FINAL REPORT: ACOUSTIC ESTIMATION OF FISH SIZE DURING PRE-CATCH IN COMMERCIAL FISHING OF PELAGIC SPECIES

FHF 901795

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Nils Olav Handegard and Atle Totland (IMR)

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Summary (English):

Fish size is critical for fishermen, as they aim to catch larger fish for higher market prices while avoiding areas with banned or low-value undersized fish. Current acoustic fish-sizing methods lack sufficient accuracy during the precatch phase of commercial fishing. This project aimed to use a combination of a narrow acoustic beam and broadband signal echosounder—state-of-the-art methods—for detecting single fish at an operational range suitable for purse seining or surface pelagic trawling.

An EK80 echosounder system with a 200-3C transducer directed horizontally was mounted on the drop keel of the FV Libas during mackerel commercial fishing in UK waters in 2024. This setup was ideal for continuous data collection without interfering with fishing operations. To ensure high-quality acoustic data, measures were implemented to mitigate noise sources and acoustic interference.

The results included broadband data (160-260 kHz) of single mackerel detected up to 100 meters from the fishing vessel, meeting the project's original aim.The fish sizing method, which proposed using the two peaks in the pulse-compressed signal in the time domain, could not be applied, as the broadband data for a single fish was more complex and lacked this feature. These findings were validated through theoretical modeling of fish and backbones.

Preliminary results suggest that the use of the maximum TS from fish tracks close to normal incidence angle could be an alternative method to compute fish size. However, size estimations did not reach the expected level of accuracy and will require robust methods for fish tracking and target strength computation from broadband data.

Additionally, it was suggested to collect data from free-swimming mackerel around salmon net pens or caged mackerel inside large pens (approximately 100 meters in diameter). This setup would facilitate easier access to acoustic data, similar to the conditions present in offshore fishing grounds.

Summary (Norwegian):

Fiskestørrelse er avgjørende for fiskere, ettersom de sikter mot å fange større fisk for høyere markedspriser samtidig som de unngår områder med forbudt eller lavverdig småfisk. Nåværende akustiske metoder for størrelsesbestemmelse av fisk mangler tilstrekkelig nøyaktighet i forkant av fangsten under kommersielt fiske. Dette prosjektet hadde som mål å bruke en kombinasjon av en smal akustisk stråle og bredbånds ekkoloddsignal—moderne metoder—til å oppdage enkeltfisk innenfor en operasjonell rekkevidde som er egnet for not- eller overflatepelagisk tråling.

Et EK80 ekkoloddsystem med en 200-3C-svinger ble montert på senkekjølen til FV Libas under kommersielt makrellfiske i britiske farvann i 2024. Oppsettet var ideelt for kontinuerlig datainnsamling uten å forstyrre fiskeoperasjonene. For å sikre høy kvalitet på de akustiske dataene ble det gjennomført tiltak for å redusere støy og akustisk interferens.

Resultatene inkluderte bredbåndsdata (160-260 kHz) fra enkeltmakrell som ble detektert opptil 100 meter fra fiskebåten, og oppfylte prosjektets opprinnelige mål. Fiskskjemetoden, som foreslo å bruke de to toppene i den pulskomprimerte signalet i tidsdomenet, kunne ikke anvendes, da bredbåndsdataene for en enkelt fisk var mer komplekse og manglet denne funksjonen. Disse funnene ble validert gjennom teoretisk modellering av fisk og ryggbein.

Foreløpige resultater tyder på at bruken av maksimal TS fra fiskespor nært normal innfallsvinkel kan være en alternativ metode for å beregne fiskestørrelse. Imidlertid nådde ikke størrelsesestimatene det forventede nøyaktighetsnivået og vil kreve robuste metoder for fiskesporing og beregning av målstyrke fra bredbåndsdata.

I tillegg ble det foreslått å samle data fra fritt svømmende makrell rundt laksemerder eller fra inngjerdet makrell i store merder (ca. 100 meter i diameter). Dette oppsettet vil gi enklere tilgang til akustiske data som i større grad gjenspeiler forholdene på offshore fiskefelt.

Content

1. Background

The size of the fish in the catch is important information for fishermen. It usually affects the selling price, and in many fisheries, there are also regulations for minimum allowable size. Typically, fish size is identified at a late stage of the catch, often only when the fish are pumped on board. Identifying fish size before the catch would make fishing more efficient and sustainable.

Manufacturers of modern echo sounders suggest that individual fish size can be estimated using data from modern narrowband echo sounders (Sonic Corporation, 2022; Simrad, 2017; Furuno, 2018). The strength of the echo from the fish (target strength) is converted to fish length based on a model where the relationship between target strength and fish length depends on the orientation of the fish relative to the acoustic beam (Peña and Foote, 2008). The challenge is to calculate the direction of the measured fish relative to the acoustic beam. Another issue with estimating the size of pelagic fish swimming in schools is that the fish in the school are so densely packed that it is not possible to detect and resolve individual fish, which is necessary to determine the target strength of the fish. Traditional fishing echo sounders typically have a beam opening angle between 7 and 25 degrees, and with such beam widths, it is generally not possible to distinguish individual fish in schools.

Using new signal processing methodologies, modern broadband echo sounders provide significantly higher range resolution compared to traditional single-frequency echo sounders (Ehrenberg and Torkelson, 2000). Furthermore, methods for estimating fish size with broadband technology have been developed (Kubilius et al., 2020). Fish size can be calculated from acoustic data using echo intensity from a single fish in either the time or frequency domain (Kubilius et al., 2022). Controlled experiments have shown that this method, combined with data collected using a narrow acoustic beam (3° beam angle), has the potential to provide estimation of fish size. In theory, the resolution should be high enough to distinguish individual fish in a school, but there is a need to test the methods under realistic conditions and adapt instrumentation and analysis methods for use in commercial fishing.

Fishermen need real-time information about fish schools (quantity, species, and individual size) before the catch to decide whether the fish are of the desired species and size. This requires effective solutions for collecting and handling large amounts of data, as well as analysis methods that provide accurate information about fish schools. The Institute of Marine Research (HI) has experience from previous projects in collecting and analyzing acoustic data from multi-frequency echo sounders in real time for species and size identification (e.g., the projects NYTID FHF 900166 and DABGRAF 900774), knowledge and experience that will be utilized and further developed in this project.

In this project we have developed and tested a system for measuring the size distribution of herring and mackerel under commercial conditions. Field experiments were conducted using research vessel GO Sars and fishing vessel Libas. The idea was to develop and test the concept and if successful, continue the development in a business-led initiative with the goal of developing a commercial product for the fishing fleet (transducer and software).

2. Objectives

The main goal was to develop and test a concept for size estimation of pelagic fish in commercial fishing using broadband echo sounders. Specific objectives were:

1. Adapt and test a narrow-beam broadband echo sounder for deployment on the retractable keel of GO Sars and Libas.
2. Collect data to test methods for estimating fish size distribution in herring schools (GO Sars).
3. Collect data to test methods for estimating fish size distribution in mackerel schools (Libas).
4. Evaluate the accuracy of the estimated size distribution of herring and mackerel.
5. Facilitate the continuation of the concept into a commercial product.

This project is linked to the Centre for Research-based Innovation in Marine Acoustic Abundance Estimation and Backscatter Classification (CRIMAC, crimac.no), where both HI and the Liegruppen are partners.

3. Assessment of industry benefits and potential use of results

The results of the project will form the basis for a tool that provides fishermen with information about the size distribution in pelagic fish schools during commercial fishing before deciding to deploy a trawl or seine net. In the short term, theoretical methods for size estimation and small-scale experiments conducted in previous projects (e.g., Dabgraf , FHF 900774, and AcoSize , NFR 255589) will be validated and adapted to the conditions of commercial fishing. The project will also facilitate the continuation of the concept into a commercial product.

In the long term, the results can be used to develop a complete commercial tool for size estimation of pelagic fish during commercial fishing. This tool would include sonar/echo sounders tailored for measuring and estimating the size of individual fish, along with accompanying software for analyzing and visualizing the data. Such a tool would provide fishermen with a better foundation for selecting fish of optimal size, potentially increasing the value of the catch while avoiding fish below the minimum size requirements.

4. Materials and methods

To have a better overview of the development of the project, the more significant events during the development of the project are presented below:

Date	Significant event
November 2022	• Planned first data collection onboard GO Sars using 200 kHz 3 degrees. • During echo sounder calibration was found out transducer damaged • Collected data using standard 200 kHz 7 degrees
February 2023	Approved by FHF and HI for additional funding to order new ES200-3C transducer
March 2023	Old ES200-3C transducer fixed by Simrad with no warranty
May 2023	Installation and testing system onboard Libas in North Sea herring fishing
September 2023	Data collection during mackerel fishing in UK waters onboard FV Libas
December 2023	New ES200-3C transducer delivered
February 2024	Approved project extension until December 2024
July 2024	Mounting of ES200-3C transducer in Libas drop keel
October 2024	Data collection during mackerel fishing in UK waters

4.1. ES200 kHz 3 deg beam opening angle transducer

The transducer used in this project is a specially built system ordered in 2013 to Simrad to satisfy two requirements under the FHF Dabgraph project: narrow beam opening (i. e. 3 deg) and full broadband capabilities (100 kHz bandwidth). Only 2 of these transducers were made, one for HI and one for the French marine research institute Ifremer. Basically, the transducer is using a 70 kHz frame containing the acoustic 200 kHz elements required to build a 3 deg opening angle.

Prior to the planned survey onboard GO Sars for November 2022, the echosounder was calibrated at Nykirkekaien in Bergen by the standard reference sphere method. During echo sounder calibration was found out the transducer was damaged, with no detections of the calibration sphere in center of the beam. A physical inspection of the transducer showed the transducer face was not flat as expected, in contrary presented a convex shape which suggested an internal damage due to a malfunction that generated gas (Figure 1). The transducer was sent to Simrad for evaluation, and a standard 200 kHz 7 deg transducer was used during G.O. Sars survey.

Figure 1. Picture of damaged transducer with convex shape in the transducer face.

Because of the importance for the project objectives of the narrow beam transducer, FHF and HI decided to order a new transducer to Simrad, with the target to have it available for the 2023 mackerel fishing season. This transducer model is not a standard product commercialized by Simrad and the production of a single unit involves longer time than a standard transducer, with an expected delivery time of 6 months.

The evaluation of the damaged transducer at Simrad workshop confirmed gas was produced internally with no clear indications of the source of the problem. The internal gas was released, transducer dried for 3 days, re-cast the vent holes, and tested in water and air. A final successful calibration was performed at Simrad large test pool. The transducer was returned to HI but with no warranties in the performance.

For the data collection period during the 2023 mackerel season, the new transducer was not ready, and the old and fixed transducer was used instead. Calibration results and acoustic data from the single target collected were of good quality.

4.2. Transducer mounting and echosounder operation

The mounting of the transducer was one of the more critical operational parts of this project. The data collection during normal fishing operations requires that the echosounder is operational before and during the catch. As no permanent mounting of the transducer in the vessel hull was possible because of the complexity and high costs involved, a temporary solution was found. A 5m aluminum pole with the hinge was used to mount the transducer in the port side of FV Libas to avoid interference during the purse seine maneuver done in starboard side.

The pole was mounted on the port side, bolted to the vessel built-in ladder (Figure 2). The attachment for the pole ensured the transducer to be 1.5 below the sea surface when deployed, and access to the transducer from the main deck when cruising at high speed (Figure 3). The mounting included a hydraulic piston to allow tilting the transducer during operation. This set up was successful tested during a fishing trip to catch North Sea herring in August 2023.

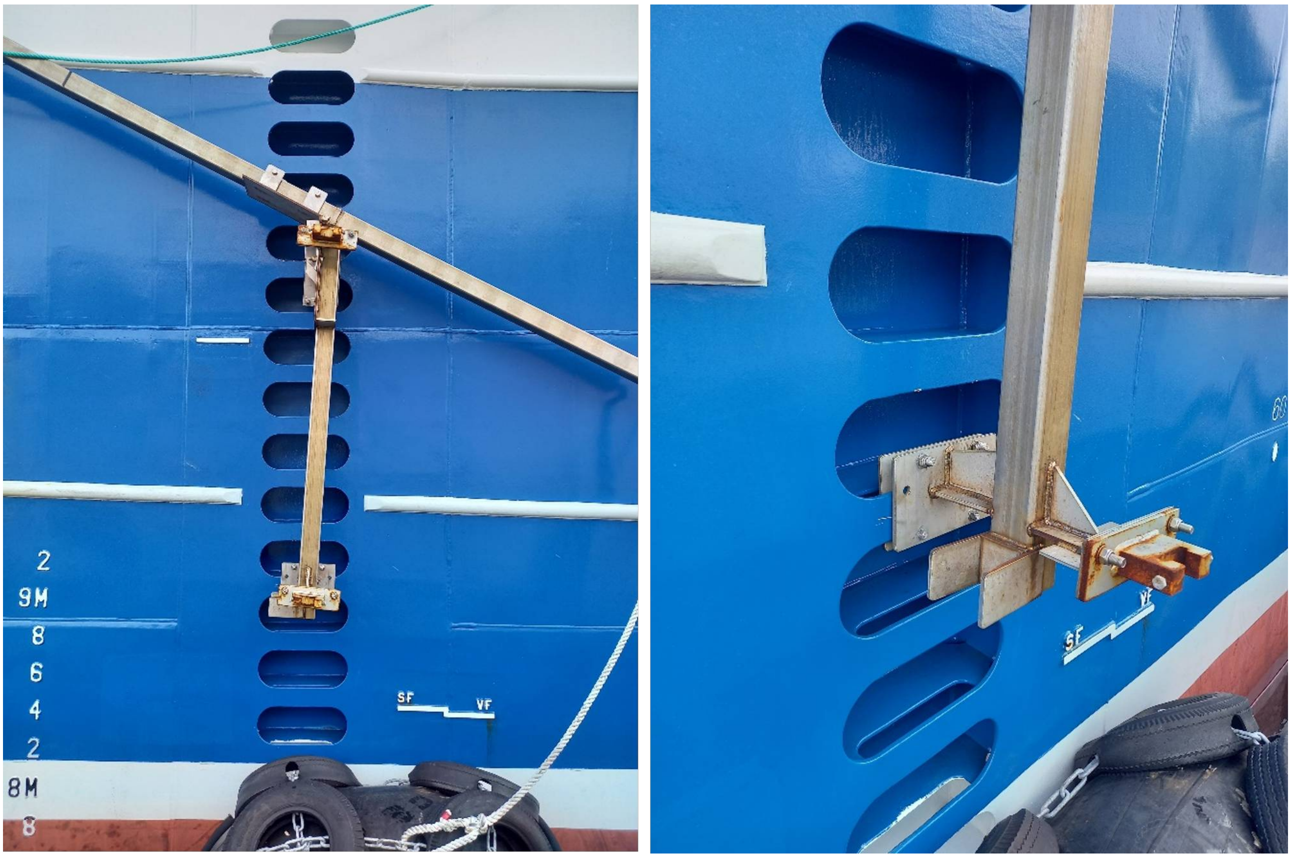


Figure 2. Mounting of pole to starboard side of FV Libas.

Figure 3.Detail of the pole and the transducer off the water during cruising. The transducer is mounted in a plate that is tilted by a hydraulic piston.

During the sampling period in the 2023 mackerel fishing season, this system was used in the first attempt to catch a mackerel school inside UK waters.

The acoustic sampling procedure agreed with the skipper was the following:

1. Once a suitable school for capture was found, the vessel will reduce the speed (i.e. 1-2 knots) and the pole lowered to its vertical position with submerged transducer.
2. When the transducer starts collecting acoustic data, the vessel will follow the target school using the sonars, aiming to keep it in close range to port side (100- 150 m).
3. Transducer tilt will be adjusted, using hydraulic piston control, to improve the acoustic sampling of the target school.
4. Collect echosounder data for ca. 3-5 minutes, aiming for regions in the school where single fish can be detected. This required close communication with the skipper, to maneuver the vessel to optimize the acoustic measurements.
5. When finished with data collection, the vessel reduced speed and pole placed in horizontal position.
6. Vessel proceeds with maneuvers to catch the target school.

The experience from this first event showed that lowering and hoisting of the transducer pole represented a larger time-consuming operation than expected during the school inspection phase prior to the catch. With a high risk of losing the target school because of the poor vessel maneuverability at the lower speed required to lower and hoist the pole (1-2 knots). This provoked a very stressfull situation for the captain, crew, and scientist, and was decided to not repeat this procedure during the 2023 fishing season.

For the 2024 season, several options were considered to mount the transducer, aiming to have it submerged all the time once in the fishing grounds, without the maneuvers of hoisting and lowering as in 2023. The use of one of the vessel's moonpool was evaluated but discarded because of the complexity to mount the transducer in a 5 m shaft. A solid metal pole firmly attached to the vessel side, that could withstand the vessel speed of 10 knots was also discarded because of the welding work required to attach such device to the vessel hull.

Finally, because the vessel needed to install new hydrophones for the pelagic trawl doors, there was an opportunity to mount the transducer under the scientific retractile keel available on FV Libas on July 31st , 2024. This keel is a steel structure that can be lowered 3 m below the vessel hull, and where vessel's echo sounders are mounted to avoid the noise created by air bubbles in adverse weather conditions (Figure 4). The demounting of the keel is a major maneuver that requires a big crane to lay the keel in the pier (see video attached with the report).

For the mounting of the ES200-3C transducer in the vessel drop-keel, we used an aluminum blister that has openings to the side and down (Figure 4 and 5). Along with the adjustments needed to attach the blister to the keel, it was necessary to get the transducer and hydraulic piston power cables through the keel and cable chain for later connection when the drop keel is inside the vessel.

The transducer mounted in the drop keel, was the old, repaired unit because the new transducer was not ready for installation, and the performance of the old unit during 2023 indicated a good and normal performance.

Figure 4. Drop keel from FV Libas with transducers mounted in the bottom, with cable chain along the left side of the keel (left). Aluminum blister containing the ES200-3C transducer when mounted (right).

Figure 5. Detail of the hydraulic piston that will provide with tilt for the transducer (left) and transducer inside the blister (right).

The echo sounder wide band transceiver unit (WBT) was mounted in a dry room close to the drop keel on the lower deck and operated with a car battery. The controller unit of the hydraulic piston was mounted in the bridge, operated by batteries, to allow for transducer tilting when viewing the echosounder display.

An extension ethernet cable was used to connect the WBT and the notebook with the EK80 software located in the bridge. An external GPS provided positioning and vessel movement information to the EK80 software.

Before departure for the first fishing trip during the 2024 season, an acoustic synchronization system, Simrad TU40, was installed onboard FV Libas. Connected to this system were the fishery echosounder ES80, the scientific echosounder EK80, the low frequency sonar Simrad ST90 and the high frequency sonar Kaijo KCH-5180. The operation of this sync unit was very efficient, allowing the simultaneous operation of these equipment with minimal acoustic interference and acceptable ping rate. However, due to lack of time prior the departure, the lateral ES200-3C echo sounder was not connected to the TU40 unit. This implied the following actions to ensure a clean acoustic data:

- The ES200-7C kHz transducer from the scientific EK80 mounted in the drop keel was turned into passive mode.
- The ES200-7C kHz transducer from the fishery ES80 mounted in the hull was turned into passive mode.
- The high frequency Kaijo KCH-5180 sonar was stopped pinging.

In addition, the vessel acoustic current profiler was turned off during all the time to avoid interference.

4.3. Broadband data analysis

4.3.1. Extracting the tracks and angle of single fish

The orientation of an elongated target has a strong impact on its target strength (TS). Tracking the fish helps to estimate the orientation of a fish inside the echosounder beam. The accuracy and reliability of this estimate can be affected by the performance of split-beam echosounders, strong currents, and vessel motion. Here we show how the method works using manual tracking of a few targets, because an accurate single target track detection algorithm for broadband data is not currently available. A track consists of two or more pings. The manual tracking should be replaced with a reliable automated tracking. As an example, manually selected track of a single target is shown in Figure 6 .

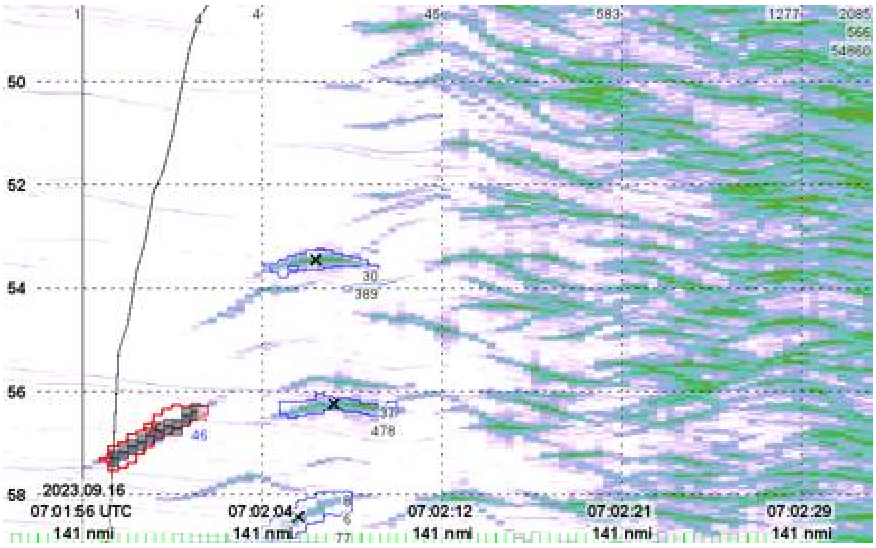


Figure 6. Echogram showing the manual selection of a single fish track encircled by red line. Individual fish track displayed as elongated shapes of green/blue color. Horizontal axis is time and vertical, range from transducer.

The range of a detected target at each ping together with the athwartship (θ_{al}) and alongship (θ_{at}) angles are estimated by the split-beam echosounder (See Figure 7). To see how these parameters are related to the Cartesian coordinates, see Equation (1) .

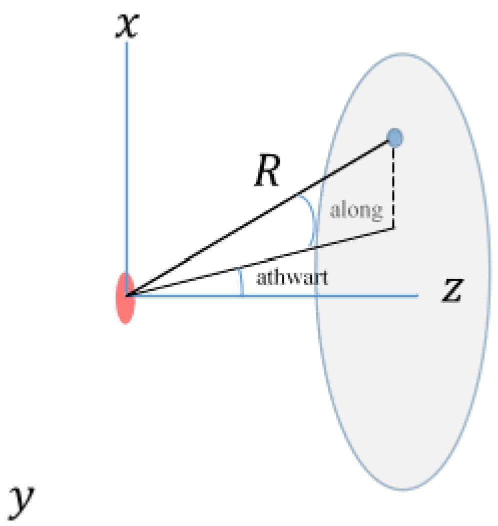


Figure 7. Split-beam and Cartesian coordinates. XY-plane of Cartesian coordinate is located on the surface of the transducer and Z axis coincides with the acoustic beam of transducer.

Cartesian coordinates are estimated from the split-beam coordinates as,

$$x = R\sin(\theta_{al}) \cdot y = R\cos(\theta_{al})\sin(\theta_{at}), z = R\cos(\theta_{al})\cos(\theta_{at}) \cdot \qquad (1)$$

The target is plotted in the 3D cartesian coordinate (Figure 8 , top right) using the estimated x, y, and z values obtained by equation (1) . A curve is fitted to the track using a second-order polynomial with the Python NumPy package. The angle between the tangential vector of the track and the acoustic axis of the transducer ($0\vec{i}+0\vec{j}+1\vec{k}$) as a function of range (Figure 8 , bottom left) is estimated. The broadband TS frequency response of different pings are plotted in the lower-middle subplot in Figure 8 . The mean TS curve is plotted by thick black line. The histogram of mean TS curve is shown in the lower-right of Figure 8 .

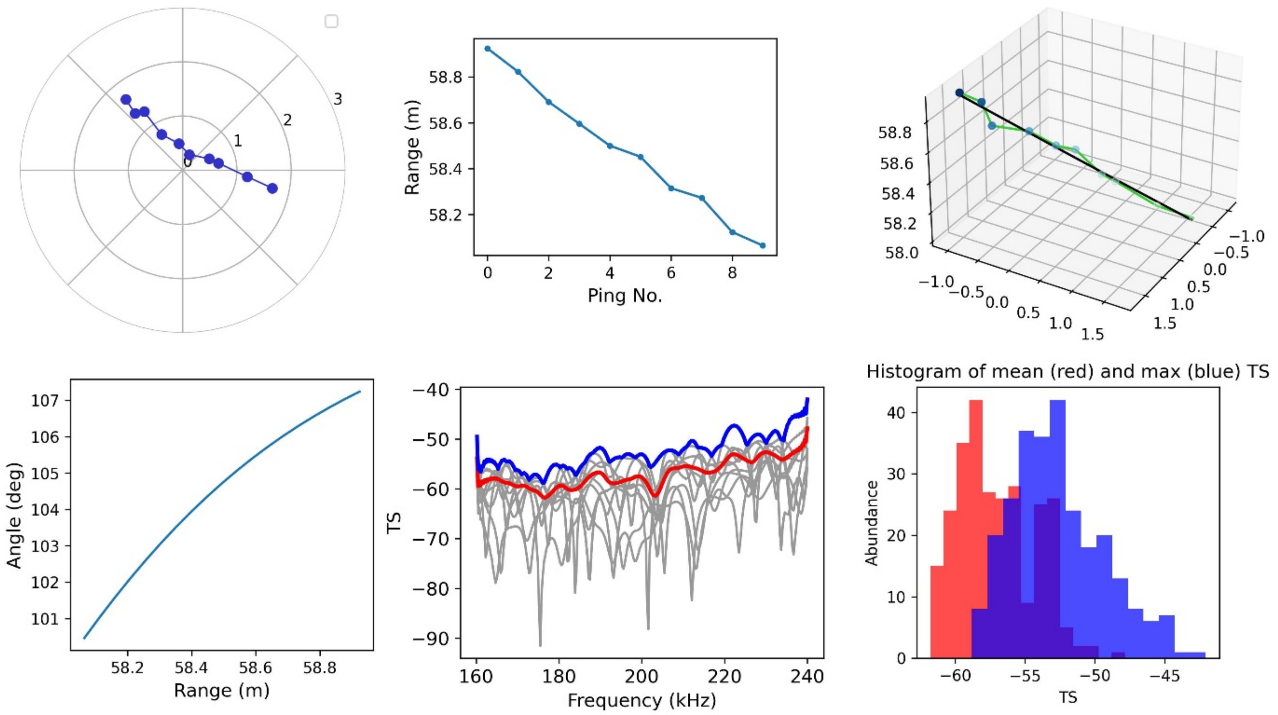


Figure 8. The location of target in the beam is estimated from athwartship and alongship angles. The target range to the transducer for different pings is estimated by split-beam echosounder. Spatial track of the target is estimated using Equation (3) . The estimated angle between the fish track and the acoustic axis of the transducer is plotted at different ranges. Measured target strength (TS) frequency response at of different pings together with the mean (red) and maximum (blue) TS as a function of frequency are shown. The histogram of the mean and maximum TS frequency responses is plotted.

Echosounder data was scrutinized using post processing system LSSS (Korneliussen et al., 2018) and ad-hoc Application Programing Interface (API) functions created to extract targets properties. The scrutinizing process included the manual identification of well-defined single fish tracks in absence of an automatic school tracking for broadband data implemented in LSSS. A sample of the fish tracks in the school were exported and analyzed, selecting those with a close to normal incidence angle (*ca* . 90 deg) to the echosounder beam.

4.3.2. Number of nulls in the TS frequency response and its relation to target size

For fluid filled targets increasing the size (width) of the target increase the number of nulls in the TS frequency response. Similarly, for a given target, changing the tilt angle from the broadside incidence, number of nulls increases (see Figure 10) because this increases the width of the target in the direction of incident wave. This method has been one of the methods for fish sizing used in the DABGRAF project.

4.4. Modelling of backscattering signal of mackerel

Modelling the backscattering signal of mackerel was not an activity considered originally in the project proposal. However, to ensure whether the detected peaks in the pulse compressed signal truly correspond to the boundaries of the target (here fish), sophisticated modeling using Finite element method (FEM) was performed. The backscattered time signal from a targets insonifield by an acoustic pulse was modeled by convolution of the acoustic pulse and impulse response of the target. We did the calculations in the frequency domain and retrieved the time domain signal using inverse Fourier transform, as

$$P_{bs}(t,r) = F^{-1}\left\{\frac{P_i(\omega,r)\, e^{-jkr}}{r} f_{bs}(\omega)\right\}, \quad (2)$$

where the incident broadband frequency modulated pulse in the frequency domain is calculated as

$$P_i(\omega,r) = F\left\{P_0\, e^{-\left(\frac{2t}{T}\right)^{\alpha}} \sin\left(\frac{\pi(f_2-f_1)}{T} t^2 + \pi(f_1+f_2)\, t\right)\right\}. \quad (3)$$

In the above equations, F and F^{-1} represent Fourier and its inverse, respectively. Start and end frequency of frequency modulated signal are f_1 and f_2 , respectively. The pulse duration is T , its rise and fall is controlled by α . We used $\alpha = 15$ for sharp rise and fall to model fast ramping signal in EK80.

FEM is a robust method to estimate the $f_{bs}(\omega)$ for targets with arbitrary shape, with several parts with arbitrary material properties. For FEM modeling we used the software COMSOL (COMSOL Multiphysics, 2020) and details of the implementation and modelling could be found in Khodabandeloo et al. (2022).

4.4.1. Fluid-filled prolate spheroid

Initially we modeled mackerel as a fluid-filled prolate spheroid disregarding its backbone (Figure 9). The material properties and dimension of the modeled target are given in Table 1. The modeling results are shown in Figure 10 .

Table 1. Parameters used for mackerel modelling as a fluid-filled prolate spheroid.

	Density (kg * m^{-3})	Sound speed (m/s)	Semi-major axis a (mm)	Semi-minor axis b (mm)
Water	1027	1500	NA	NA
Liquid	1027 * 1.05	1500 * 1.05	90	30

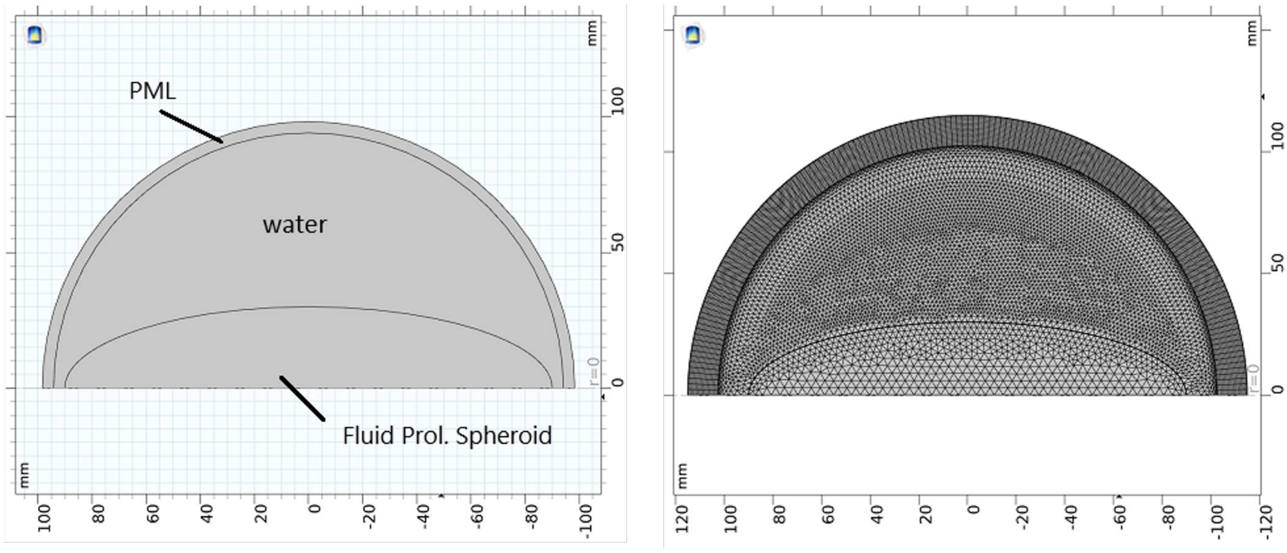


Figure 9. FEM implemented in COMSOL for TS frequency response of a prolate spheroid. Fluid-filled prolate spheroid in the water domain (left) and meshed domains at 30 kHz (Right).

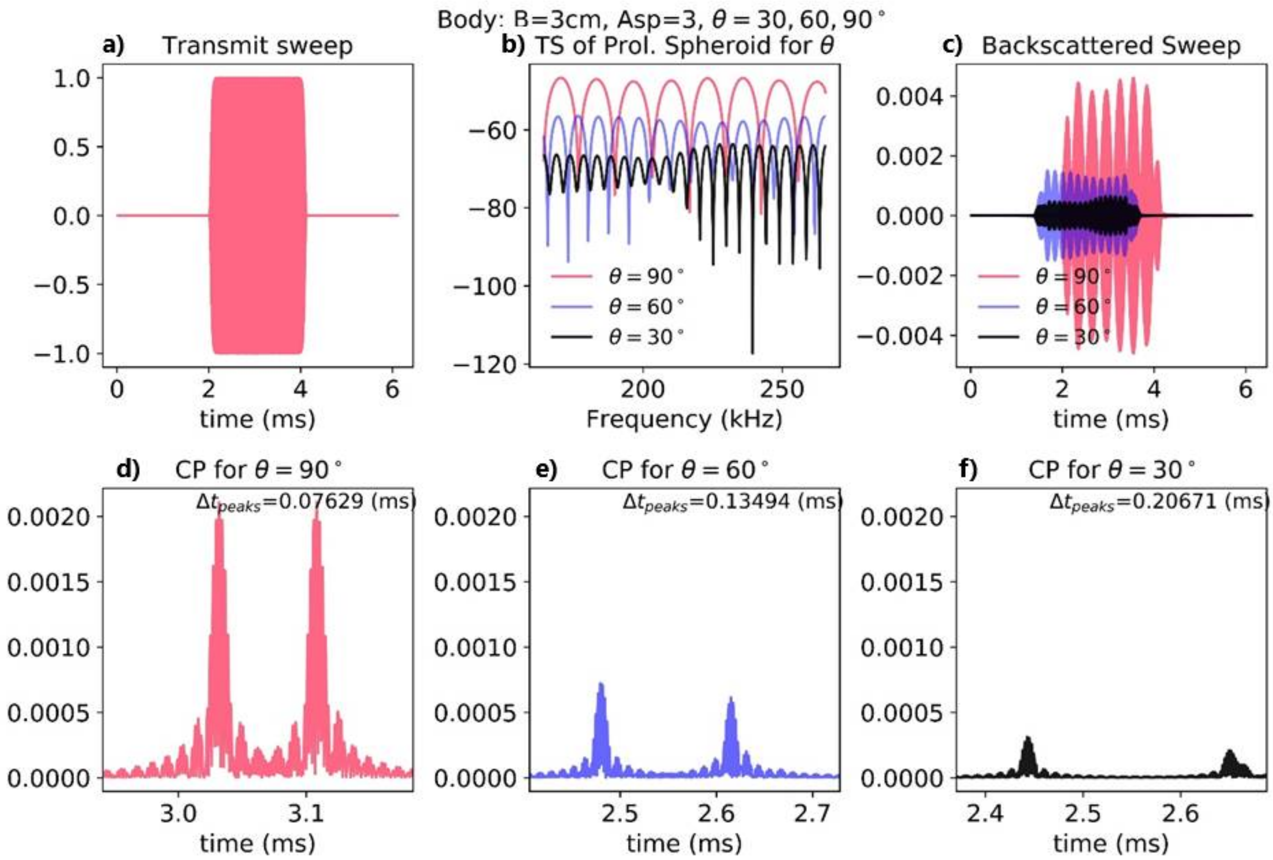


Figure 10. Modeled pulse compressed signal from a fluid-filled prolate spheroid subjected to a linear frequency modulated broadband pulse. a) The transmit pulse, b) TS frequency response estimated by COMOL for three different incident angles, c) modeled backscattered time domain signal for three incident angles. 90 degrees corresponds to broadside incident. d, e, and f) modeled backscattered pulse compressed signal.

For the simple case of fluid-filled prolate spheroid, the detected peaks in the pulse compressed signal can be translated directly to the dimensions of the target. For example in 10(d), $\Delta t_{peaks}=0.07629$ corresponds to $d=\Delta t_{peaks}\cdot c_f/2=0.07629\cdot 0.001\cdot 1.05\cdot 1500/2=0.06\,m$ which corresponds to the width ($2\times b$) of the prolate spheroid in broadside incident.

4.4.2. Fluid-filled prolate spheroid with an elastic prolate spheroid inside

To have a more realistic model of mackerel, we included an elastic elongated prolate spheroid inside the fluid prolate spheroid to model the fish body with backbone, also modelled in COMSOL (Figure 11). Parameters used in the modelling are presented in Table 2.

Table 2. Parameters used for mackerel modelling as a fluid-filled prolate spheroid and elastic elongated prolate spheroid inside

	Density (kg * m-3)	Compressional Spund speed (m/s)	Shear Sound peed (m/s)	Semi-major axis a (mm)	Semi-minor axis b (mm)
Water	1027	1500	1500	NA	NA
Liquid	1027 * 1.05	1500 * 1.05	NA	80	20
Elastic	1027 * 1.09	2200	1400	60	2.5

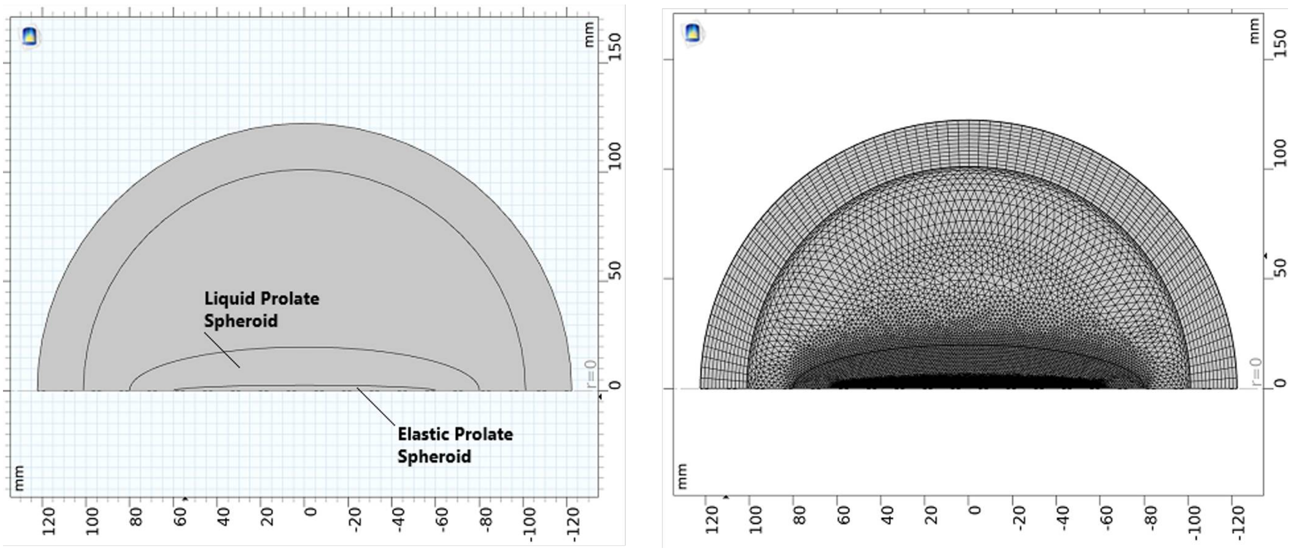


Figure 11. FEM implemented in COMSOL for TS frequency response of a prolate spheroid. (Left) Fluid-filled prolate spheroid and the elastic elongated prolate spheroid represent fish body and backbone, respectively. (Right) Meshed domains at 17 kHz (Right).

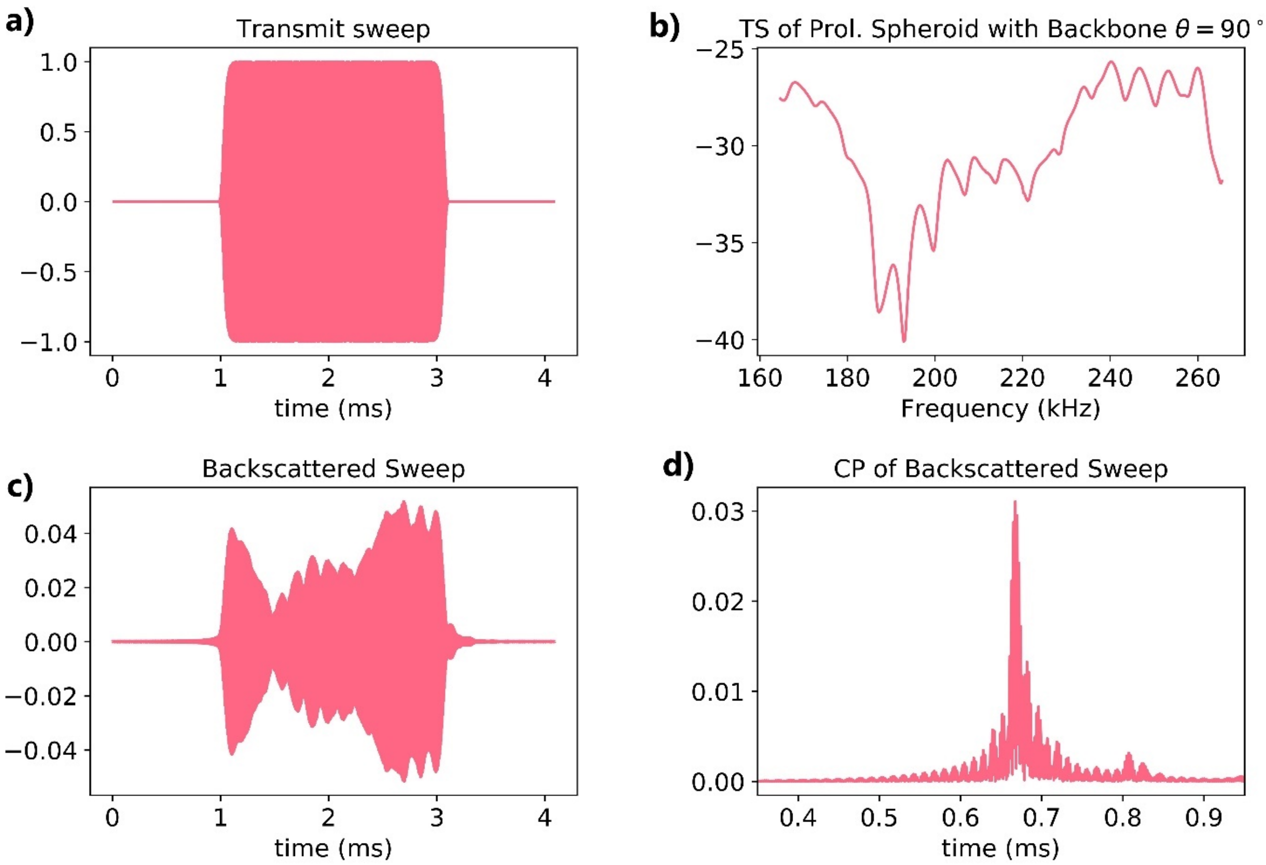


Figure 12. Modeled pulse compressed signal from a fluid-filled prolate spheroid with an elongated elastic spheroid inside subjected to a linear frequency modulated broadband pulse. a) The transmit signal b) TS frequency response of the target by COMSOL c) backscattered time signal, and d) pulse compressed signal.

When the elastic backbone is included within the liquid-filled fish body, associating the peaks in the pulse-compressed backscattered signal with the geometry becomes more complex (Figure 12). The distance between the first and second distinct peaks is around 0.13 ms which corresponds to 10 cm while the width if the modelled target was 4 cm. Therefore, inclusion of an elastic backbone significantly affects the peaks in the pulse compressed signal.

5. Results

5.1. 2023 fishing season

Two sampling periods onboard FV Libas were carried out during the 2023 fishing season. The first on August 6 to 9, together with mounting and testing of the system, data was collected during commercial fishing of North Sea herring in the North Sea. The second period included two fishing trips, from September 15 to 29 during mackerel fishing inside UK waters (Table 3).

*Table 3. Summary of catches during the two sampling periods; August 6 to 9 and September 15 to 29, 2003. All catches are from purse seine except *, which was a 2-hour pelagic trawl.*

Trip	Catch	Date	Time (local)	Latitude	Longitude	Catch	Species
1	1	07.08.2023	14:00	59 38 N	0 12 W	100	North Sea herring
2	1	16.09.2023	19:50	58 52 N	0 08 W	0	Mackerel
2	2	17.09.2023	20:38	58 49 N	0 33 W	0	Mackerel
2	3	18.09.2023	12:30	59 53 N	0 14 W	110	Mackerel
2	4	18.09.2023	16.05	59 53 N	0 14 W	300	Mackerel
3	1	22.09.2023	11:05	59 35 N	0 48 W	0	Mackerel
3	2	23.09.2023	13:44	59 27 N	0 40 W	0	Mackerel
3	3*	23.09.2023	15:36	59 31 N	0 47 W	0	Mackerel
3	4	23.09.2023	20:23	59 27 N	0 47 W	0	Mackerel
3	5	24.09.2023	10:20	59 23 N	0 27 W	0	Mackerel
3	6	25.09.2023	19:20	59 25 N	0 36 W	0	Mackerel
3	7	27.09.2023	11:45	59 25 N	0 14W	0	Mackerel
3	8	27.09.2023	14:30	59 29 N	0 30 W	0	Mackerel
3	9	27.09.2023	17:52	59 34 N	0 34 W	0	Mackerel
3	10	27.09.2023	00:00	59 33 N	0 29 W	80	Mackerel

During the mackerel fishing trips, the fish was not aggregated in dense and well-defined schools as expected for the date and geographical location. During trip 2, mackerel aggregations were loose and unstable, reacting to the approaching vessel and dispersing very quickly. Two empty casts reflect the difficulties to catch target aggregations. Conditions became more extreme during trip 3 where schools were extremely reactive and avoided the purse seine and pelagic trawl, with 9 empty casts and only 80 tons captured after 6 days fishing.

In addition to evasive fish behavior, weather storms and pressure for fishing made the data collection with the lateral echosounder very challenging. The sampling procedure implied spending additional time following the school with the risk of losing it because of reduced vessel speed when lowering and raising the pole or the dispersion of the school as reaction to the approaching vessel. As result, on Trip 3, in agreement with the skipper it was decided to prioritize the catch of a school and leave the echosounder sampling of a neighbour school when a catch was secured.

Due to the challenges enumerated earlier, only one data set with single targets detections of mackerel was obtained during trip 2, on 16.09.23 at 07:00 hrs. (UTC). After the school was measured with the lateral ES200-3C echosounder from FV Libas, it swims away when vessel speed was reduced to hoist the echosounder pole and was captured by FV Hargo (total catch of 320 tons). A sample from this catch was measured to obtain biological information (length and weight) of the mackerel.

5.2. 2024 fishing season

Before departure for the 2024 fishing season it was expected to have 2 fishing trips based on the mackerel quota left (ca. 900 ton) and the good fishing conditions by the rest of the Norwegian fleet operating in UK waters.

Two fishing trips into UK waters were made from 29 September to 08 October (Table 4). Trawls fluctuated between 2 to 3 hours with variable catches ranging from 55 to 240 tons. During trawl 1 there was a problem with the net and no catch pumped onboard, however a fish sample for length measurements were collected from the deck.

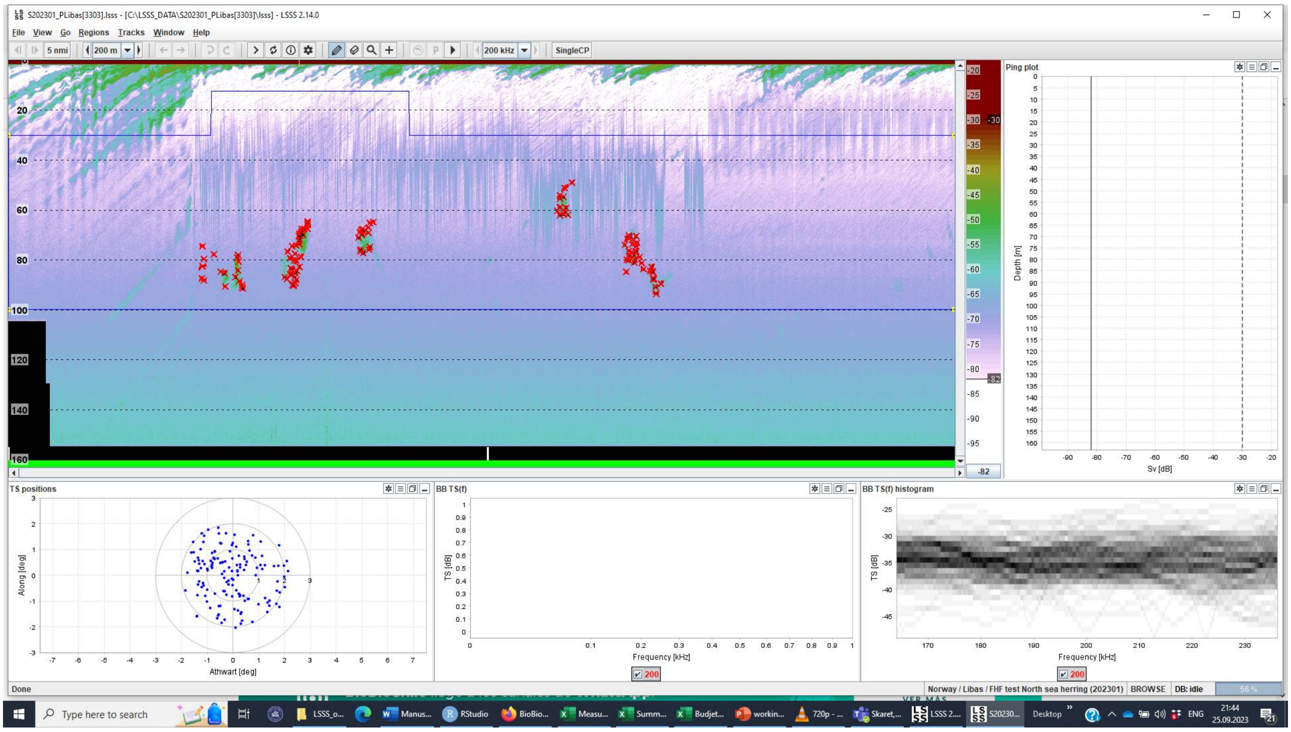
Table 4. Summary of mackerel catches during the two fishing trips; Trip 1: September 29 to 04 October, Trip 2: 05 to 08 October, 2024. All catches are from pelagic trawling. Start and stop time of the pelagic trawl is indicated.

Trawl	Trip	Date	Time start	Time end	Catch (ton)
1	1	01.10.2024	18:12	20:48	0
2	1	01.10.2024	23:21	02:00	55
3	1	02.10.2024	06:30	10:11	87
4	1	02.10.2024	12:15	14:20	116
5	1	02.10.2024	19:20	21:28	240
6	1	03.10.2024	00:19	03:00	116
7	2	06.10.2024	10:27	12:20	93
8	2	06.10.2024	14:20	16:30	40
9	2	07.10.2024	04:58	07:15	140
10	2	07.10.2024	10:55	14:20	136
11	2	07.10.2024	16:04	18:24	66
12	2	07.10.2024	20:35	23:17	116
Trip 1					614
Trip 2					591
Total					1205

5.3. Data quality

5.3.1. 2023 fishing season

During the first trip for fishing North Sea herring on 07 August 2023, electrical noise from the vessel power source was clearly observed starting from ca . 20 m range (Figure 13 , upper panel). Noise was removed from Trip 2 using battery power source, observing a clean echogram up to a range of 120 m using a threshold of -82 dB (Figure 13 , lower panel).



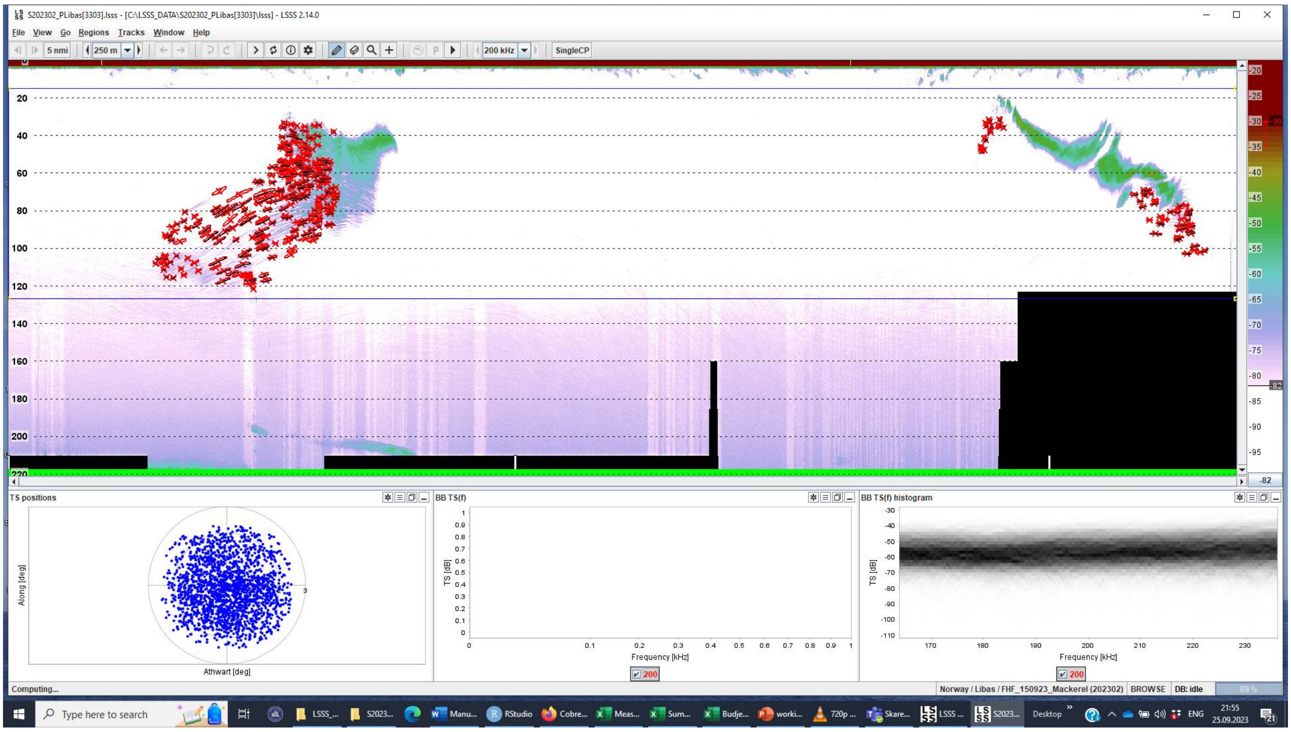


Figure 13. Echogram showing acoustic data when echosounder operating using vessel power source during trip 1 (upper panel) and using battery power source during trip 2 (lower panel).

5.3.2. 2024 fishing season

In the fishing grounds mackerel was found mostly as non-dense layers from 20 to 60 m during daytime (Figure 14), and during night hours more disperse all the way to surface. Occasionally more dense layers and schools were observed during daytime (Figure 15). In both echograms it is possible to identify acoustic noise (yellow to green vertical lines) from the Kaijo high frequency sonar. The periods this noise is absent was when the skipper stopped the sonar, to allow noise free data collection with the lateral ES200-3C echosounder.

In all 12 trawls, clean echosounder data was collected from the mackerel that was caught. This data will be the primary source for single fish detection and fish tracking. However, it will be also possible to use periods with noisy data after a noise filtering process using ad-hoc algorithms in the post processing system LSSS.

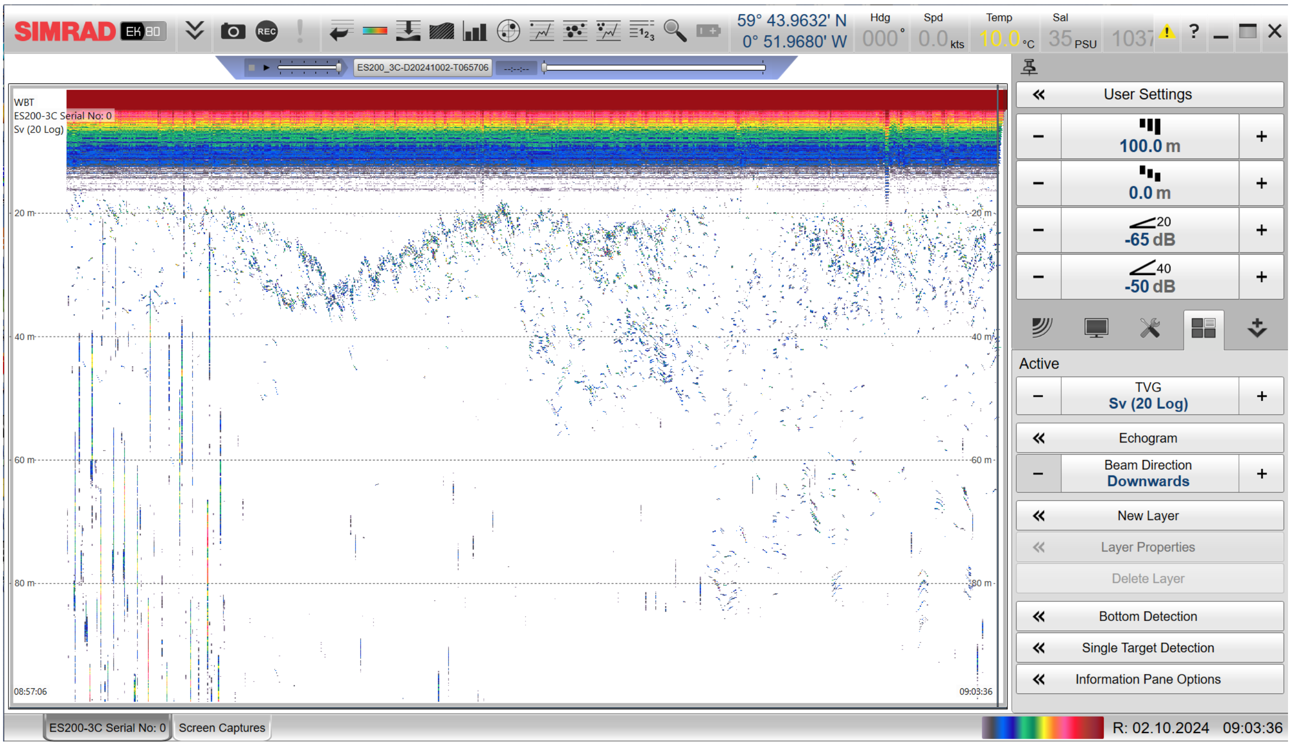


Figure 14. Mackerel disperse from 20 to 80 m from the vessels, observed as blue and green short traces. In the left of the echogram is possible to observe the noise from the Kaijo sonar, as yellow to green vertical lines. (threshold to -65 dB).

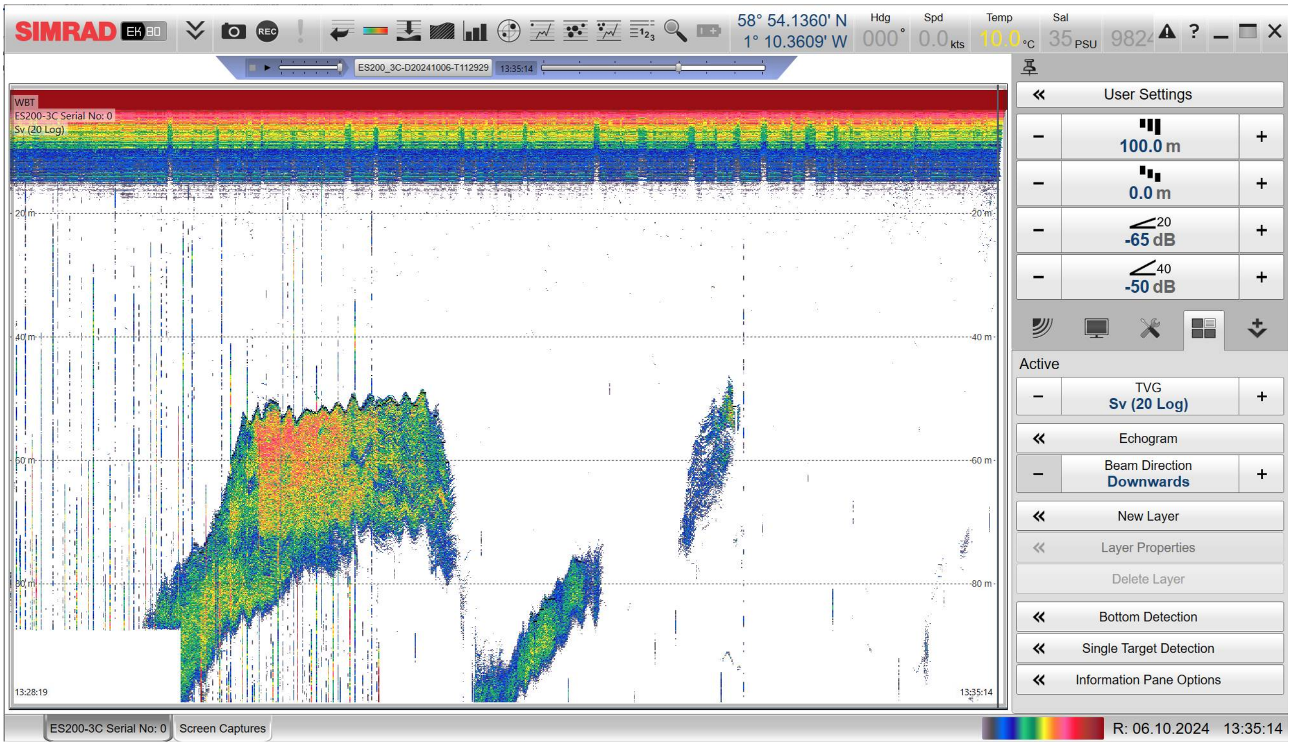
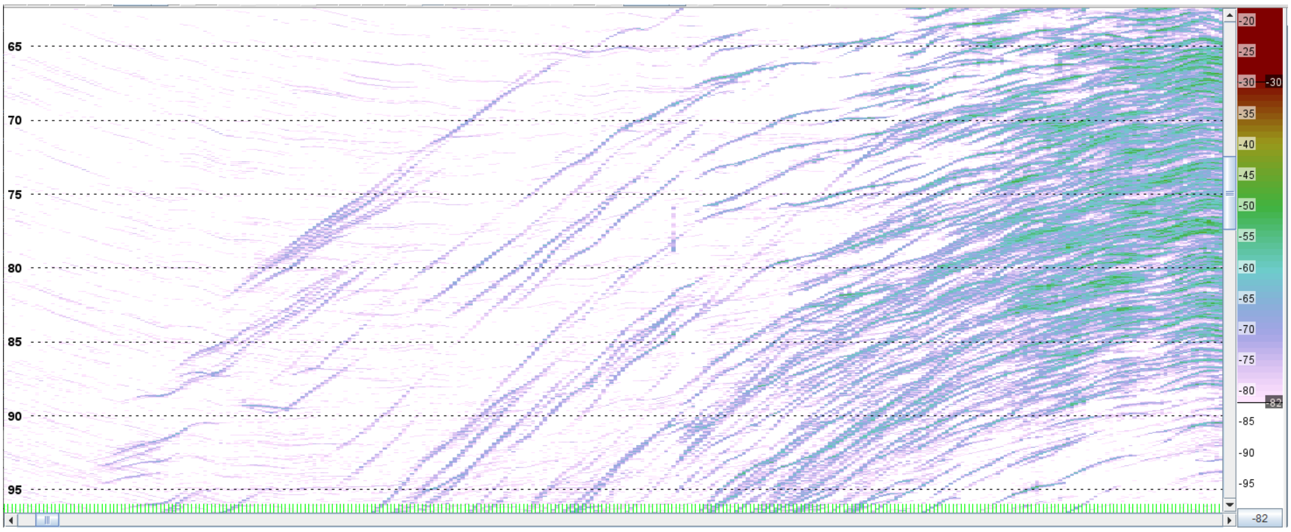


Figure 15. Mackerel in more dense aggregations during daytime. In the left of the echogram it is possible to observe the noise from the Kaijo sonar, as yellow to green vertical lines. On the right half of the echogram Kaijo sonar was stopped and clean data obtained (threshold to -65 dB).

Detailed analysis of the acoustic data from single fish indicated abnormal high noise level when using -82 dB threshold level, and all other acoustic equipment turned off (Figure 16).



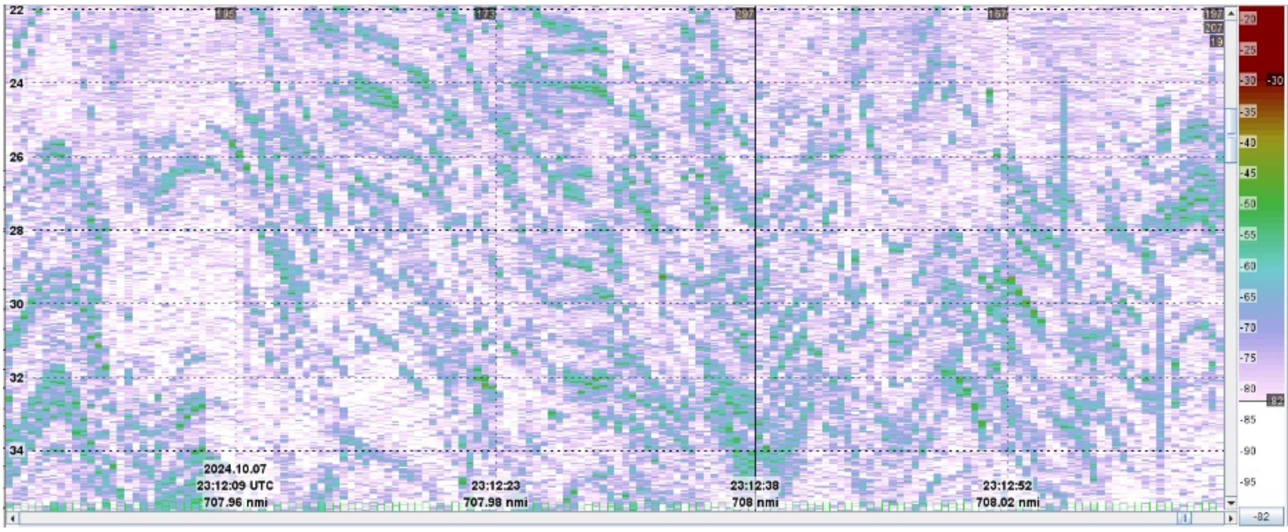


Figure 16. Detailed echogram with tracks of single mackerel fish (threshold to -82 dB). Data collected during 2023 (upper panel) and during 2024 (lower panel).

The explanation for this high noise level was found in the impedance of one of the transducer sectors (Sector 1; red line in Figure 17 central panel) which presented values of ca. 100 Ω in comparison with the other 3 sectors that had values ca. 300 Ω . This was only possible to visualize during post processing of the data, as during the data collection onboard the data looked normal. Another consequence of this abnormal impedance is the non-random distribution of targets in the acoustic beam (Figure 17).

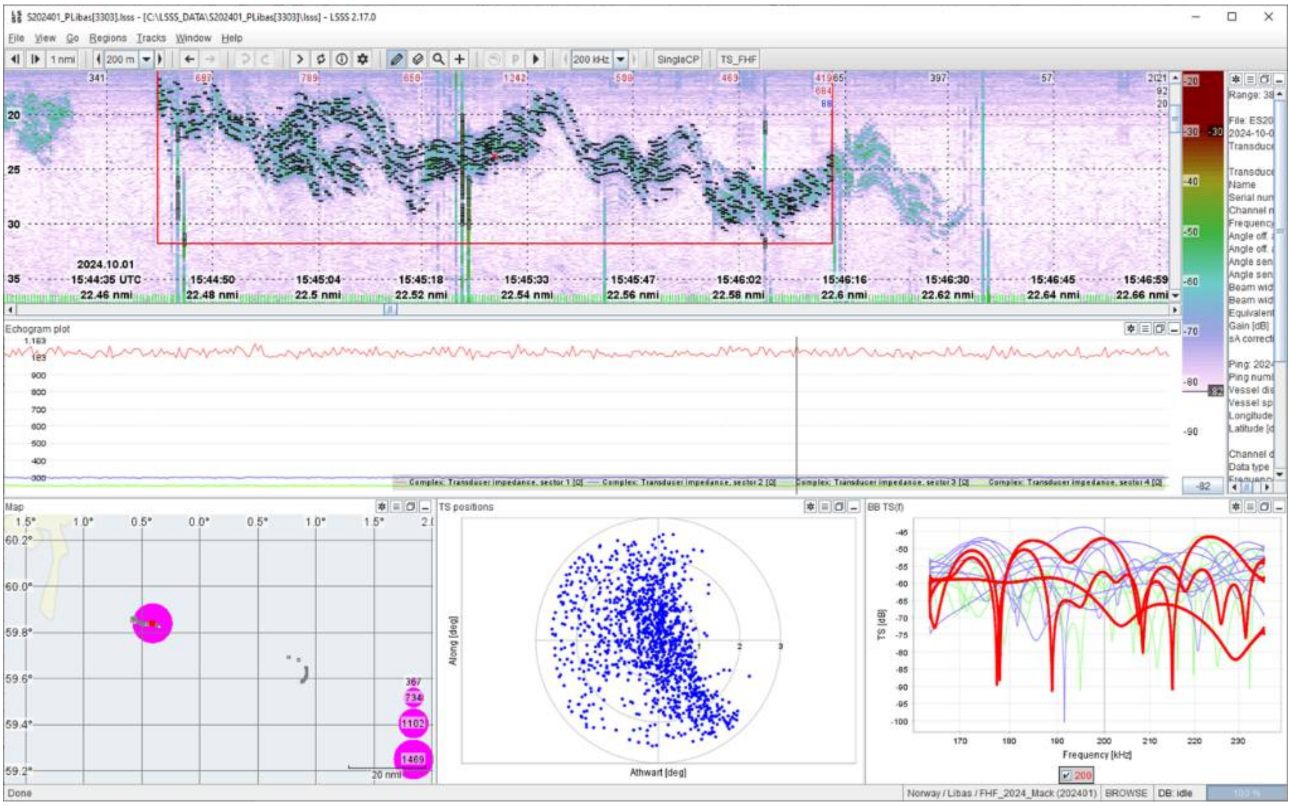


Figure 17. Echogram from mackerel aggregations from 1st October 2024 (Top panel). Impedance (ohms) plot by time for all 4 transducer sectors (center panel). Position of targets in the acoustic beam (Centre lower panel).

Therefore, all data collected during 2024 season (Table 4) was evaluated not suitable for further use for broadband analysis and fish sizing, and only data from Trip 2 in 2023 (Table 3) was used.

5.4. Single target analysis

Preliminary analysis of the target strength in the range/time domain for individual mackerel from Trip 2 in 2023 (Table 3) showed in most cases the presence of a major peak that corresponds to the echo from the fish in lateral aspect. However, the presence of the two peaks that were reported by Kubilius et al. (2020), in the echo of the fish-like artificial objects observed in lateral aspect, were absent, because of a more complex backscattering response from broadband data, as anticipated from the FEM modelling results (Figure 18).

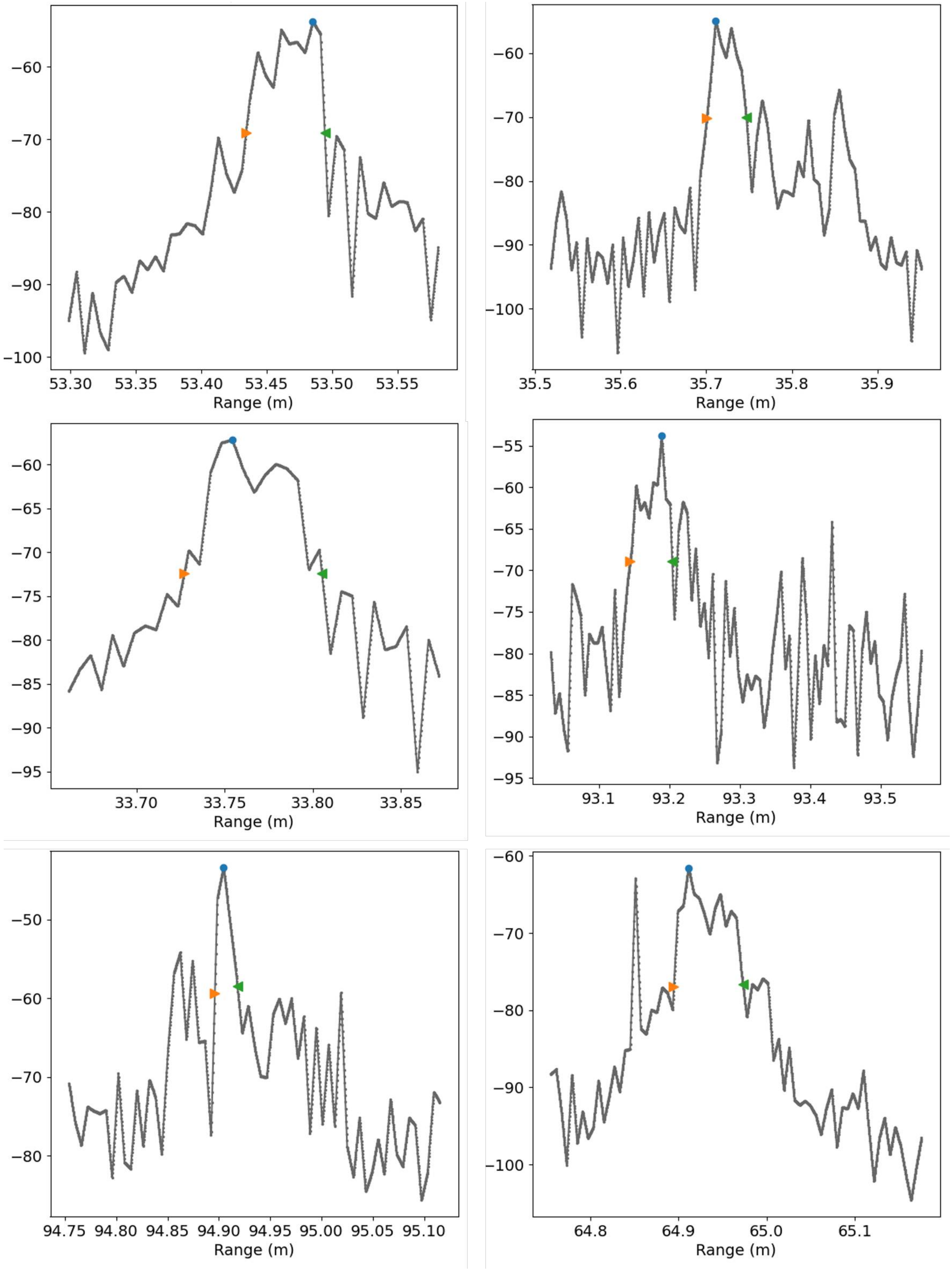


Figure 18.Target strength (dB) by range (m) of selected mackerel. Plots represent the TS from the central ping of each fish track. In these examples the range of the targets varied between 35 and 95 m. Orange and green triangles indicate the width of the echo from the fish in lateral aspect.

The presence of the two peaks in the fish response curve was the main source for the direct estimation of the fish width and its use to derive fish length proposed in the project.

5.4.1. Fish size estimates from TS and angle data

The absence of the two peaks in the backscatter intensity of individual fish necessitated the investigation of an alternative method using the target strength and swimming angle of the fish track (i.e. incidence angle between fish and acho sounder beam). This method has been proposed earlier and was implemented as one of three sizing methods in the Dabgraf software (Ona et al., 2017). From the acoustic measurements of tethered fish used in Kubilius et al. (2023), a regression curve relating TS, incidence angle and fish size was used (Figure 19). Results from near normal incident angle (*89-91* deg) from the net pen measurements will be used to derive fish size from the vessel measurements.

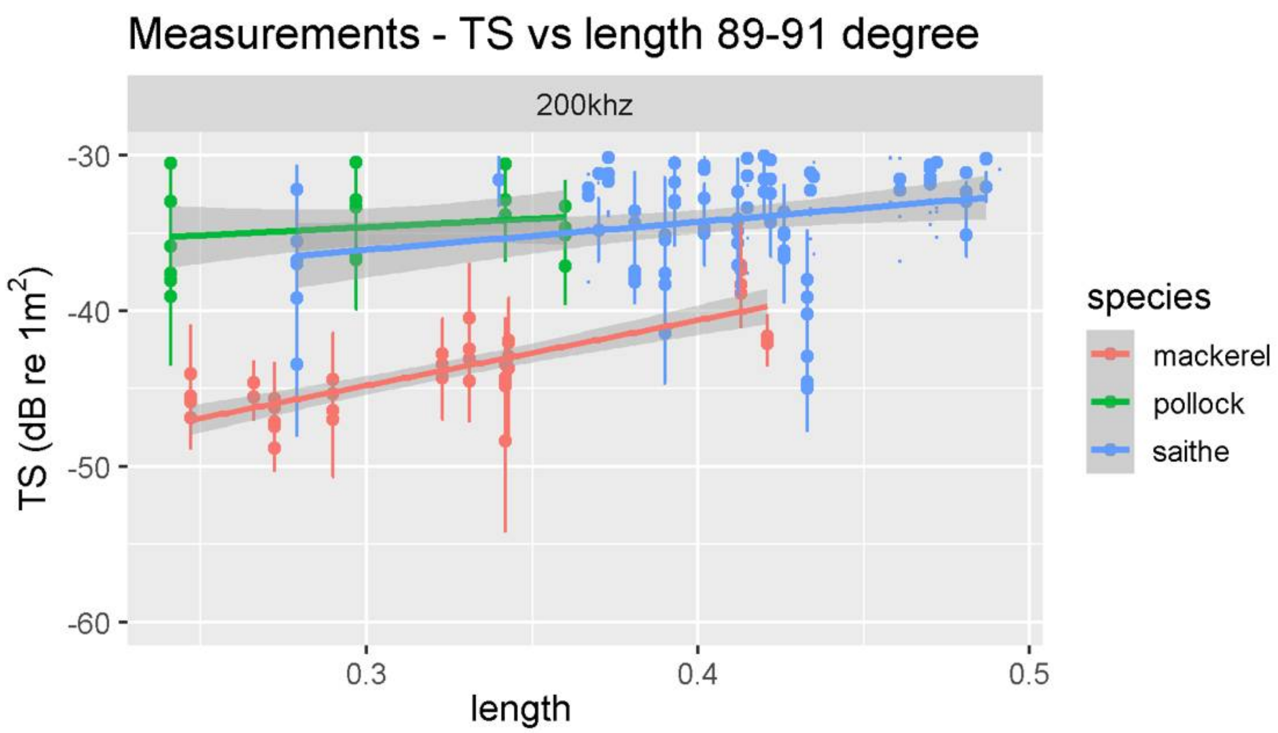


Figure 19.The target strength (TS, dB) at 200 kHz and fish length (m) from tethered mackerel measurements for incidence angles between 89 and 91 degree. (Adapted with permission from Berges et al., ICES WGFAST 2023 oral presentation).

The mackerel size estimates from the catch on 16 September 2023 are based in the target strength measurements of selected mackerel at close to normal incidence angle (88 to 93 deg, Table 5) and the regression curve in Figure 17 (incidence angle 89 to 91 deg) . Mackerel size using the mean TS values per track showed values smaller than 250 mm, and when using maximum TS values sizes ranged between 250 and 420 mm, with a mean length of 348 mm, in the range of the 362 mm mean length measured fish from the catch. The mean deviation between measured and estimated length was 45.4 mm. These preliminary results suggest that the use of the maximum TS from fish tracks close to normal incidence angle could be an alternative method to compute fish size.

Table 5. Results from selected mackerel tracks from data collected on 16.09.23. Mackerel sizes were computed using the mean and maximum TS of the pings included in the fish track. Mean fish length from catch the catch of FV Hargo was 362 mm (see section 5.1) . Mean deviation between measured and estimated length was 45.4 mm.

Target	Incidence angle (deg)	Mean TS (dB)	Length from Fig.5 (mm)	Max TS (dB)	Length from Fig.5 (mm)
1	90	-50	<250	-44	325
2	91	-44	310	-40	420
3	91.5	-54	<250	-47	250
4	93	-50	<250	-45	300
5	89	-50	<250	-45	300
6	91	-47	250	-43	350
7	90	-46	270	-41	395
8	88	-47	250	-42	370
9	91	-53	<250	-43	350
10	88	-46	270	-40	420

5.4.2. Number of nulls in the TS frequency response and its relation to target size

We tested the null counting method with the tethered fish data (see Kubilius et al., 2023) . Detected nulls for two different fish sizes (M23 = 284 mm) and (M10 = 356 mm) at two different incident angles (Φ) are shown in Figure 20.

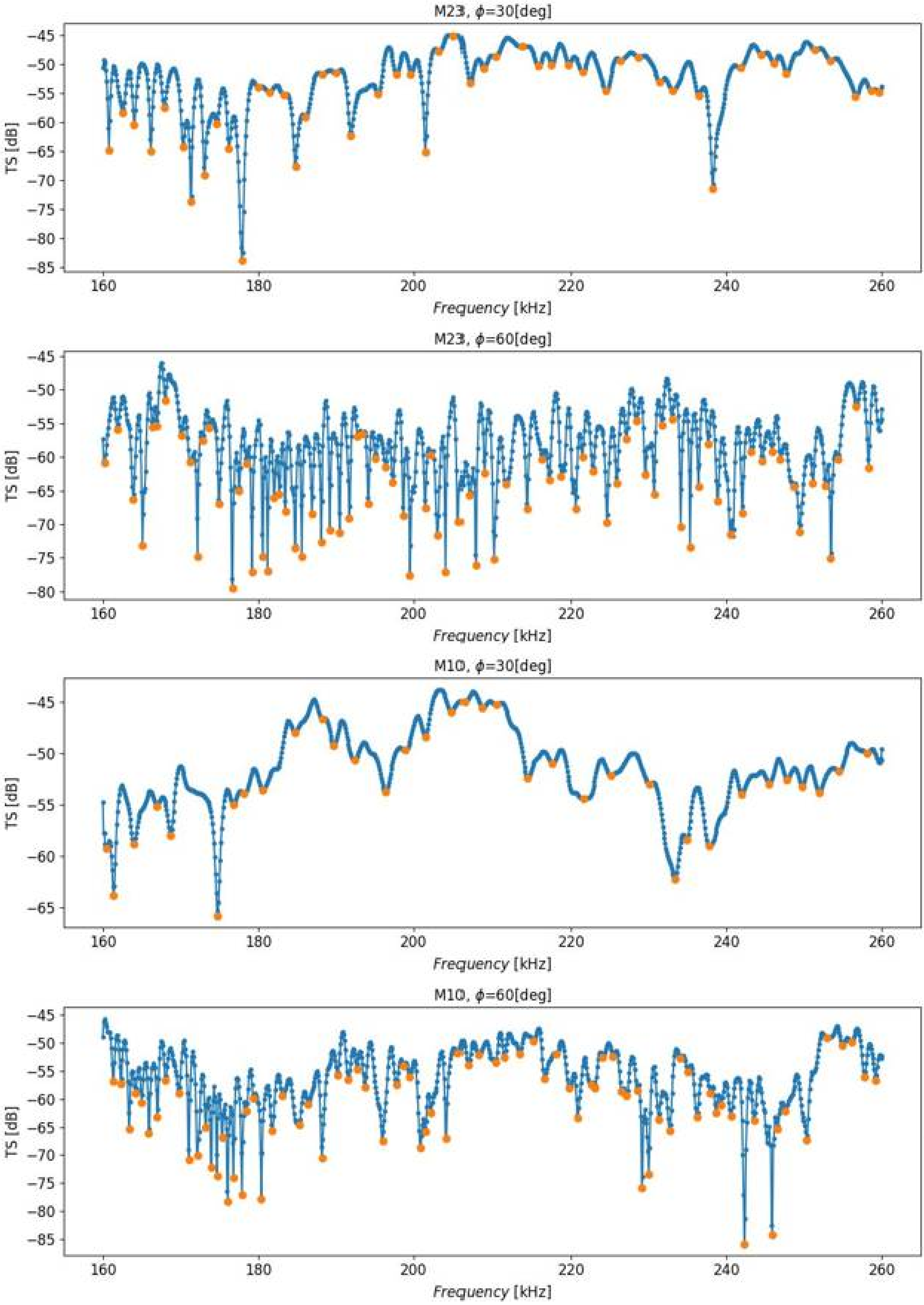


Figure 20. Detected nulls from measured TS frequency response of tethered mackerel for two different fish size and incident angle of 30 and 60 degrees. Note in this experiment 0, 180, and 360 degrees corresponds to the broadside incident angle. For more details of experiment see (Kubilius et al., 2023) .

The number of nulls as a function of tethered fish orientation for 13 different measured tethered mackerel is shown in Figure 21. It is seen that the number of nulls increases as the fish is tilted from 0 degree to 90 degrees and then decreases by tilting toward 180 degrees (broadside incidence).

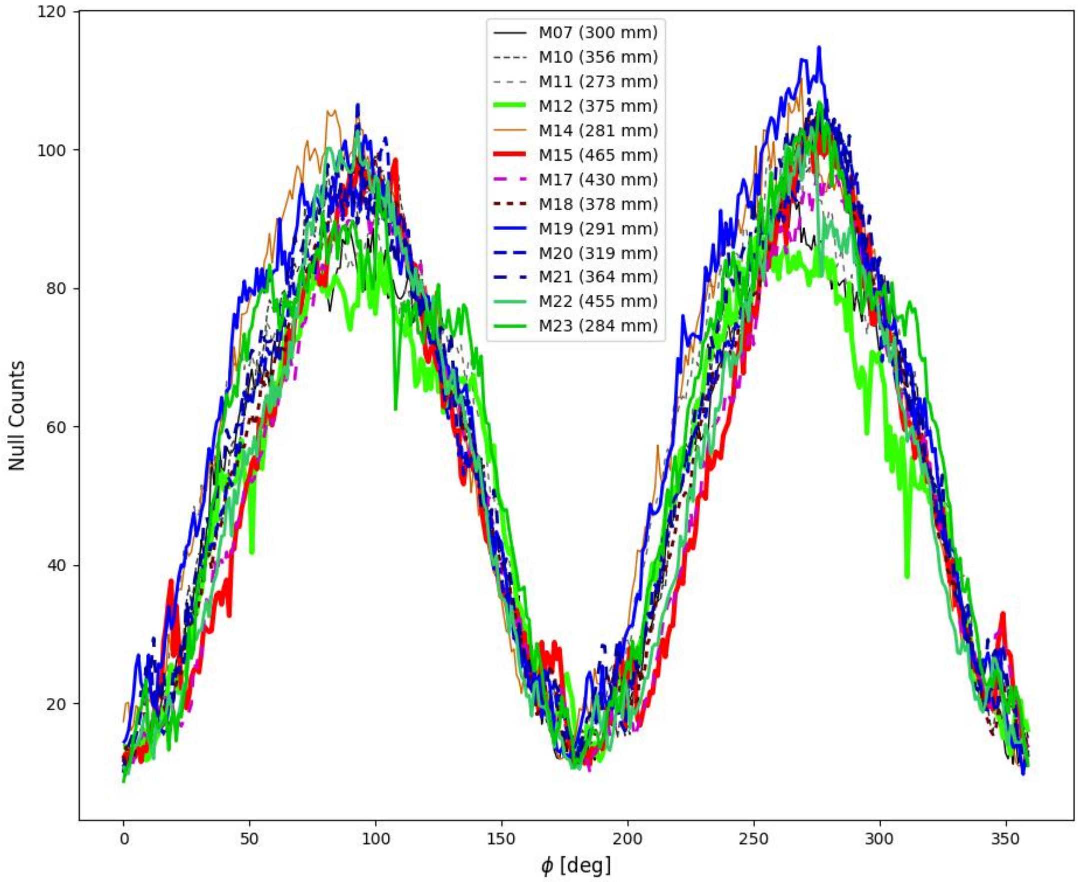


Figure 21. Number of detected nulls as a function of tilt angle for 13 different fish. Note that in this experiment, 0°, 180°, and 360° correspond to broadside incidence.

Although the number of nulls and tilt angles is consistent with the expectation for each individual fish, plotting the number of nulls and different fish size at a given tilt angle does not agree with the expectation. Which is a positive correlation between the number of nulls and the fish size. This is shown in Figure 22, where average number of nulls at 10-degree tilt intervals are plotted versus fish sizes.

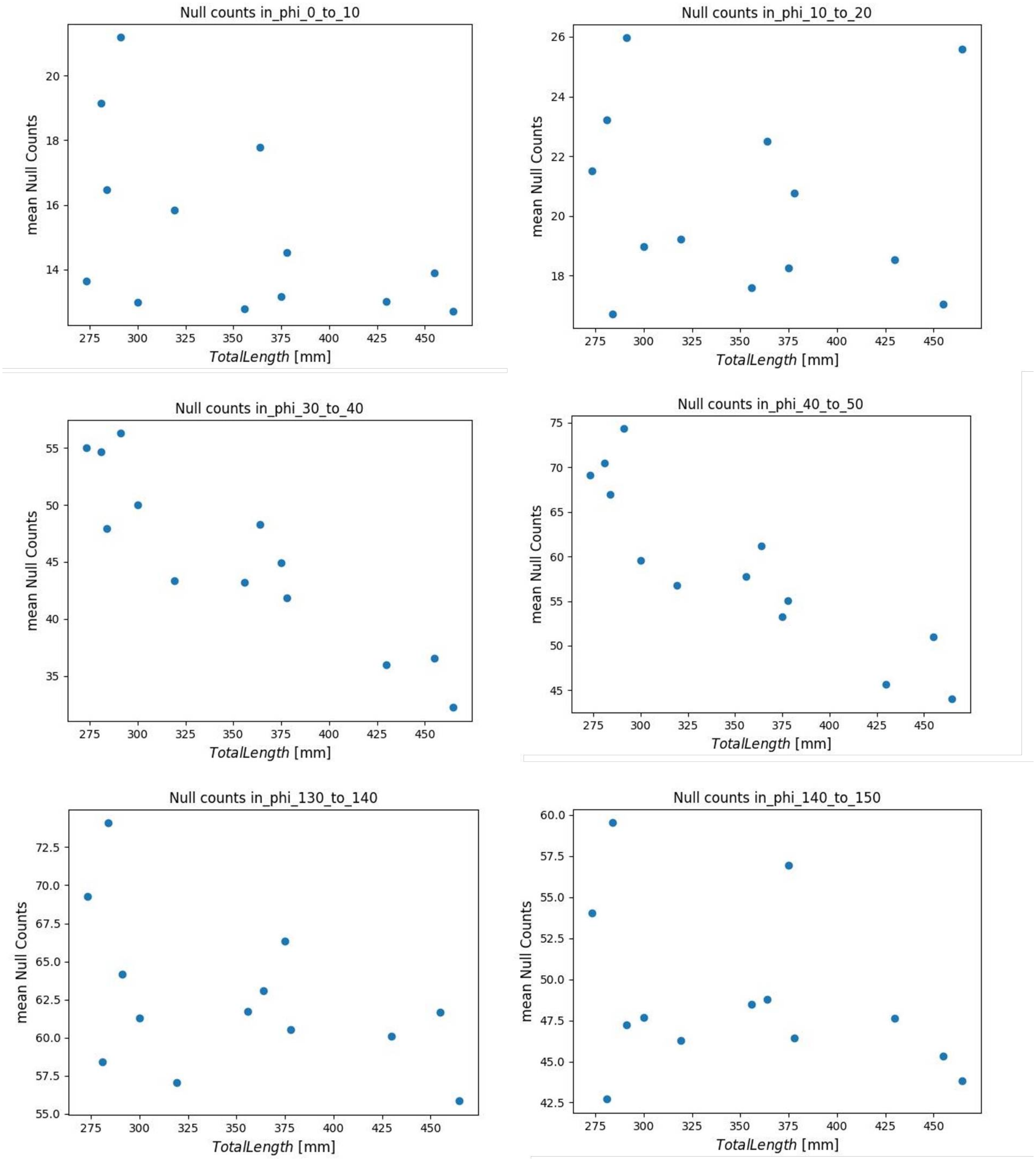


Figure 22. Average number of detected nulls in the measured TS frequency response within 10-degree tilt angles as a function of fish length. A clear correlation is not observed between the number of nulls and fish size. Even though, for tilt angles within 30–40° and 40–50°, there is a correlation, the number of nulls decreases as fish length increases, which is the opposite of expected.

5.5. Mackerel biological sampling

In the 2023 season, the mackerel measured from the catch from FV Hargo on 16 September had a mean length of 36.2 cm (S.D. 2.4), mean weight of 415 g (S.D. 87.8) (Figure 23).

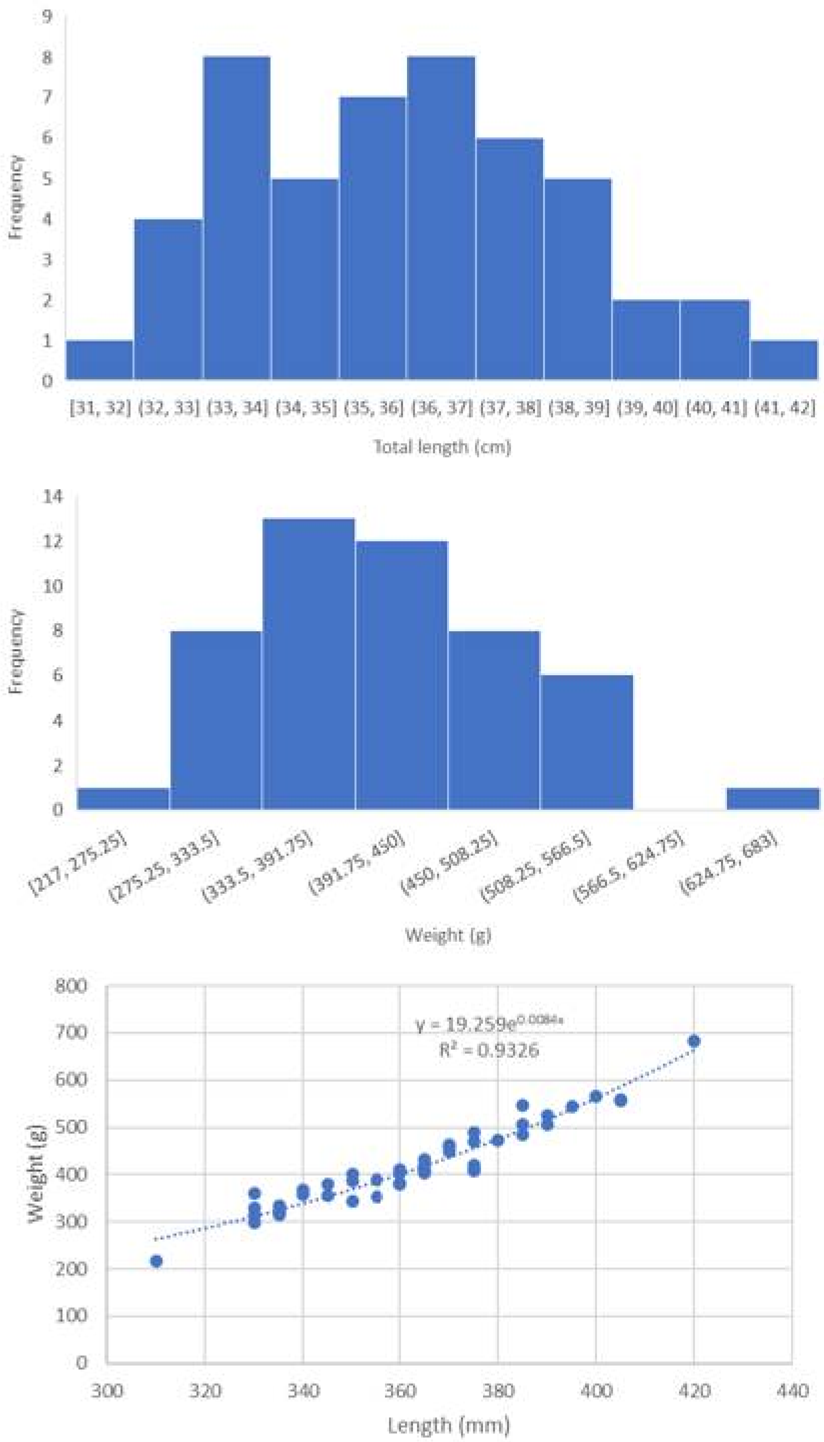


Figure 23. Length, weight, and length-weight relation of mackerel sampled from FV Hargo, caught on 16.09.23 inside UK waters.

For the 2024 season, the total length from a random sample of 100 fish were measured from each trawl. In addition, fish weight from measurements done onboard by the crew were also collected and processed. The weight measurements are done during the whole period fish is pumped onboard and included between 150 to 440 fish per trawl.

The mean length of mackerel fluctuated in a narrow range of a 2.8 cm, between 34.4 and 37.2 cm, (Figure 24 and Table 6). Although the mean mackerel length did not fluctuate largely, the length distribution showed differences between trawls, with predominance of 33 cm mode in trawl 1, 3, and 4 and mode centered in 37 cm in trawl 5. The mean weight varied between 357 and 473 g, with a difference of 116 g.

Table 6. Summary of length and weight of mackerel from pelagic trawling onboard FV Libas during October 2024.

		Total length (cm)		
Trawl	Mean	Minimum	Maximum	Mean weight (g)
1	35.7	24.4	40.5	-
2	36.4	30.2	42.5	440.4
3	35.1	28.6	41.4	396.6
4	35.7	29.2	42.6	417.9
5	37.2	28.4	42.5	460.8
6	35.7	30.6	42.6	408.5
7	35.8	29.2	42.6	422.0
8	34.4	23.1	41.5	357.0
9	36.1	28.5	42.4	437.0
10	36.7	29.0	42.6	456.0
11	36.4	27.5	41.5	434.0
12	36.2	29.7	42.1	473.0

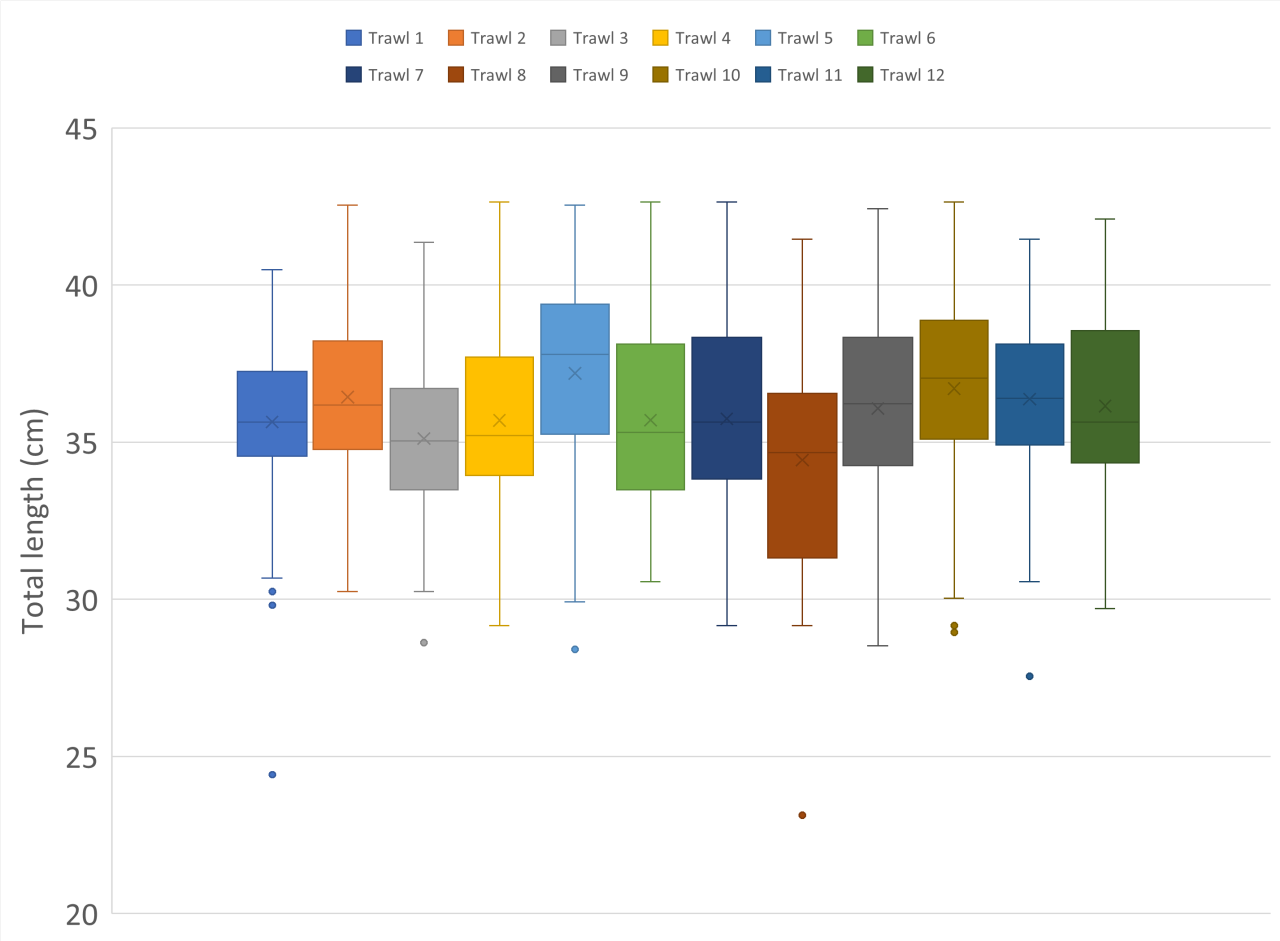


Figure 24. Length distribution of mackerel from the 12 trawls in the first fishing trip onboard FV Libas during October 2024.

6. Concluding remarks

The overreaching goal of fish sizing in this project had two components; the operational feasibility to obtain high quality broadband acoustic data from single fish during commercial fishing operations and fish sizing based in the detection of the peaks in the pulse compressed signal in the time domain. The main findings were:

- The mounting of the narrow beam transducer in FV Libas drop keel allowed broadband data collection continuously during fishing operations, with single fish successfully detected at distance of 120 m away from the vessel.
- The fish sizing method, which proposed using the two peaks in the pulse-compressed signal in the time domain, could not be applied, as the broadband data for a single fish was more complex and lacked this feature.
- Preliminary results suggest that using the maximum TS from fish tracks near the normal incidence angle could serve as an alternative method for estimating fish size. However, this approach requires a better understanding of how to compute TS from broadband data in conjunction with field measurements of wild mackerel in coastal areas, such as around fish farming facilities.

More detailed analysis of these two components is presented as follows:

6.1. Operational development

Despite the problems in 2024 with the damaged transducer, the mounting of the transducer in the FV Libas in a suitable way represented a mayor challenge. The requirements for a mounting that does not interfere with the fishing operations was accomplished during the 2024 season, with the transducer installed in a blister under the drop keel. This solution allowed a continuous data recording, and mounting a transducer directly in the drop keel (without the blister) is the recommended solution for future investigations.

The drop keel mounting solution will be suitable for both purse seining and pelagic trawling, requiring a side or down looking transducer mounting depending on the requirements of the fishermen.

The capability to tilt the transducer proved to be beneficial for adequate data collection during the 2023 season, when purse seining. And should be a strong argument to ask for an electronically tilted transducer to echo sounder manufacturers.

The quality of the broadband data collected from the side looking ES200-3C echosounder was high after using the power source from batteries and not from the vessel power source. In addition, the use of a synchronization unit during 2024, Simrad TU40, allowed the simultaneous operation of the other sonar and echosounder onboard without acoustic interference. Although it was not possible to connect the side looking echosounder to this system due to time constrains, it was evident that is the recommended set up for a suitable data collection of broadband data for fish sizing.

In summary, the operational development of the project was successful and give strong guidelines on how to proceed in the future, either for scientific or fishing purposes.

6.2. Fish sizing method development

The acoustic data collected from the 2023 season was of high quality, with single mackerel detected up to 100 m away from the vessel. The data was absent of electrical noise and acoustic interference from other equipment.

The absence of the two peaks in the pulse compressed signal in the time domain, which corresponds to the sides of a single fish, was not expected. This motivated the work with theoretical modelling of the mackerel backscattering to ensure whether the detected peaks in the pulse compressed signal truly correspond to the boundaries of the target.

The finite element modeling included a more realistic approach adding an elastic elongated prolate spheroid inside the fluid prolate spheroid to model the fish body with backbone. Results indicated that the response is much more complex and the presence of the two peaks is absent, like observed from the field data.

Two alternative sizing methods were tested: using the fish target strength and swimming angle, and the counting of the nulls in the frequency domain. Preliminary results suggest that the use of the maximum TS from fish tracks close to normal incidence angle could be an alternative method to compute fish size. However, this method requires more refinement, with a robust TS-fish length relation which include a larger number of fish in the suitable size ranges at close to broadside incidence angles.

The results of the null counting method, using the tethered mackerel, did not showed a good correlation between the number of nulls and the fish size, for the size range available (281 to 465 mm).

A practical challenge encounter when processing the acoustic data was the lack of a reliable automatic target tracking algorithm for broadband data in the post-processing system LSSS. This tool is essential to allow an efficient and objective selection of fish tracks, especial in large datasets. In addition, standardized methodologies to compute TS values from broadband data (when used for fish sizing) are still not available among the scientific community. These two aspects are currently priority activities inside the CRIMAC center of excellence, and it is expected that during 2025, there will be significant advances in these topics that could be available for general use.

To facilitate the access to acoustic data like the one collected in the fishing grounds with the fishing vessel, it was suggested by the Project reference group to obtain measurements of wild mackerel around fish farming facilities, during the summer season. This will provide easier access to broadband data from free-swimming fish and the opportunity to collect fish samples for size validation. Due to time constraints, this suggestion could not be tested; however, it will be valuable for a follow-up phase of the current project, especially once the broadband tracking and TS methods are ready.

7. Acknowledgements

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8. References

COMSOL Multiphysics, 2020. COMSOL Multiphysics 5.6 Acoustics Module User Guide (COMSOL, Inc., Burlington, MA).

Ehrenberg, J.E., Torkelson, T.C., 2000. FM slide (chirp) signals: a technique for significantly improving the signal-to-noise performance in hydroacoustic assessment systems. Fish. Res. 47, 193–199. https://doi.org/10.1016/S0165-7836(00)00169-7.

Furuno, 2018. Operator's manual. Fish size indicator. Model FCV-2100. Furuno Electric Co., Ltds. 123 pages.

Khodabandeloo, B., Ona, E., Pedersen, G., Korneliussen, R., Melle, W. and Klevjer, T., 2022. Mesopelagic fish gas bladder elongation, as estimated from wideband acoustic backscattering measurements. The Journal of the Acoustical Society of America, 151(6), pp.4073-4085.

Korneliussen, R. J., Heggelund, Y., Macaulay, G. J., Patel, D., Johnsen, E., and Eliassen, I. K. 2016. Acoustic identification of marine species using a feature library. Methods in Oceanography, 17: 187–205.

Kubilius, R, Macaulay, G. J., Ona, E. 2020. Remote sizing of fish-like targets using broadband acoustics, Fisheries Research, Volume 228, 105568, ISSN 0165-7836, https://doi.org/10.1016/j.fishres.2020.105568.

Kubilius, R., Bergès, B., Macaulay, G.J., 2023. Remote acoustic sizing of tethered fish using broadband acoustics. Fish. Res. 260, 106585. https://doi.org/10.1016/j.fishres.2022.106585

Ona E., Korneliussen, R., Totland, A., Pobitzer, A., Eliassen, I., Heggelund, Y., and Macaulay, G. J.2017. Sluttrapport: Sluttrapport for DABGRAF: Datafangst, beregnings og grafisk presentasjons-verktøy for størrelsesmåling av fisk med bredbåndsekkolodd. Fiskeri- og havbruksnæringens forskningsfinansiering (FHF), 15 pp.

Peña, H., and Foote, K. G. 2008. Modelling the target strength of Trachurus symmetricus murphyi based on high-resolution swimbladder morphometry using an MRI scanner. ICES Journal of Marine Science, 65: 1751–1761.

Peña, H., Tenningen, M., Zhang, G. and Skaret, G. 2021. Toktrapport: Utvikling av metoder for mengdeestimering av Makrellstørje i Norske farvann. Havforskningsinstituttet. Rapport fra havforskningen, ISSN:1893-4536.

Simrad, 2017. Simrad ES80 Wideband fish finding echo sounder Operator Manual. Release 1.2.x. 302 pages

Sonic corporation, 2022. KSE-310 Type fish sizing echo sounder. Instruction Manual. Ver. 5.04E. 200 pages.

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