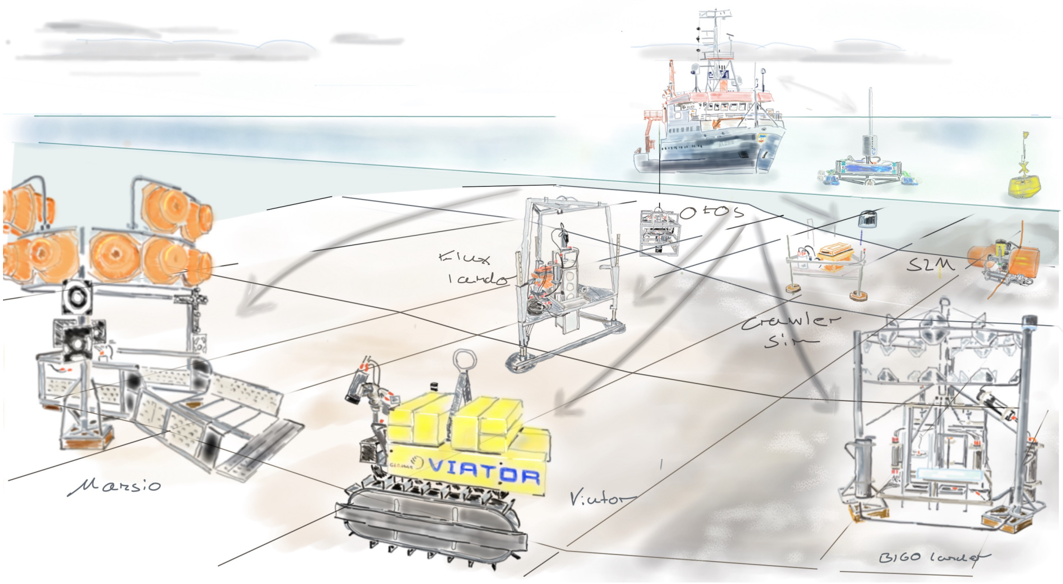

Fig. 5.1.1 Scheme of the ARCHES underwater network placed on the ridge-like structure Mittelgrund at the entrance of the Eckernförder Bay (western Baltic Sea) in water depths of 16 – 27 m. *Graphics S. Sommer*

Stationary platforms comprised the BIGO type lander (Biogeochemical Observatory, Fig. 5.1.2a), the CRAWLER SIM (Crawler Simulator, Fig. 5.1.2b), the FLUX Lander (Fig. 5.1.2c), the MANSIO Lander (Fig. 5.1.2e), which together with the crawler VIATOR (Fig. 5.1.2d) forms a system unit further including the WLAN-Katamaran (Fig. 5.1.2f). The network further includes the towed camera system OFOS (Ocean Floor Observation System, Fig. 5.1.2g).

The benthic chamber lander BIGO (Sommer et al. 2017) is equipped with two benthic chambers that retrieve sediments for later onboard biogeochemical and biological analyses. However, during this cruise sediments were not recovered for further analyses. O_2 sensors (Aanderaa) are present inside each benthic chamber as well as outside. O_2 consumption inside the benthic chamber was recorded to calculate the total O_2 consumption (TOU) of the enclosed sediment community. The outside O_2 sensor records fluctuations of ambient O_2 levels. A Seabird pump allows to periodically replace the bottom water enclosed in each chamber allowing to determine fluxes at different bottom water oxygen concentrations. The FLUX lander, a reduced version of the deep-sea lander system (Donis et al., 2016), also allow the measurements of O_2 in the bottom water as well as the measurement of O_2 fluxes across the benthic boundary layer. The CRAWLER SIM, a simulator for the benthic crawler TRAMPER and NOMAD (Wenzhöfer et al., 2016; Lemburg et al., 2018), was deployed to simulate various functions of the crawler systems.

The VIATOR- MANSIO system (Figure 5.1.2d, e; Flögel et al. 2018) comprises a stationary lander system (MANSIO) and the mobile deep-sea crawler (VIATOR). The hangar (MANSIO) is used for the transport of VIATOR to the site of investigation and for its recovery to the ocean surface as well as to recharge the lithium polymer (LiPo) accumulators on the crawler. Currently, the hangar is improved to facilitate data transfer from the lander system to the crawler, and vice versa, and ultimately to the sea surface by acoustic modems. The system carries 12 kWh, four 2 kWh LiPo blocks are located on the crawler and currently two 2 kWh blocks on the lander. Energy transfer between the two components is provided via inductive coupling. Depending on CPU load, this allows for transects of about 2 – 4 km. The system has been designed to operate fully autonomous for scientific missions of up to 3 months and to be operational from mid-sized research vessels. After deployment, the crawler will leave the hangar and start its pre-programmed scientific mission or can interact with commands from outside. After mission completion VIATOR returns to the lander to recharge its power supply. During its mission, the crawler records oceanographic and biogeochemical parameters such as temperature, salinity, pressure, currents, O_2, pH, turbidity, and chlorophyll. The system can be deployed in water depths of up to 6000 m. In addition to the physical and biogeochemical sensors the system is equipped with a pan and tilt unit (PTU) carrying a camera and a laser line projector, which are used for navigational purposes and collecting data for a 3D-reconstruction of the seafloor. Please note that during this cruise only video footage was obtained and O_2 measurements were conducted. Via the WLAN catamaran, which was towed behind the VIATOR a rapid data connection between the ship and the crawler was established for the transfer of video signals, which due to the low band-with of the USBL modems was not possible hydro-acoustically. Apart from the visual inspection of the seafloor, the towed camera system OFOS was used for hydro-acoustic tests and for repeated measurements of O_2, nitrate, turbidity, conductivity, temperature, density, depth and sound velocity, see section 5.3.

The network was supplemented by the SLM Lander (Satellite Lander Module, Figure 5.1.2h) for the measurement of the current regime and O_2. It was placed on the sea floor a few hundred meter away from the network area. The SLM lander was not connected to the network and the RV ALKOR. Occasionally, a hydro-acoustic recorder (Figure 5.1.2i) was mounted on various platforms to obtain an extended data base for the improvement of underwater navigation and communication, see section 5.4.

Fig. 5.1.2 The ARCHES underwater network consists of the following mobile and stationary sensing platforms. BIGO-Lander, b. CRAWLER SIM, c., FLUX Lander, d. VIATOR, e. MANSIO, f. WLAN-Katamaran (in the background the RV ALKORis visible), g, towed camera and sensor system OFOS, h, SLM Lander, i. acoustic recorder. *Photos: Submaris, Flögel, Sommer, Walter, Wenzhöfer.*

5.2 Operation of the ARCHES Network

For the operation of the network the software ROS (Robotic Operation Software) including a Digital Twin software architecture was used (Barbie et al. 2020, Barbie et al. 2022). Within the Digital Twin approach each physically existing robotic platform is further represented by a virtual Digital Twin. By this, complicated procedures or operations can be simulated without any risks before they are applied to the physical entities in reality. The operation of the network has been described in detail by Barbie et al. (2022), hence in the following only a brief summary will be provided.

To investigate the suitability of the Digital Twin approach for under water networks four different scenarios were evaluated, Figure 5.2.1. The approach was considered feasible, if all the scenarios can be repeated independently and the network systems synchronize environmental data and status reliably. As a common standard between all participating platforms, four basic messages are exchanged (Barbie et al. 2022): *StandardO2*, *StandardStatus*, *SetBehavior*, and *O2Event*. *StandardO2* messages carry a timestamp, the O_2 value, O_2 saturation and the temperature. *StandardStatus* messages include a timestamp, the current behavior ID (activity of the platform) and the status of the behavior such as running, finished, or failure. *SetBehavior* messages carry the ID of the behavior to execute. *O2Event* messages represent a string that indicates a detected environmental event. During the cruise two event-scenarios were tested, “Oxia”, chosen for well ventilated conditions in the ambient water body of a respective platform and “Hypoxia”, indicating environmental conditions with reduced O_2 levels.

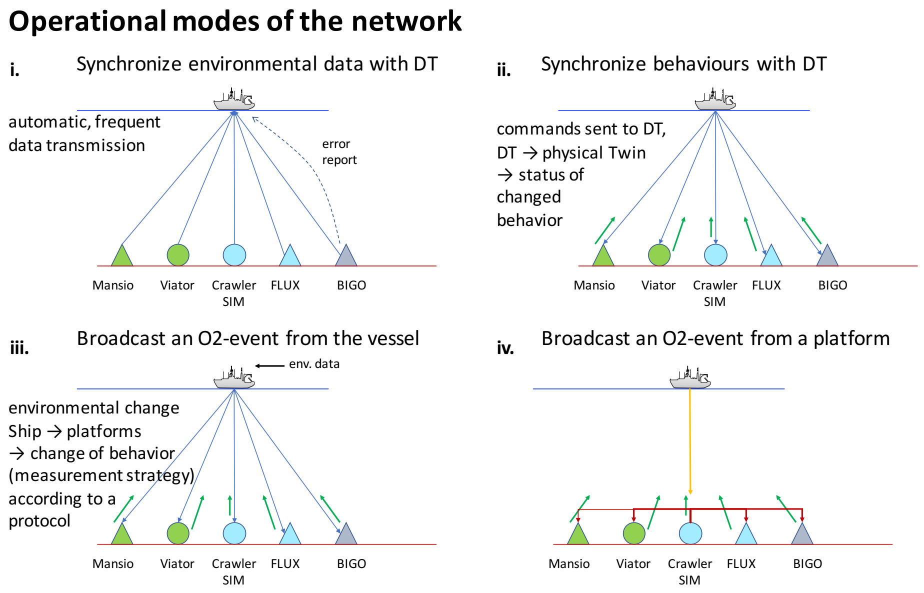

Fig. 5.2.1 Scenarios tested with the ARCHES underwater network during cruise AL547. For details see text. DT: Digital Twin.

Scenario I: All platforms were placed at the seafloor and synchronize their measurements to the corresponding Digital Twins on the research vessel. The physical twins (really existing platforms at the seafloor) are programmed to different measurement cycles, which were automatically started during the startup.

Scenario II: Manual transfer of commands to the digital twin and synchronization before these were transferred to the physical twin. Subsequently the physical twin responds with a status message and a confirmation about the change of its operation mode.

Scenario III: The O_2 data of the platforms are used to identify changes of the O_2 content in the surrounding bottom water of each measurement platform and to classify them either as "Oxia" (high O_2 availability) or as "Hypoxia" (low O_2 availability). Subsequently, the decision whether the environment corresponds to "Oxia" or "Hypoxia" will broadcasted to all platforms, which will change their measurement strategy according to a programmed protocol.

Scenario IV: This scenario addressed the communication between the different platforms. The environmental status "Oxia" or "Hypoxia" is recognized from one of the participating platforms (e.g. CRAWLER SIM) and broadcasted to all others including the ship. The other platforms change their measurement behavior and synchronize their status with the digital twin.

During the cruise these scenario tests were successfully performed, a total of 87853 messages were sent hydro-acoustically, of which 71734 messages contained O_2 data, 15177 were status messages, 926 messages were commands to trigger a change of the measurement behavior of a platform and 16 messages represented broadcast about the environmental status (Oxia/Hypoxia).

Another major success was to directly communicate with the platforms to retrieve data in real time and to manipulate their measurement behavior, which in future allows controlled and interactive in situ measurements and experiments. An example is given for the BIGO deployment depicted in Figure 5.2.2. As described above BIGO contains three sensors for O_2 measurements inside chamber 1 (Figure 5.2.2., red circles) and chamber 2 (Figure 5.2.2., blue plus signs) as well as the ambient bottom water (Figure 5.2.2. green dots). Measurements in the bottom water revealed a major variability ranging from high O_2 availability of up to 250 µmol l^{-1} to strongly hypoxic O_2 levels approaching anoxic conditions at the 29th of October. In contrast to typical BIGO deployments where flux measurements inside the chambers were initiated automatically according to a programmed protocol, this time all commands to trigger chamber measurements were given manually, see the command list (Behaviour & ID) at the right-hand side of the figure. Chamber 1 was initiated at the end of 26. Oct., as soon as the chamber was closed O_2 was consumed as indicated by the steady decline of the O_2 concentration. At the 27. Oct. chamber 1 was moved upwards (out of the sediment) subsequently the O_2 levels measured in the chamber were similar to those recorded in the bottom water. Same procedure was successfully performed for the chamber 2 (28th of Oct.).

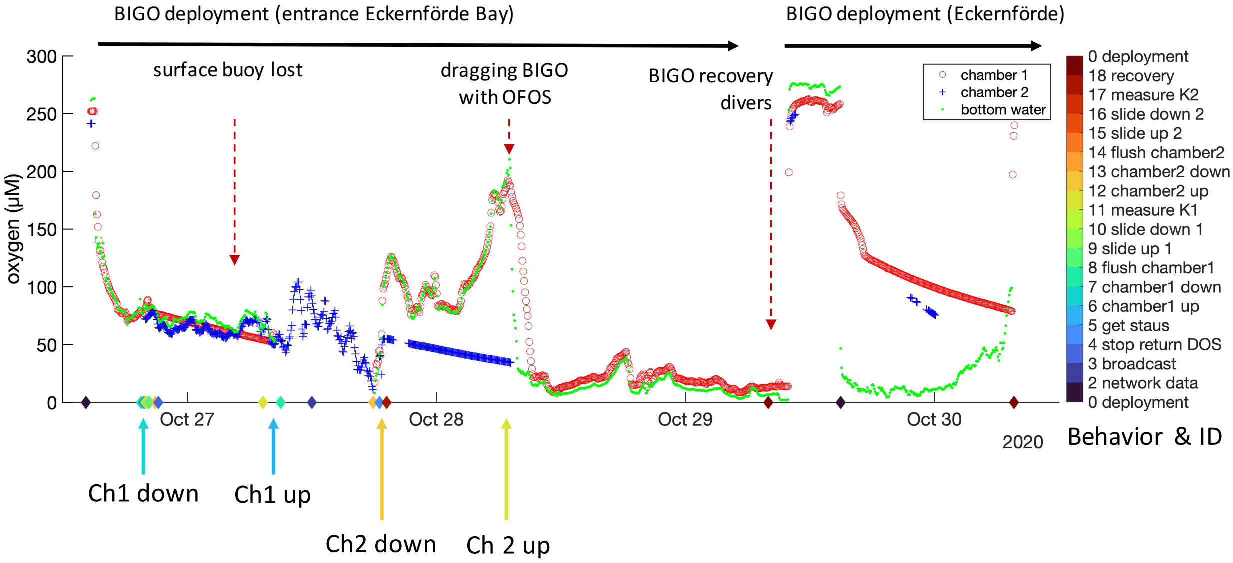

Fig. 5.2.2 Manually transferred commands to initiate O_2 flux measurements inside the chamber 1 and 2 implemented in the BIGO lander. The command list and the respective ID number (Behavior & ID) is given at the right side of the graph. The figure further depicts the time periods when the BIGO was deployed at the entrance and the inner part of the Eckernförder Bay. It further displays the times when the surface buoy for recovery of the lander was lost and when the BIGO was recovered by the Submaris diving team.

5.3 Oxygen Dynamic and Physical Properties of the Water Column

Though the focus of ALKOR cruise AL547 was on establishing and operating a robotic sensing network, primarily O_2 and physical parameters were measured to address the O_2 dynamic in coastal waters.

O_2 time series from different platforms are displayed in Figure 5.3.1 indicating as already described above a high variability ranging from O_2 concentration of 302 µmol l^{-1} (recorded by MANSIO) to almost anoxic conditions within only a few days. Within the first period (23.- 25. Oct.) when all platforms were placed in greater water depths, O_2 levels were rather low and exceptionally reached O_2 concentrations of up to about 80 µmol l^{-1}. After recovery and replacement of the various platforms at shallower water depths (26.-29. Oct.) substantial differences in O_2 magnitude and variability were observed between the time series recorded by the BIGO, the FLUX lander and the CRAWLER SIM, which might be related to different water depths and wind driven seiches that interact with the seafloor topography. When during seiches the thermocline as well as the halo- and oxycline move up and down a sloping sea bed, a transition zone at the seafloor is induced where temperature, salinity and O_2 in the bottom water can vary considerably strongly affecting the ecosystem functioning of the benthic habitat. During extended periods of bottom water anoxia, the likelihood for the release sulfide from organic rich sediments into the bottom water forming toxic sulfidic plumes increases, severely affecting aerobically living organisms.

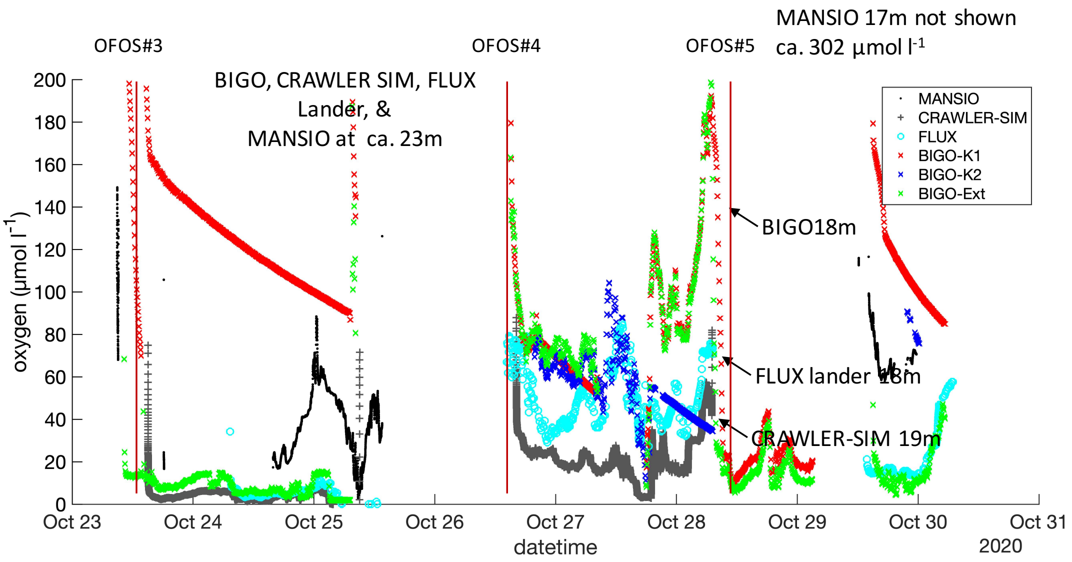

Fig. 5.3.1 O_2 times series simultaneously recorded from the various platforms during 3 different time periods where the network was operated at the seafloor (23. - 25. Oct. and 26. – 29. Oct at the entrance of the Eckernförde Bay (A1), 29. – 30. Oct. at the inner part of the Eckernförde Bay (A2)). The vertical red lines indicate the time when OFOS sections were conducted.

In addition to the O_2 time series recorded by the ARCHES network, OFOS sections were performed over the network area at different times.

Several CTD profiles were collected during 6 deployments of the OFOS along the section displayed in Figure 3.2.1. During the entire cruise a Seabird CTD unit SBE 19plus V2 was used, which was mounted into the OFOS frame. The SBE19plus V2 was equipped with one Digiquartz pressure sensor (s/n 7967) a sensor for temperature (s/n 01907967) and one sensor for conductivity (s/n 01907967) Additionally, a WET Labs turbidity meter (WET Labs, ECO-NTU, s/n NTURTD-5667) was attached to the SBE19plus V2. All sensors worked well throughout the cruise. Data acquisition was done using the Seabird Seasave software. A SUNA sensor (Seabird Satlantic) measuring nitrate concentrations was attached to the OFOS frame. O_2 concentrations were measured using an Aanderaa Optode. Visual sea floor inspection was enabled using a HD camera and two additional light sources. The O_2 sensor was calibrated at the sea surface and water samples, which were taken in parallel whose O_2 concentration were analyzed using automated Winkler titration.

Data from the SUNA nitrate sensor were post-calibrated at the GEOMAR laboratory. The independently collected and processed nitrate data and O_2 data were later synchronized with the CTD data. The CTD and the SUNA sensor recorded elapsed time, which was converted into date and time using the starting time. For the recording of the O_2 measurements a Hyper Terminal was used with a sampling frequency of one second. A time stamp for each measurement was not provided by the Terminal. Hence difficulties were encountered to synchronize O_2 values with the CTD measurements.

Figure 5.3.2 shows selected CTD profiles from the OFOS sections #3 to #6 indicating a pronounced shift of the pycno-, thermo- and halocline towards shallower water depths associated with a marked surface water cooling indicating that warmer more saline water presumably from the Kiel bight is pushed into the Eckernförde Bay. This water mass is slightly enriched with nitrate but depleted in O_2.

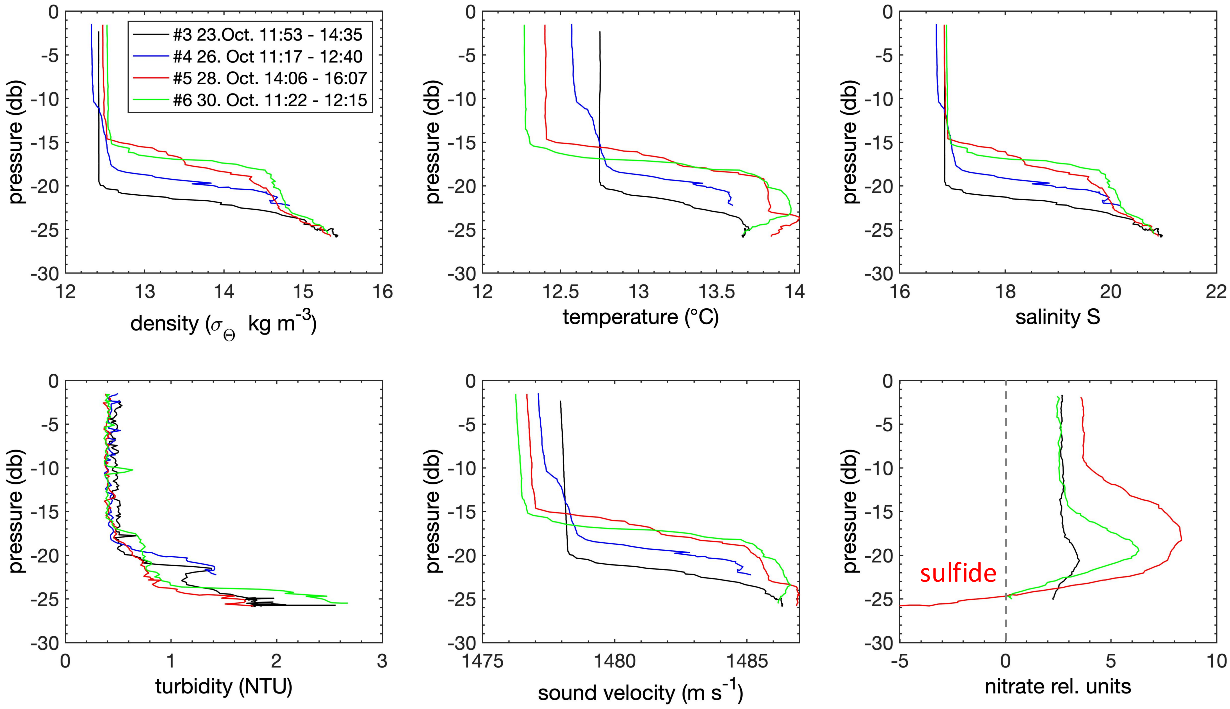

Fig. 5.3.2 Profiles of physical properties of the water column in research area A1 deduced from the OFOS sections #3 to #6. The nitrate concentration was measured using a SEABIRD SUNA V2 sensor. Negative values of the SUNA sensor likely indicates presence of sulfide.

Drivers of the above described fluctuations are most likely atmospheric forcing as well as seiches that interact with the seafloor topography. In a modelling study Dietze and Löptien (2021) identified two antagonistic processes that explain the dynamics of bottom water hypoxia in the Eckernförde Bay, i. inflow of hypoxic bottom water from the Kiel bight and ii. ventilation by local (within the Eckernförde Bay) subduction and vertical mixing. As major driver for these processes Dietze and Löptien (2021) recognized wind forcing. During westerly winds when the surface water is pushed out of the bay, for continuity reasons bottom water in the Eckernförde Bay is replaced from O_2 depleted bottom water of the Kiel bight. During periods of easterly winds when the surface water is pushed into the Eckernförde Bay, parts of it is sub-ducted and is exported at depth into the Kiel Bight. Figure 5.3.3 shows how strong bottom water O_2 fluctuations are correlated with wind. Highest O_2 levels were measured during the passage of a low pressure area under conditions of wind strongly turning from 185° to 210° with high wind speeds of up to 15 m s^{-1}. Low O_2 concentrations were observed directly after the passage of the low pressure area in the morning hours of the 28. Oct., with still strong southwesterly winds whose direction of 220° gradually declined to 200°, which confirms the reasoning made by Dietze and Löptien (2021).

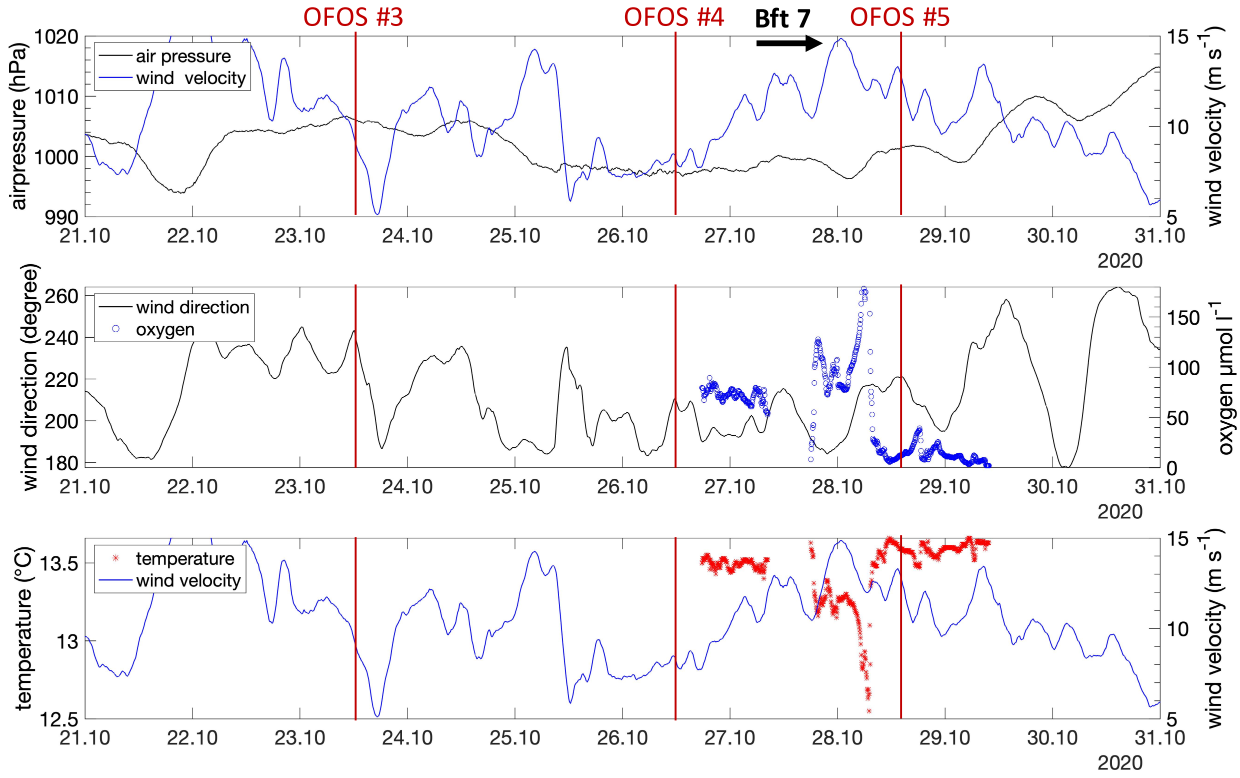

Fig. 5.3.3 Air pressure, wind direction and wind velocity (data from Kiel Lighthouse) in relation to O_2 (blue circles) and temperature (red stars) measured during a BIGO deployment in the bottom water at the entrance of the Eckernförde Bay (working area A1). The vertical red lines indicate when the OFOS sections where measured.

During the above described period of low O_2 concentrations after the passage of the low pressure area north-easterly currents prevailed, Figure 5.3.4. Whereas during elevated O_2 levels the bottom currents tend to flow into south-westerly directions further corroborating the concept suggested by Dietze and Löptien (2021). Magnitude of O_2 concentration changes seems to be further related to the magnitude of current velocity and how fast current velocity and direction is changing. Short-term O_2 fluctuations (hours scale) might be further caused by seiches.

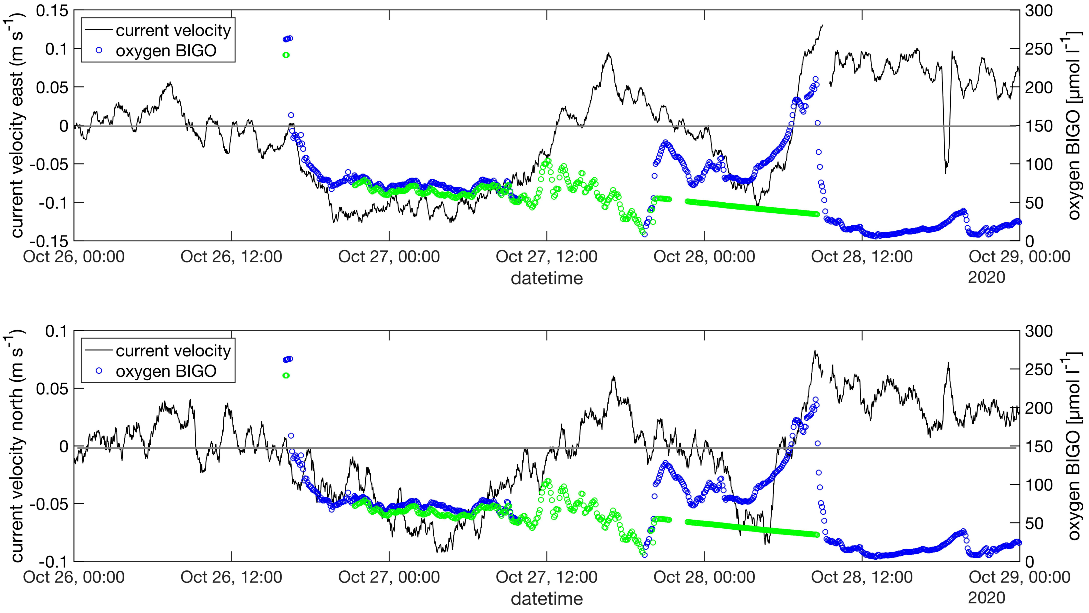

Fig. 5.3.4 Current velocity east (upper panel) and current velocity north (lower panel) measured 1 m above the SLM lander in relation to the bottom water O_2 concentration measured by BIGO. O_2 measurements in the bottom water were performed by two optodes, one mounted inside chamber 2 (green circles) the second one was mounted externally (blue circles). At the 28. Oct. the chamber 2 was inserted in the sediment (indicated by the steady decline of the O_2 level) otherwise the optode was exposed to the ambient bottom water.

5.4 Underwater Recorder Data

One focus of the DLR research is the development of a radio localization system for a swarm of driving robots for space exploration, e.g., exploring the canyon system on Mars. The concepts and algorithms developed in this field shall be transferred for underwater applications. The degree of autonomy required for robots/sensors in the deep-sea are similar to those of the space environment and infrastructure is commonly not available at all.

Current literature on underwater channel modelling (e.g, Stojanovic and Preisig, 2009) identified major gaps with respect to underwater localization. We will use the raw measurement data sent out by the acoustic modems and recorded by the underwater recorders to create an underwater channel model that characterizes the multipath components in such an environment particularly for localization. It is envisioned to use a geometric-stochastic channel model (GSCM) in order to capture time-variant effects of the channel. The GSCM method is currently used in many applications to model non-stationary device-to-device channels. This means the geometry of the propagation environment is included in the model and the stochastic part of the model makes it applicable to more than one specific environment. Consequently, a GSCM enables development of advanced channel and multipath component tracking. Depending on the results of the underwater channel characterization, DLR adapts the parameters of its tracking algorithms in order to enable the radio-based underwater localization. Instead of using a dedicated navigation system to locate the sensors/robots underwater, DLR enables the positioning of the devices by using communication signals only. Apart from the approach of multipath assisted positioning, DLR will also investigate its algorithms on network-based localization and ranging based cooperative positioning technologies dependent on the signal waveform of the communication system. The improved localization accuracy can be used by other researchers to improve for example the velocity field estimation of the ocean currents.

As mentioned in Section 1 the measurement network comprised six mobile and stationary platforms (BIGO, OFOS, Mansio, Viator, Flux Lander, Crawler SIM), which were provided by AWI and GEOMAR and adapted accordingly with respect to their network capability. Each of these platforms was equipped with a USBL modem (EvoLogics, 7-17 kHz) for hydroacoustic-based navigation and communication. Another modem was located in the moon pool of the FS ALKOR and allowed interaction between the network and the control room on the ship. Underwater recorders (Figure 5.1.2i) were attached to the AWI and GEOMAR measurement platforms (BIGO, OFOS, Viator, Flux Lander) to capture pulses from the acoustic modems. The recorded pulses were used to characterize the water as a propagation medium using the synchronization sequences. The measured acoustic data are shown in Figure 5.4.1 and Figure 5.4.2. The pulses of the different modems can be distinguished by their different amplitudes in Fig. 5.4.1 due to their different distances to the platforms. In the time-frequency domain in Figure 5.4.2 the frequency range of 7-17 kHz of the modems can be seen. The pulses have different distances to each other, which is due to the update frequency of the modems. With the help of the synchronization sequence of the modems it is possible to detect exactly the beginning of the pulses in the receiver. If the time instant of the modem transmission is known, the propagation time between transmitter and receiver can be determined and thus also the distance between them when the sound velocity in the water is known.

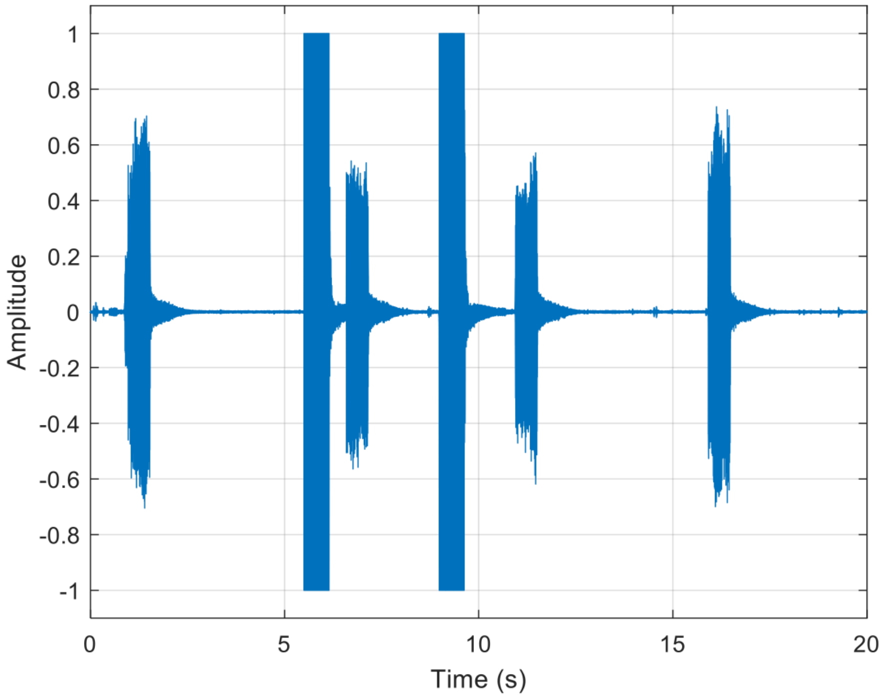

Fig. 5.4.1 Recorded pulses from different modems on different platforms in the time domain

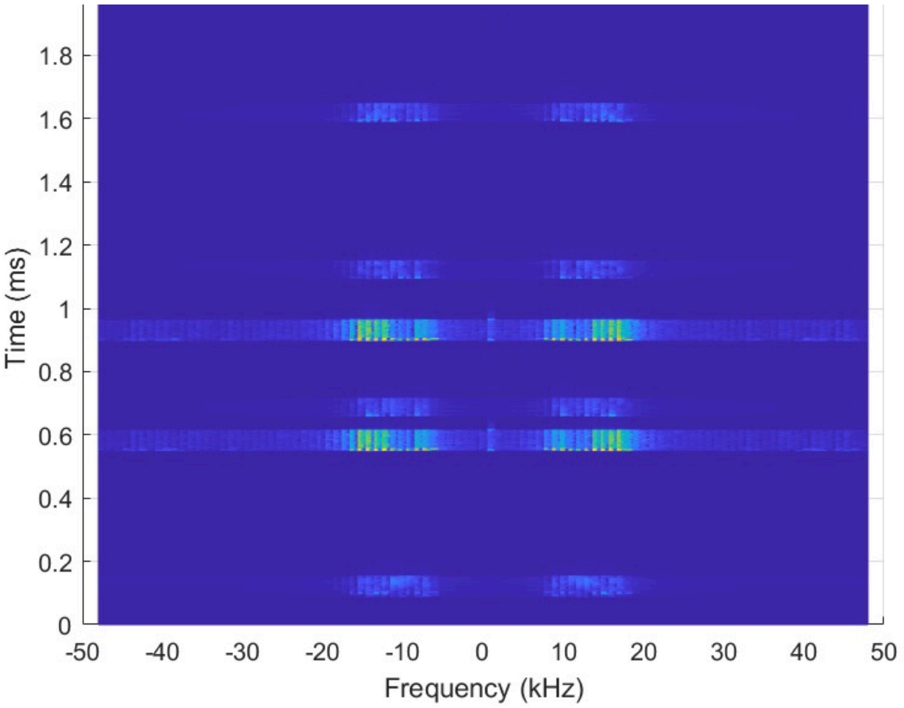

Fig. 5.4.2 Recorded pulses from different modems on different platforms in the time domain

5.5 Expected Results

Major aim of the ALKOR cruise AL547 was to establish and to operate an underwater interconnected, robotic sensing network, which was considered as the final demo-mission of the HGF funded ARCHES project. Despite limitations caused by the Covid pandemic we successfully set up a heterogeneous interconnected network from AWI and GEOMAR. We demonstrated that our sensing platforms were able to simultaneously acquire data at different location and share them on a server on the ship. We successfully manipulated and controlled online in situ measurements, which represents an important step towards future in situ experiments and measurements. By this we achieved the project goals outlined in the cruise proposal and the marine part of the ARCHES project. The field study as well as the software architecture of the network operational software including the Digital Twin Technology were already published or accepted for publication by Barbie et al. (2020, 2022). The software to operate the network was partly developed within the framework of the PhD thesis (ongoing) by Alexander Barbie in cooperation with the Software Engineering Group at the University of Kiel (Prof. Dr. W. Hasselbring). After completion of the thesis the software will become open source. Specific developments of the underwater network will be continued in the large scale HGF projects MUSE (Marine Environmental Robotics and Sensor Technologies for sustainable Research and Management of Coastal, Ocean, and Polar Regions) and iFOODis (Improving the sustainability of food cycles through intelligent (robotic) systems).

As science case ARCHES addressed the O_2 dynamic of coastal waters. The progressing loss of O_2 in coastal systems represents a pressing topic as it encompasses major implications for ecosystem health and functioning especially within the context of eutrophication and the increased occurrence of toxic sulfidic events with major implications for the society. The environmental data measured during the cruise served primarily to operate and to survey the functioning of the network. Whether the data base is large enough and the quality of the data sufficient for scientific publication depends on the further analysis of the data. In the future, the data might be combined with new data sets further including O_2 flux measurements.

6 Ship's Meteorological Station

RV ALKOR provides weather data, which are accessible through the D-Ship portal. Further weather data were obtained by the Kiel Leuchtturm weather station operated from GEOMAR. The data will be analyzed jointly with the O_2 and physical data as indicated in section 5.3. A weather service similar to that provided on RV METEOR is not provided by RV ALKOR.

7 Station List AL547

station #	date	time (UTC)	gear #	latitude N	longitude E	depth (m)	remarks
AL547_1	20.10.20	12:43	OFOS-1	54°32.004'	010°04. 422'	27	in water
AL547_2	21.10.20	07:01	MANSIO-1	54°31.324'	010°04.869'	17	deployment
AL547_3	21.10.20	10:40	OFOS-2	54°31.363'	010°04.923'	17	in water, com. test
AL547_4	22.10.20	07:29	MANSIO-1	54°31.312'	010°04.906'	16	retrieval
AL547_5	23.10.20	08:48	MANSIO-2	54°31.490'	010°04.795'	23	deployment
AL547_6	23.10.20	10:17	BIGO-I-2	54°31.558'	010°04.764'	23	Deployment[1]
AL547_7	23.10.20	10:47	FLUX-1	54°31.558'	010°04.854'	23	deployment
AL547_8	23.10.20	13:19	SLM	54°31.479'	010°04.276'	24	deployment
AL547_9	23.10.20	13:47	BIGO-I-2	54°31.555'	010°04.765'	23	retrieval
AL547_10	23.10.20	14:07	BIGO-I-3	54°31.557'	010°04.755'	23	deployment
AL547_11	23.10.20	14:32	FLUX-1	54°31.568'	010°04.775'	21	retrieval
AL547_12	23.10.20	15:03	CRAWLER SIM	54°31.524'	010°04.701'	23	deployment
AL547_13	24.10.20	07:21	FLUX-2	54°31.563'	010°04.873'	23	deployment
AL547_14	24.10.20	10:26	VIATOR-1	54°31.448'	010°04.859'	22	Depl., incl. WLAN
AL547_15	24.10.20	11:39	OFOS-3	54°32.136'	010°04.492'	26	[2]End 14:40
AL547_16	25.10.20	07:17	BIGO-I-3	54°31.563'	010°04.758'	24	retrieval
AL547_17	25.10.20	07:34	BIGO-I-4	54°31.397'	010°04.859'	20	effect of pycnocline
AL547_18	25.10.20	09:06	CRAWLER SIM	54°31.520'	010°04.709'	24	retrieval
AL547_19	25.10.20	13:17	FLUX-2	54°31.560'	010°04.873'	23	retrieval
AL547_20	25.10.20	13:34	MANSIO-2	54°31.494'	010°04.798'	23	retrieval
AL547_21	25.10.20	13:49	VIATOR-1	54°31.509'	010°04.787'	23	retrieval
AL547_22	26.10.20	11:26	OFOS-4	54°31.507'	010°04.796'	23	[3]End 12:42
AL547_23	26.10.20	14:14	FLUX-3	54°31.345'	010°04.824'	18	deployment
AL547_24	26.10.20	15:01	BIGO-I-5	54°31.373'	010°04.888'	18	deployment
AL547_25	26.10.20	15:32	MANSIO-3	54°31.355'	010°04.918'	17	deployment
AL547_26	26.10.20	16:12	CRAWLER SIM	54°31.421'	010°05.065'	19	deployment
AL547_27	27.10.20	09:35	MANSIO-3	54°31.360'	010°04.946'	17	retrieval
AL547_28	27.10.20	09:51	MANSIO-4	54°31.348'	010°05.023'	17	deployment
AL547_29	27.10.20	10:13	VIATOR-2	54°31.392'	010°05.126'	17	depl., WLAN buoy
AL547_30	28.10.20	07:04	CRAWLER SIM	54°31.428'	010°05.074'	19	retrieval
AL547_31	28.10.20	07:18	FLUX-3	54°31.346'	010°04.837'	17	retrieval
AL547_32	28.10.20	07:35	VIATOR-2	54°31.323'	010°05.065'	16	retrieval
AL547_33	28.10.20	07:49	MANSIO-4	54°31.342'	010°05.019'	16	retrieval
AL547_34	28.10.20	08:30	OFOS-BIGO	54°31.384'	010°04.913'	18	[4]recovery stopped
AL547_35	28.10.20	13:10	OFOS-5	54°31.361'	010°05.151'	17	13:40 aborted sensor
AL547_36	28.10.20	13:58	OFOS-5	54°32.111'	010°04.519'	26	[5]End 16:11
AL547_37	29.10.20	10:02	BIGO-I-5	54°31.362'	010°04.910	18	Recov. by Submaris
AL547_38	29.10.20	12:05	MANSIO-5	54°27.921'	009°51.072'	15	depl., A2 Submaris
AL547_39	29.10.20	12:16	VIATOR-3	54°27.910	009°51.162'	16	depl., A2 Submaris
AL547_40	29.10.20	13:44	FLUX-4	54°27.969'	009°51.157'	16	depl., A2

AL547_41	29.10.20	14:59	BIGO-I-6	54°27.889'	009°51.300'	17	depl., A2
AL547_42	30.10.20	07:40	BIGO-I-6	54°27.871'	009°51.323'	17	retrieval, A2
AL547_43	30.10.20	07:56	VIATOR-3	54°27.930'	009°51.115'	16	retreival, A2
AL547_44	30.10.20	08:08	MANSIO-5	54°27.918'	009°51.097'	15	retrieval, A2
AL547_45	30.10.20	08:24	FLUX-4	54°27.957'	009°51.156'	16	retrieval, A2
AL547_46	30.10.20	11:22	OFOS-6	54°32.123'	010°04.531'	27	profile #1
AL547_46	30.10.20	11:40	OFOS-6	54°31.889'	010°04.727'	25	profile #2
AL547_46	30.10.20	12:00	OFOS-6	54°31.613'	010°04.980'	23	profile #3
AL547_46	30.10.20	12:17	OFOS-6	54°31.372'	010°05.173'	18	profile #4
AL547_47	30.10.20	12:50	SLM Lander	54°31.477'	010°04.286'	25	retrieval

[1] deployment of BIGO-I-1 was aborted; [2] OFOS-3 (AL547-15) end of section: 54°31.362'N 010°05.137' 17m;

[3] OFOS-4 (AL547-22) end of section: 54°31.294'N 010°05.076' 16m; [4] 08:58 BIGO recovery was stopped

[5] OFOS-5 (AL547-36) end of section: 54°31.304'N 010°04.956' 16m.

8 Data and Sample Storage and Availability

The software developments and data collection were conducted within the project ARCHES (HGF). As the major focus was on tests and operation of the interconnected robotic network technical data were obtained, which are only of relevance for the engineering community of ARCHES and their partners. The results of the network tests and the operational software has been published by Barbie et al. (2020, accepted). After the completion of the PhD thesis of A. Barbie the software will become open source. Presently it's unclear whether the collected environmental data base is sufficient and its quality is good enough for publication. Until their further use, the platform specific environmental data will be hosted by the respective principal investigators, see section 2.1. If the data will be published, the data will be submitted to PANGAEA. Water- or sediment samples, or any other samples were not taken during ALKOR cruise AL547.

9 Acknowledgements

We very much thank Captain Jan Lass, the officers and the entire crew of RV ALKOR for their excellent support. They created a very professional working environment and contributed a lot to the success of this cruise. The friendly atmosphere aboard is greatly acknowledged.

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