

On the use of the HUGIN 1000 HUS Autonomous Underwater Vehicle for high resolution zooplankton measurements.

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Author's biography

Dr O P Pedersen completed his PhD (2000) with Professor K S Tande at the University of Tromsø and Professor D Slagstad (SINTEF), modelling zooplankton life strategies. As a research fellow at the University of Tromsø, he currently works with AUV technology and scientific applications. Dr P Lågstad got his PhD in Engineering Cybernetics at the Norwegian University of Science and Technology in 1998 and has been at the Norwegian Defense Research Establishment since, working with different aspects of AUV technology. Professor Tande received his Dr. Phil. in Marine Biology in 1992 from the University of Tromsø where he held a professorship up to 2008. He has been working with projects facilitating introduction of advanced marine platforms to study bio-physical processes in the ocean. He is a member of the Board of Ocean and Coast in the Research Council of Norway, and is now professor in ecosystem analysis at the Bodø University College. F Gaardsted holds a MSc in oceanography from the University of Bergen.

Synopsis

This paper evaluates and tests the HUGIN 1000 HUS AUV as a carrier platform for the Laser Optical Plankton Counter (LOPC). The LOPC was mounted outside on top of the carrier platform, and the tests confirm that this concept did not create turbulence and zooplankton avoidance. A negligible velocity difference between the flow passing through the sampling tube and the AUV speed was detected. The abundance recorded by the LOPC onboard HUGIN 1000 HUS was within the same order of magnitude compared to the zooplankton abundance from traditional net-based measurements. Our results showed zooplankton abundance in the range of 70 to 180 individuals m^{-3} , while other, traditional net-based measurements have indicated 27 - 332 individuals m^{-3} from the same area and same depth layer. Note that these numbers are minimum and maximum values observed from a vast number of samples. The mean is approximately 200 individuals m^{-3} .

The results provide new and unique high-resolution biological data of deep-water copepod communities. The application of AUVs in marine ecological research introduces advanced methodology with potential to address new scientific questions in deep water habitats.

Introduction

Sampling and identification of zooplankton has traditionally relied on conventional net sampling, like the Hydro-Bios MultiNet and MOCNESS¹. These are non-synoptic devices, and require substantial amount of manual operation and handling of biological samples during the survey, as well as time consuming processing in laboratory. Limitations on sampling approaches have to a large degree restricted scientific advances in zooplankton dynamics and ecology. The increasing demand for biological and physical data of high spatial and temporal resolution has promoted recent development of new instruments and sophisticated platforms.

During the 80s and 90s, the Laser Optical Plankton Counter (LOPC) and its predecessor, the Optical Plankton Counter (OPC) was developed². This was a non-invasive, highly automated instrument, which automatically counted and sized particles passing through a flow-chamber, hence greatly reducing the need of manual handling. These devices were further successfully mounted on vessel-towed, undulating platforms, like the SCANFISH (MacArtney A/S, Denmark), providing semi-synoptic zooplankton data along transects in surface waters³. Other recent advances feature 4 video technology, such as the Video Plankton Recorder (VPR)⁴, the ZooScan system⁵, and machines capable of pattern recognition^{6,7,8}.

Autonomous Underwater Vehicles (AUVs) for scientific purposes are now more readily available. AUVs are small, unmanned underwater robots, often similar to small submarines, without any physical connection to the mother vessel. They come in a range of sizes and capabilities, from 1 – 6 m in length, weighing between 30 to 3000 kg and having maximum depth ratings from 100 to 6000 m. Endurance varies between a few hours and a few days and is greatly dependent on cruising speed and the sensors applied. Generally, larger AUVs have higher depth range and longer endurance – and they have the ability to carry both large and/or multiple payload sensors. For scientific users, the main reasons for employing AUVs are the potential of significant reduction in time and costs compared to traditional methods, but also the retrieval of data with a higher spatial and temporal coverage compared to previous methods⁹.

Despite the rapid development of laser based instruments in plankton research and autonomous carrier platforms, the synergy of these two technologies has not been exploited to its full potential in marine science. A major proportion of plankton research is still net based,

while autonomous platforms are primarily used for physical oceanography, military purposes and in the oil industry. Generally, there has been a lack of appropriate data-intensive methods to provide the spatial and temporal resolutions required to quantify growth rates, mortality and advection of zooplankton communities. This paper attempts to describe how the usage of autonomous platforms can be extended into marine biology to improve the data insufficiency.

In the early 90's the Norwegian Defence Research Establishment (FFI) initiated research with respect to AUV technology, and a few years later FFI and Kongsberg Maritime (KM) joined forces and started the development of what has become the HUGIN family. Recognising that the AUV technology would have a major impact on various civilian fields in addition to the military applications, a dual use philosophy was adopted: By pooling the resources of the civilian and military AUV development communities, cost-efficient technologies were developed with civilian and military applications in mind¹⁰. The objective of this study is to evaluate and test the suitability of an AUV (HUGIN 1000 HUS as an autonomous instrument platform for the LOPC to measure copepod abundance and size distribution in deep waters. The platform is being tested on *C. finmarchicus* at their diapausing stage (stage IV /V), in their overwintering habitats in the NE North Norwegian Sea. Here it has been shown that the spatial variability of abundance of *C. finmarchicus* varies considerably and that the population of *C. finmarchicus* seems to be located in several 'hot spots' pulsing back and forth along the shelf break between the Barents Sea and the North Norwegian Sea^{11,12,13}. The aggregation of biomass is believed to be physically controlled by subsurface mesoscale eddies. However, our present understanding of the zooplankton overwintering habitats in this area is entirely based on studies using limited quantitative conventional net samples of zooplankton and point-samples of the hydrography¹⁴.

This study addresses a novel approach in marine science, using the HUGIN 1000 HUS AUV as a carrier platform for the LOPC. The results provide new and unique high-resolution physical and biological data, addressing the biological system described above with unprecedented resolution.

Materials and methods

Study area, current regime and survey conduction

The study was performed on the western border of the Barents Sea, along the continental slope between the Norwegian mainland and the Spitsbergen Archipelago (Fig. 1). This is a region where the Barents Sea, a relatively shallow shelf sea with a mean depth of approximately 230 m, slopes down into the NE Norwegian Sea. The depth in the study area is in the range of 1800 - 2200 m and several small canyons intersect the shelf break forming channels from the continental shelf into the deep basin areas.

The circulation in the western Barents Sea is influenced by the Norwegian Atlantic Current (NwAC) flowing northwards along the continental slope of Norway, transporting relatively warm and saline Atlantic water masses. When the NwAC enters the Norwegian Sea, the temperatures are in the range 6-9°C, and the salinity is 35.1-35.3. Further north, the temperature falls below 5°C, and the salinity is below 35.15. On the western side of Spitsbergen, this current changes name to the West Spitsbergen Current (WSC). For a synthesis and review of the physical oceanography in the Greenland, Iceland and Norwegian Seas (GIN Sea), see [15].

The survey was conducted during a 5 day period (19th – 24th of January 2009) and consisted of three vertically stacked survey grids centered at 71°N, 15°E (Fig. 1). Each horizontal survey grid consisted of interconnected latitudinal and longitudinal transects, covering approx. 780 km². The grids were placed at depths of 600, 800 and 1000 m (Fig. 2). The location of the survey grids and depths were chosen based on prior knowledge of this area, and the expected high abundance of the standing stock of copepods¹¹. Due to weather problems and technical challenges, the 600 m horizontal grid was not covered fully. Each horizontal grid was completed in 15-20 hours, depending on dive depth and current velocity.

The Laser Optical Plankton Counter (LOPC)

The details of the measurement principles of the LOPC are well documented elsewhere and will only briefly be repeated here². The LOPC counts and estimates the size of particles that move through a laser beam inside the instrument. This produces a size spectrum where particles are grouped according to their Equivalent Spherical Diameter (ESD). It is also

possible to estimate the volume of water passing through the LOPC from the transit time of small particles through the instrument¹⁷. From the count data and the flow data, the abundance of particles in the different size ranges can be calculated.

Zooplankton quantification in our study area in winter has traditionally been carried out by MultiNet sampling, and new approaches, such as LOPC sampling, need to be introduced with reference to this prior approach. To compare the two sampling methods, MultiNet and LOPC were applied simultaneously in January 2007. The LOPC was mounted on the inside of the MultiNet, vertical hauls were carried out and the results compared. It can be difficult to separate different species in an LOPC size spectrum as the signals from similarly sized species may overlap. However, in the winter deep water off the coast of northern Norway, *C. finmarchicus* is by far the most abundant species (>80%) and the low species diversity makes the possibility of interference of the *C. finmarchicus* signal insignificant. The results from the LOPC / MultiNet comparison in fact showed that the LOPC was well suited as a stand-alone tool for *C. finmarchicus* quantification in this area in the winter season¹⁴. In this study, we take advantage of these results, assume that an ESD range from 960 µm to 1260 µm represents *C. finmarchicus*, stages IV and V.

The HUGIN 1000 HUS AUV System and the LOPC integration

The available power, volume and weight determine the number and types of sensors any particular AUV can carry. Hitherto, AUVs have typically been equipped with one or more of the following sensors: Side scan sonars (SSS), synthetic aperture sonars (SAS), multibeam (MBE) and fishery echo sounders, sub-bottom profilers (SBP), CTD sensors, acoustic doppler current profilers (ADCPs), video and still image cameras, optical backscatter (OBS) sensors, chemical sniffers and magnetometers. Other, more specialized sensors (as shown later in this paper) have also been integrated to some AUVs. When it comes to integrating sensors, the main difference between an AUV and a remotely operated vehicle (ROV) is the power constraints an AUV has to operate under. But for some sensors the inherent stability of an AUV can also significantly improve the quality of the data.

The first HUGIN class AUV specifically designed for military and civilian scientific application was delivered in 2008. HUGIN 1000 HUS, the most common member of the HUGIN class AUVs, is around 5 m long, has a dry weight of 600-900 kg, a nominal speed of

2-6 knots, depth range extending down to 3000 m and an operational time span of up to 30 hours. This AUV is primarily intended for use in arctic and sub-arctic waters. It is not only designed to be equipped with a range of different, interchangeable scientific sensors, it also has a modular design allowing for easily interchangeable/extendable centre sections. This facilitates a multi-purpose philosophy where different research projects or groups can equip the AUV with sensor packages tailored to meet specific research objectives. This ability is ideal from an efficiency and resource perspective.

The main concern when integrating the LOPC, was to ensure the water-flow through the sensor and at the same time make sure the pressure front from the vessel did not affect the behavior of the zooplankton (turbulence and avoidance) – whilst ensuring the safe operation of the vehicle. This resulted in an almost narwhal-like design (Fig. 3AB). As later shown in this study, the design proved successful, meeting the criterion of a minimal velocity difference between the flow passing through the LOPC sampling tube and the AUV speed. This was computed by the internal navigation system of the AUV, measuring the speed of the AUV propelling through the water, whilst comparing this velocity with the flow measured independently by the LOPC. Ideally, they would show the same velocity, indicating that the flow through the LOPC tube was undisturbed by the platform motion. Results from these measurements are shown further on. The other criterion required was the consistency between LOPC based measurements of zooplankton abundance and traditional net-based measurements.

Data analysis

For interpolation of the collected data, Objective Analysis (OA) was applied¹⁶. OA is a synonym for statistical estimation based on the Gauss-Markov theorem. The major benefit of OA is that the method yields an estimate at every point (x, y, z, t) which is optimal to the least square error. Along with the interpolated field, an errorfield is calculated. With this method, the correlation function can be direction specific, being especially useful in anisotropic physical fields.

The dataset was smoothed and filtered through several steps. This was done in order to reduce the actual number of data points relayed into the interpolation routine, but also to remove

high-frequency variability. The horizontal spatial fields were blocked and averaged into ensemble sizes of 360 datapoints (approx. 3 minutes of sampling time, on the average equivalent to 350 m). This proved to be a reasonable, heuristic approach, where spatial structures in the dataset were clearly identified, whilst numerical artifacts from the interpolation were avoided.

Results

Each horizontal layer covered (at 600, 800 and 1000 m) is considered as an AUV mission. During the survey, three separate AUV missions were conducted. The 600 m mission was aborted due to operational difficulties, and the data from this depth is not presented. The 800 m mission consisted of four long and three short transects, while the deepest at 1000 m had three long and three short (Fig. 2 and 4). At these levels, the abundance of *C. finmarchicus* ranged from 70 to 180 individuals m^{-3} (Fig. 4). At 800 m, the highest concentrations were found in the northern part of the survey grid, with two well defined hot-spots at the northern side of transect 2 and 4. At 1000 m depth, the situation was reversed. The highest concentrations were located in a longitudinal strip in the southern part of the survey grid. This high-abundance region stretched across the entire survey grid in a consistent and well-defined pattern. The corresponding 2D bird's eye view of error fields from the OA algorithm are shown in Fig. 5.

The AUV performed according to plan, both with respect to navigational performance and as a carrier platform for the LOPC. The AUV was able to conduct all pre-programmed mission plans. Whilst performing the different missions, *in situ* zooplankton size distributions were relayed to the survey vessel continuously, along with navigational data. When the AUV was retrieved after completion of each mission, the raw data, stored in the AUV computer, was downloaded and analyzed.

Discussion

The HUGIN 1000 HUS AUV as an instrument platform

Field operational techniques at sea generally have one basic requirement: A survey ship to transport and operate the sampling device, either towed or dropped vertically. Traditionally, there has been a tethered connection between the sampling device and the survey vessel (e.g. a wire), and cable drag and length have posed significant limitations with respect to performance. This is also the situation for ROVs. SCANFISH is another example with a practical dept range of 150 m. Other, more classical approaches, like the MultiNet, faces challenges with respect to time and synopticity. One MultiNet cast can typically take 1-2 hours, depending on the depth; hence the number of point samples will be limited and restricted by the survey duration. The introduction of an AUV as instrument platform ideally removes the limitations posed by a direct physical link between the survey vessel and the sampling device. Manual operations on deck and manual processing of biological samples are also limited to a minimum. AUVs can penetrate down to 3000m or more, operate in fully autonomous mode, relay synoptic data in real time and be reprogrammed while *en route*. As pointed out by [1] “*We can anticipate a development of real-time four-dimensional plankton sampling and concurrent environmental measurements systems, and ocean-basin scale sampling with autonomous vehicles*”. The development and the application of HUGIN 1000 HUS in marine science is a direct response to these predictions.

Other unmanned, submerged vehicles, like the Spray glider designed by Woods Hole Oceanographic Institution and Webb Research Corporation, is designed to be self propelled. This glider harvests energy for propulsion from the differences in temperature between warm surface waters and colder, deeper layers of the ocean. However, battery capacity is still required to operate sensors onboard. The positioning of the glider is based on GPS fixes obtained when surfacing, and the data is relayed by satellite to ground services concurrently. This is contrary to the HUGIN 1000 HUS, which is able to georeference the craft at any given time, whilst transmitting data through an acoustic communication link. However, while the HUGIN 1000 HUS has to be brought on deck for battery recharge, the low power consumption by Spray glider allows it to stay *en route* for months at a time, making it practically independent of a survey vessel. The disadvantage of the Spray Gliders is the slow

speed (max 0.25 m s^{-1}), which makes them suboptimal for surveys near strong fronts or coastal jets, while AUVs with higher nominal velocity can overcome the strong currents and provide the rapid sampling required. There is a whole suite of AUVs on the market besides HUGIN, e.g. the ABS/Sentry, Jaguar, Puma, Remus and SeaBed. They all have different advantages and disadvantages, which define their scientific scope and versatility. It is beyond the scope of this paper to do a comparative analysis of the whole suite of AUVs available on the commercial market. The major advantage of the HUGIN 1000 HUS is the modular system, the depth range, the *en route* georeferencing and two-ways acoustic communication. Few other systems can display these characteristics combined and the potential versatility. The HUGIN 1000 HUS can also operate in fully autonomous mode, i.e. without any acoustical communication or accompanying mothership. On such instances, the AUV follows a preprogrammed mission pattern, and is able to georeference itself by acquiring GPS-fixes entering the surface and utilizing inertial positioning.

Data validity – Proof of Concept of the HUGIN 1000 HUS / LOPC System

Since there is no straightforward way to take separate and independent *in situ* samples of zooplankton while conducting the HUGIN surveys with the LOPC, we have to assess the quality of our data indirectly from other sources. In between HUGIN missions, we took two LOPC profiles while running CTD casts, using the same set-up as described in [14]. These were taken at transect two and four (Fig. 4), and confirmed the vertical range of copepods with maxima in numbers between 600 m and 1200 m (Fig. 6 and 7). The zooplankton abundance measured by the LOPC mounted on the AUV, showed a concentration between 100 and 150 individuals m^{-3} at the position of the CTD cast along transect 2 (Fig. 4A) and a concentration between 75 and 155 individuals m^{-3} at the position of the CTD cast along transect 4 (Fig. 4B). How well do these numbers match with data obtained from the same LOPC instrument, mounted on the CTD a rig during a vertical cast? The zooplankton abundance measured with the LOPC lowered vertically showed a concentration between 95 and 150 individuals m^{-3} at the position of the CTD cast along transect 2 and between 80 and 120 individuals m^{-3} at the position of the CTD cast along transect 4 (Fig. 7). A blow up of the profile data in the region relevant to the AUV horizontal tracks are shown in Fig. 8. The vertical profiles are calculated with a moving average window and summarized in Table 1.

	Transect 2 [individuals m ⁻³]	Transect 4 [individuals m ⁻³]
LOPC mounted on HUGIN (horizontal measurement)	100 - 150 (Fig. 6)	75 - 155 (Fig. 6)
LOPC mounted on a CTD rig (vertical measurement)	95 - 150 (Fig. 7)	80 - 120 (Fig. 7)

Table 1. Comparison between zooplankton abundance measurements from the LOPC mounted on HUGIN or the vertically lowered CTD rig.

The readings from the LOPC mounted on the HUGIN shows very little discrepancy at both transects compared to the readings from the LOPC used in the CTD cast mode (Fig. 6 and 7). Actually, along transect 2, the results are strikingly similar, while a slightly bigger discrepancy occurs at Transect 4. *We therefore conclude that the LOPC operated from HUGIN as a carrier platform record the abundance and the size spectrum similar to the cast mode operation from a research vessel.* This is as close we can get to establish confidence to the HUGIN as a carrier platform for LOPC in deep waters.

At any given time while the HUGIN 1000 HUS / LOPC is on a mission, a particle size distribution is transmitted to the survey ship and displayed in real time. Hence we were able to monitor, record and assess the sampled size spectrum in real-time while conducting the missions. The size spectrums showed the distinct signature for *C. finmarchicus* stage IV/V. An example of the size spectrum obtained is shown in Fig. 9. This was also apparent from the analysis of the raw data. Both prior knowledge regarding species composition for our survey area and the observed size spectrum support the assumption that the data shows *C. finmarchicus* stage IV/V.

Platform dynamics

When mounting the LOPC on the HUGIN 1000 HUS, we were aware that the long tube would give rise to increased roll during turns. The added weight on top of the vessel also changed the metacentric height of the AUV, also affecting the roll stability during turns. The HUGIN 1000 HUS is equipped with active roll stabilization, but due to increased power

consumption this is only used when extra roll stability is needed. Since the LOPC missions were conducted offshore, where the turn ratio is of no importance, the maximum rudder deflection was reduced by 50%, thus keeping the roll during turns in check (Fig. 10). Note that the roll without the LOPC mounted is with the normal maximum rudder deflection value. The active roll stabilization was not active in either run.

Another vital issue during the design phase was to ensure that the water flow through the LOPC sampling tube was undisturbed by vessel movement or vessel-induced turbulence. Hence the sampling tube was designed to be fairly long (Fig. 3) and protrude past the wave front or potential turbulence created at the head of the AUV. Ideally, the water flow through the LOPC sampling tube and the measured velocity of the AUV should be comparable, or within the same level. The ground referenced velocity of the AUV in x-direction is shown in Fig. 11. The x-direction relates to the AUV-fixed coordinate system and x velocity is then in along-ship direction. The velocities measured were generally in the range of $1.9 - 2.1 \text{ ms}^{-1}$, with a mean velocity of 1.95 ms^{-1} . As seen, during the mission, the AUV velocities changed markedly. This is caused by the combined effect of residual currents and tidal fluctuations. Considering merely the residual current, when the AUV is moving upstream, a decrease of velocity is expected, and conversely when moving downstream. However, tidal currents can potentially change this situation significantly. It depends on the relative magnitude between the tidal currents and the residual currents in the survey region, but also on the diurnal and monthly tidal cycle.

The calculated water velocity from the LOPC sampling tube is shown in Fig. 12. It has a mean velocity of 1.48 ms^{-1} for the entire mission at 1000 m depth. This amounts to 75% of the mean AUV velocity. However, the AUV velocity is earth referenced, and does not show the absolute velocity through the water column. Hence, any current movement or fluctuation will create deviations between ground referenced velocity and water column velocity. The sampling area is located on the continental margin of the western Barents Sea (Fig. 1). The NwAC flows northwards along this slope with velocities in the range of 0.2 ms^{-1} . In addition to this, the region also has subsurface mesoscale subsurface eddies, adding complexity to the current regime. This will create an offset between ground referenced velocity and water column velocity, which is a plausible explanation for the 25% discrepancy observed between LOPC water flow calculations and AUV ground referenced velocity.

Future applications

With respect to zooplankton measurements, using an LOPC sensor with the HUGIN 1000 HUS as a carrier, introduces a whole suite of novel possibilities. It is feasible to get semi-synoptic and high-resolution measurements over large areas and volumes, getting far more detailed information at a much higher rate than earlier. Given the current properties of the HUGIN AUV, it is now possible to conduct efficient measurements at depths down to 3000 m. Furthermore, using an AUV as a platform, introduces a new range of choices with respect to sampling strategy. One possibility would be to let the AUV actively search for large concentrations of zooplankton or map the spatial extent of the concentrations. Another option would be to let the AUV follow different types of oceanographic gradients (temperature, pressure, salinity etc.) and determine whether there is any correlation with the zooplankton abundance or species composition. Bearing this in mind it is also important to be aware of the limitations of using an AUV as a platform, which are mostly speed and battery capacity. Work in AUV design and operation is already addressing battery technology and energy consumption in order to increase operational range and to limit demands for recharging of batteries. Whilst getting extraordinarily detailed data from a specific area, spatial coverage of larger areas is limited at present. Consequently, AUVs are a potentially powerful new platform, supplemental to other tools in this field of science.

Conclusion

As the commercial market for AUVs matures and the number of operational systems rises, we can expect the reliability of AUVs to increase and the cost to go down. This will increase the number and types of possible applications. For the scientific community in particular, this will mean that AUV technology will become much more readily available, and open up opportunities for new and novel uses. However, in order to capitalize on this technological development, the scientific community needs to focus on how to optimize use of AUVs with the focus on new or improved sensors, new applications and new operating areas. The HUGIN 1000 HUS AUV equipped with the LOPC, targeting deep-water zooplankton communities, performed according to the preplanned missions and has proved capable of providing high-resolution data of zooplankton abundance and size classes. The AUV collected zooplankton abundance and size data, and the data was also transmitted in real time

to the survey vessel. The data shows a number of deep-water zooplankton patches on the mesoscale order.

Acknowledgements

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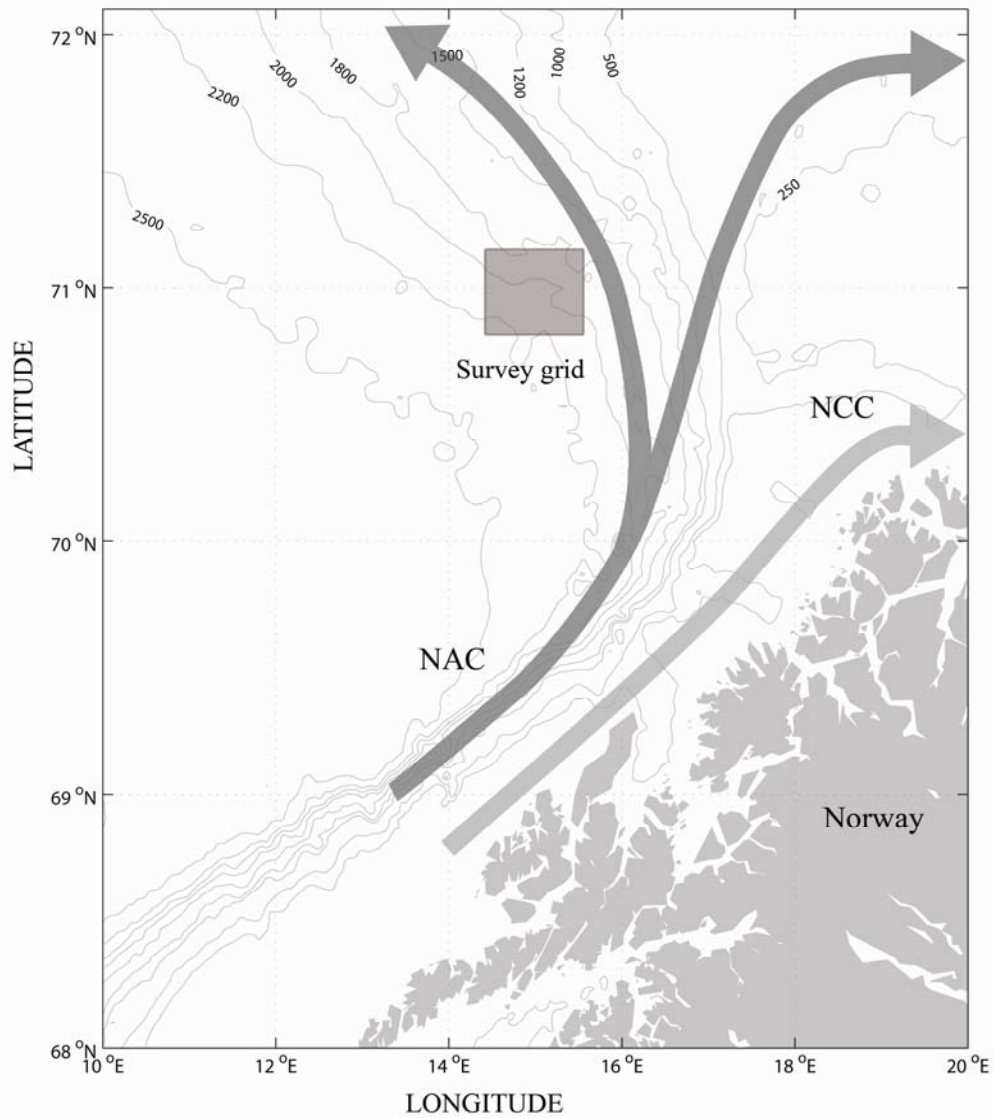


Fig. 1. Study region (grey square) including idealized surface circulation map.

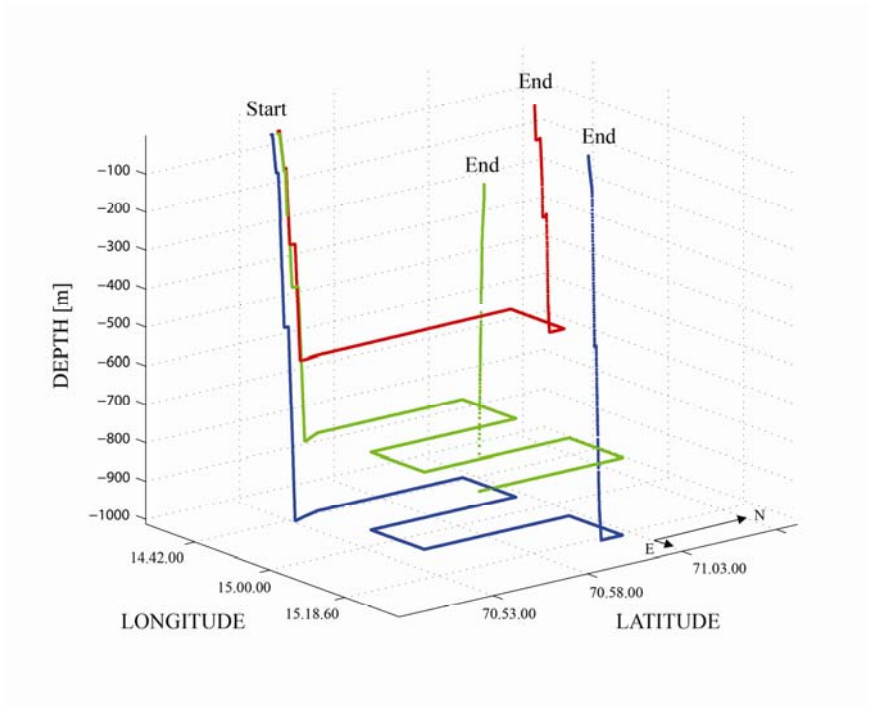


Fig. 2 The 3D HUGIN Survey tracks.



Fig. 3. A) The HUGIN 1000 HUS AUV during a launch sequence. The AUV is released from a hydraulic sledge system mounted at the stern of the ship. The AUV system is designed as a stand-alone, container based system and can be released and controlled from any survey vessel having the required facilities. B) The HUGIN 1000 HUS AUV with the LOPC mounted on top.

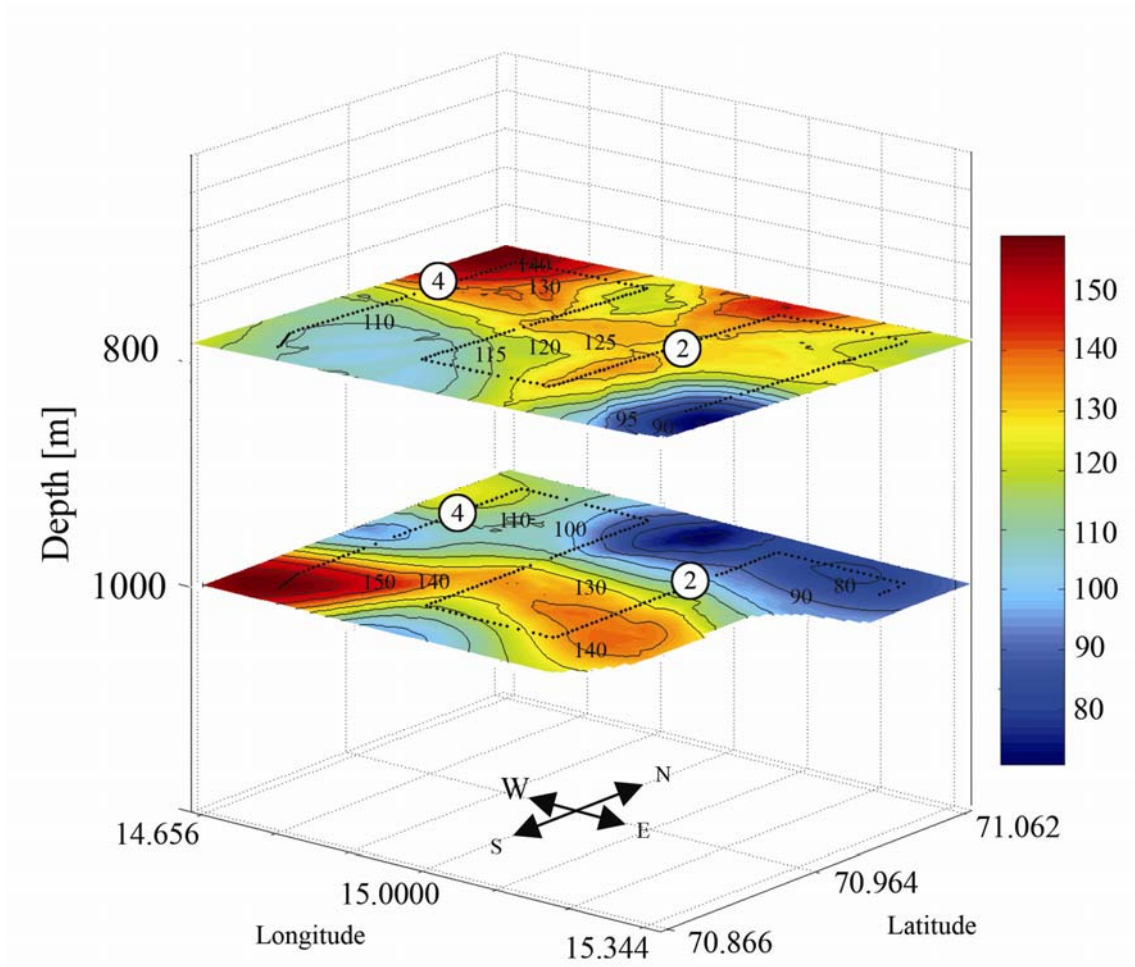


Fig. 4. *C. finmarchicus* abundance [ind m^{-3}] at 800 m and 1000 m measured with the HUGIN 1000 S / LOPC System. 2 and 4 refers to transect numbering adressed in the text.

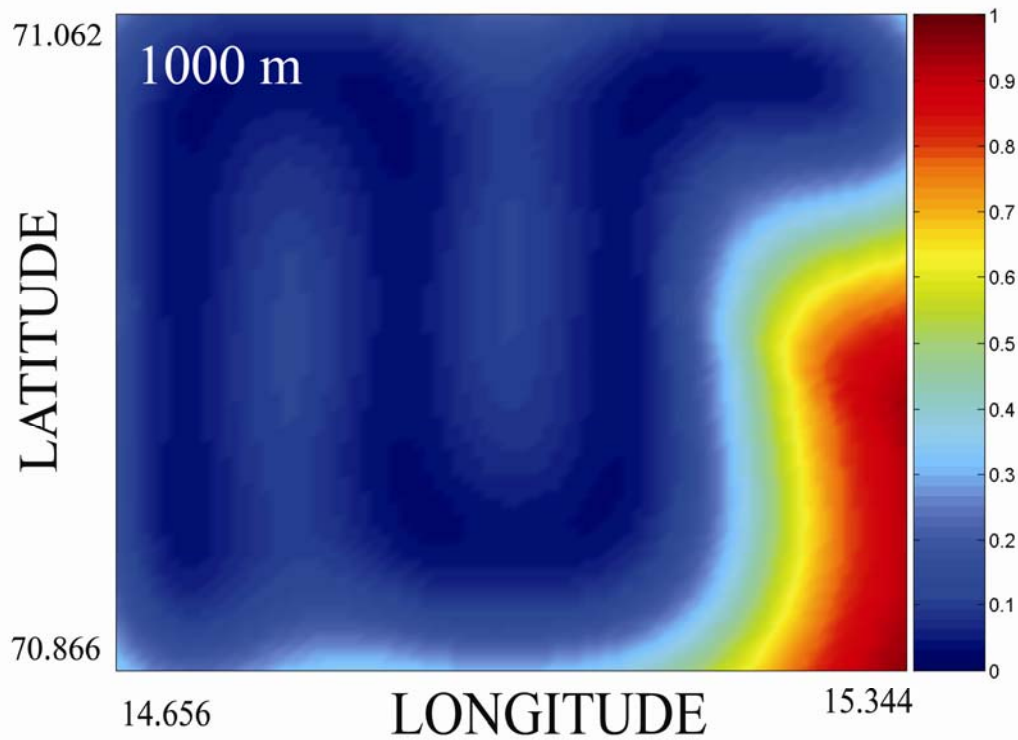
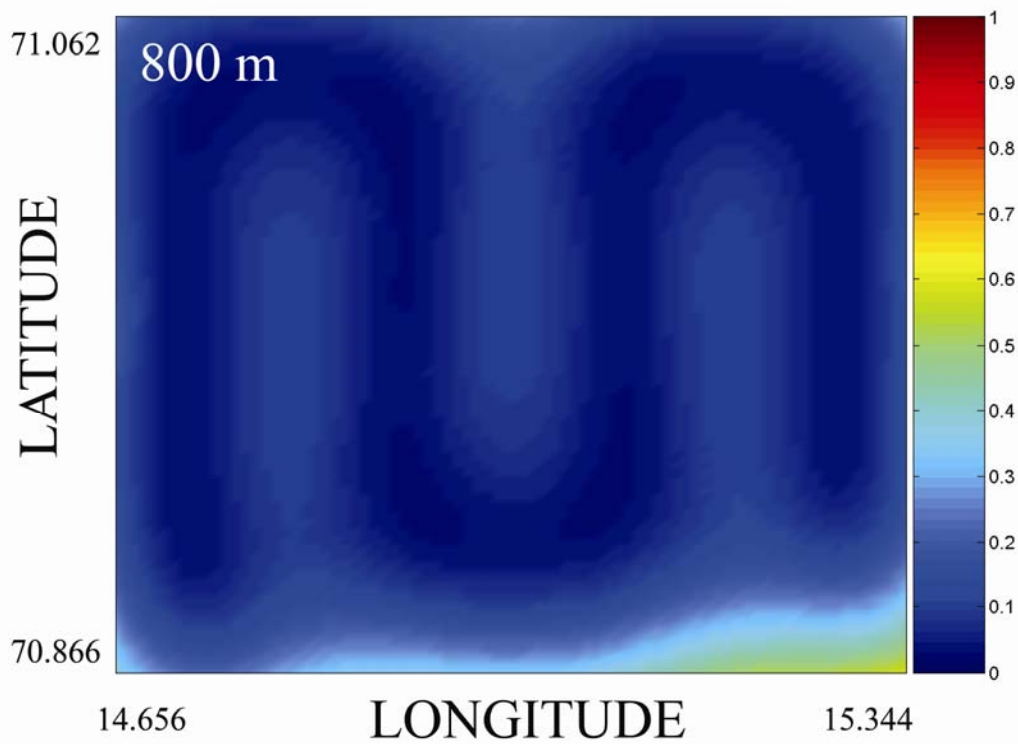


Fig. 5. Error fields from the OA interpolation at 800 m and 1000 m.

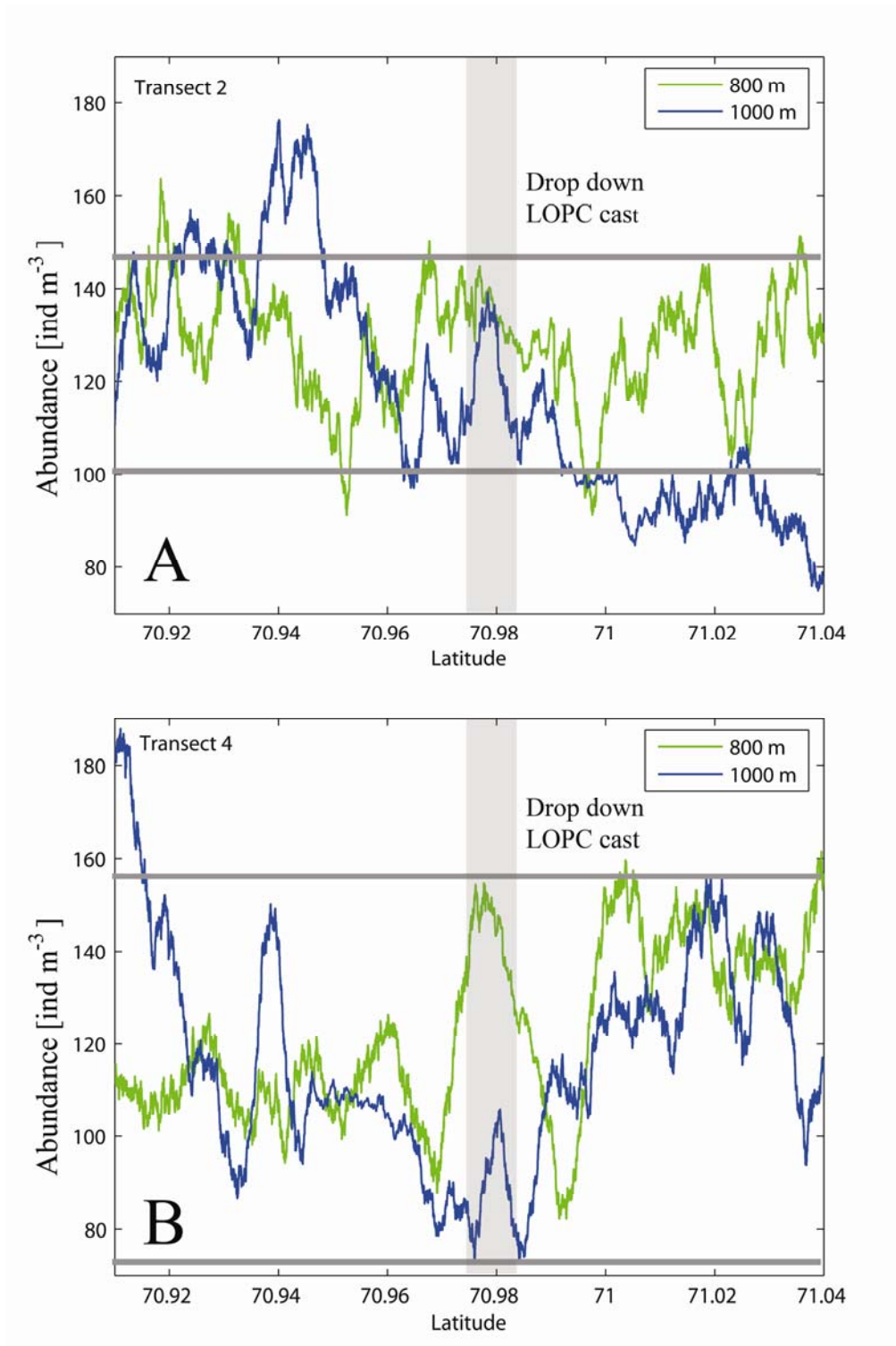


Fig. 6. *C. finmarchicus* abundance [ind m⁻³] along Transect 2 and 4 (See Fig. 4) as measured by the HUGIN / LOPC System.

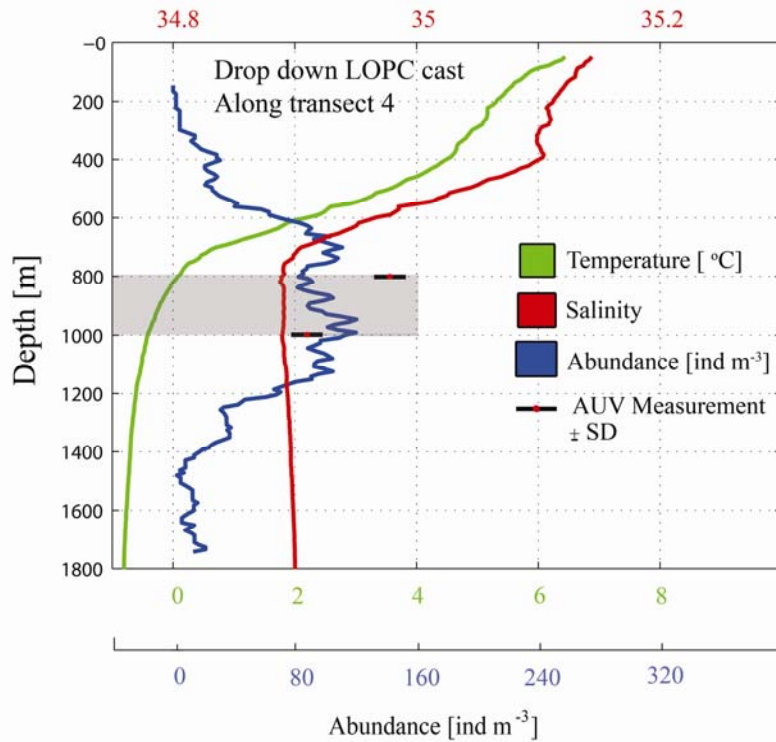
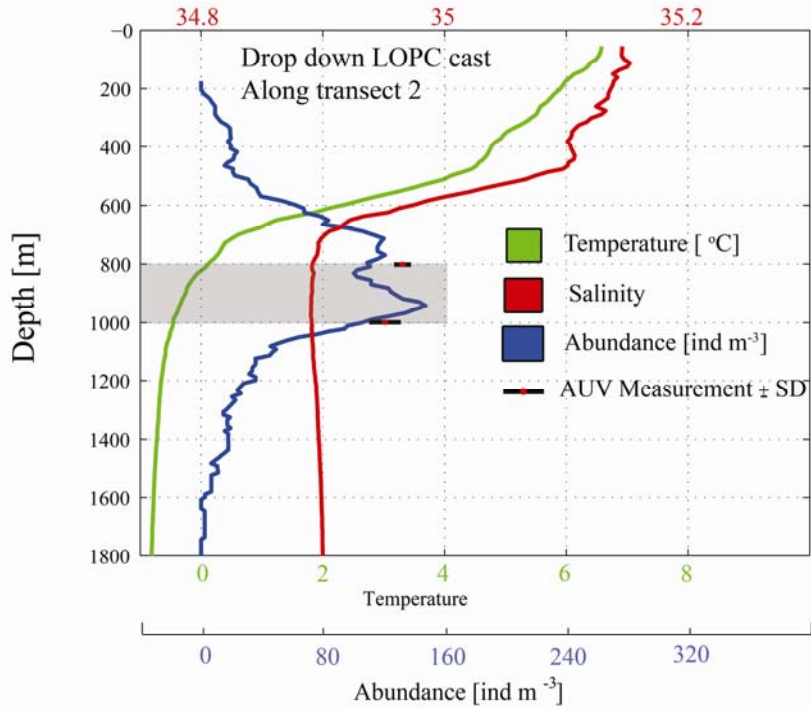


Fig. 7. Drop down measurements of *C. finmarchicus* abundance at two stations along Transect 2 and 4. (See Fig. 4). The LOPC was mounted on a CTD rig and lowered vertically.

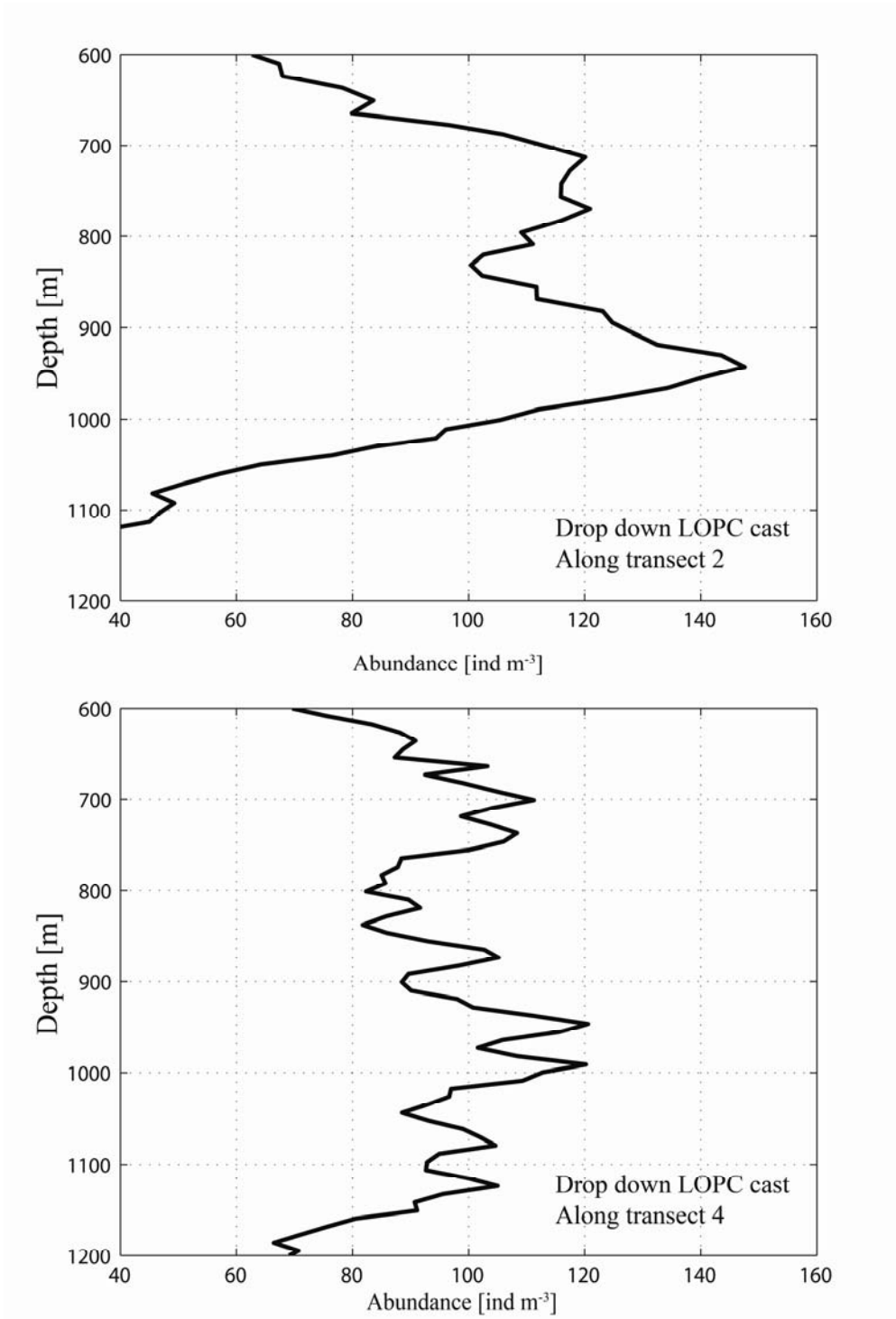


Fig. 8. A blow up of the zooplankton abundance data in the region relevant to the AUV horizontal tracks.

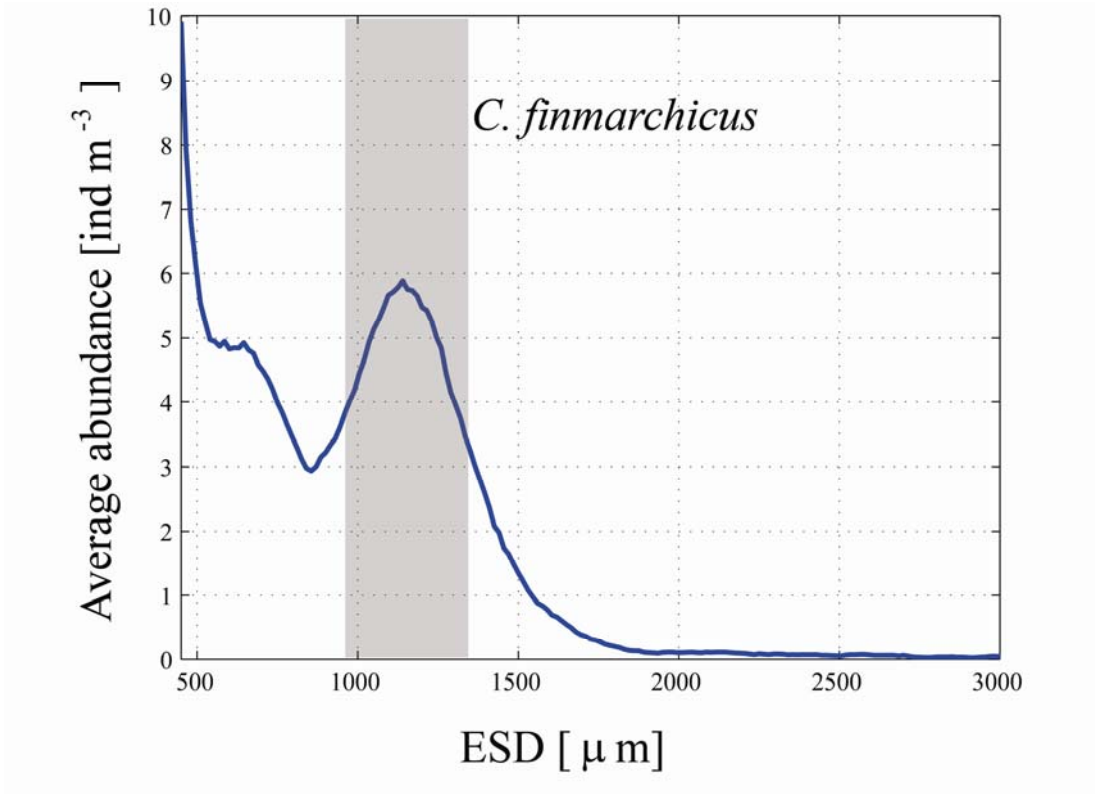


Fig. 9. A sample size spectrum obtained from the LOPC / HUGIN AUV.

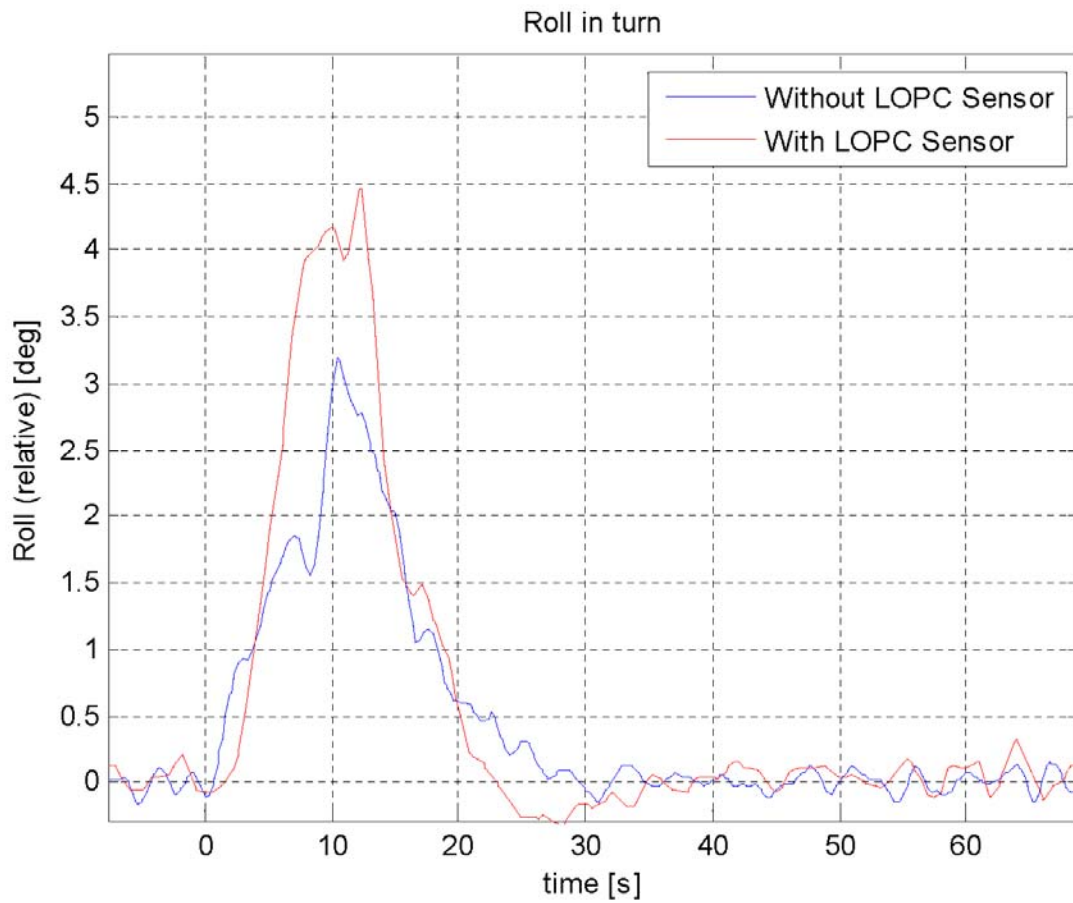


Fig. 10. A comparison of the AUV roll [deg] in a turn with and without the LOPC sensor.

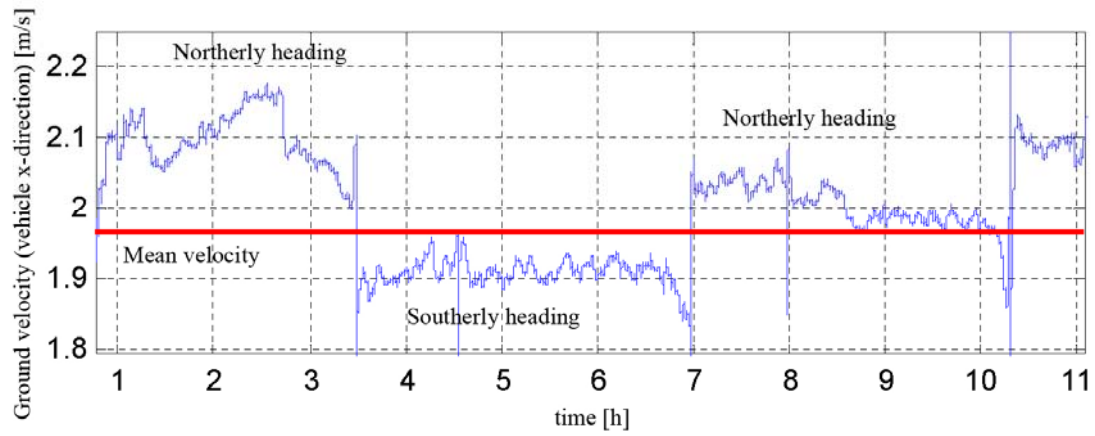


Fig. 11. AUV ground referenced velocity in x-direction as calculated by the onboard navigational system.

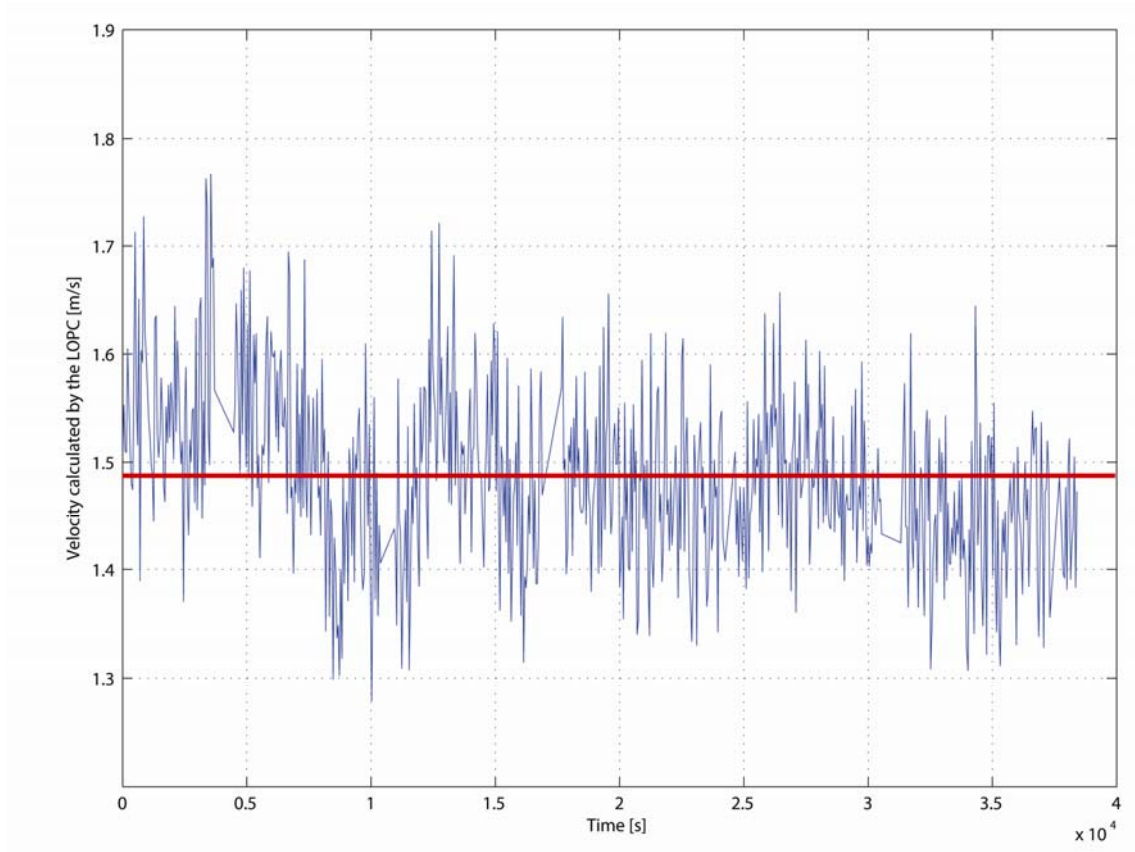


Fig. 12. Water velocity as measured through the LOPC sampling tube for (mission at 1000 m depth).

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