SURVEY REPORT: DEVELOPING METHODS FOR ABUNDANCE ESTIMATION OF BLUEFIN TUNA IN NORWEGIAN WATERS

TOKTRAPPORT
No.5 2022

Title (English and Norwegian):

Survey report: Developing methods for abundance estimation of bluefin tuna in Norwegian waters

Subtitle (English and Norwegian):

Toktrapport: Utvikling av metoder for mengdeestimering av Makrellstørje i Norske farvann

Report series: Toktrapport
ISSN:1503-6294

Year - No.: 2022-5

Date: 16.05.2022

Author(s):
Hector Pena, Maria Tenningen, Guosong Zhang and Georg Skaret (IMR)

Approved by: Research Director(s): Geir Huse Program leader(s): Bjørn Erik Axelsen

Cruise leader(s):

Distribution:
Open

Project No.:
2021815

Program:
Norskehavet

Research group(s):
Pelagisk fisk

Number of pages:
30

Summary (English):

The major aim of this survey was to map and quantify distribution, school size and behaviour of Atlantic bluefin tuna (*Thunnus thynnus*) migrating to and feeding in Norwegian waters.The survey covered the region between Bergen and Molde, between 4th to 15th October, onboard hired vessel M. Ytterstad (75 m long) with promising preliminary results for acoustic methods for monitoring the distribution, abundance and behaviour of bluefin tuna in Norwegian waters. The advantages and disadvantages of the different sonars used can be summarized as:

i) Simrad SU90 (26 kHz low frequency, 360 deg omni): Good for long range detection (800 -1000 m), Not suitable for fish counting (except few fish in soldier formation) and not the best for identifying BFT schools

ii) Simrad CS90 (82 kHz medium frequency, 360 deg omni): Good for long range detection (800 m), good for identifying BFT school, suitable for fish counting in medium and small size schools

iii) Simrad SN90 (75 kHz medium frequency, 160 deg sector): Good medium range detection (400 m), good for identifying BFT school, suitable for fish counting in medium and small size schools. Limited sampling volume compared with omni medium frequency

iv) Kongsberg M3 (500 kHz high frequency, 120 deg sector): Best for fish counting. Only short range (< 100 m) detection and small sampling volume. Only operational at low vessel speed < 5 knots

The results indicate that the omnidirectional medium frequency sonar (Simrad CS90) was the best sonar for detecting and inspecting the schools out of the sonars used in the survey. It was possible to identify bluefin tuna schools based on the sonar signature and swimming speed at a range up to 800 m. It was further clear that visual monitoring provides useful extra information but, is inefficient in monitoring the stock in a routine survey as daylight, good weather conditions and fish close to surface are required. The Simrad SN90 sonar with its high resolution, showed good results for counting individuals in schools, and methods for automatic and objective counting individual fish are investigated.

Promising results were also achieved of BFT sizing using broad band echosounders and we obtained the broadband frequency spectrum (from 55 to 250 kHz) from single bluefin tuna, especially important for BFT where trawl sampling is not an option.

School sizes varied from a few fish to several hundred individuals. The mean depth of the schools fluctuated from surface to 50 m and schools were detected both during the day and night. Some schools were monitored for several hours and despite a relatively fast swimming speed and same swimming direction the schools were observed to make large circles and stayed in the same area, most likely feeding.

Acoustic and visual monitoring of the size and distribution as well as understanding the behaviour of BFT in Norwegian waters will be increasingly important in the years to come, because the number of fish, fishing quotas, challenges related to unwanted bycatch of BFT in other pelagic fisheries as well as the ecosystem impact may increase in Norwegian waters.

Content

1 - Background and objectives

Atlantic Bluefin Tuna (BFT) is the largest of all tuna species and an important commercial fish species worldwide. The total allowable catch (TAC) of bluefin tuna in the eastern Atlantic and the Mediterranean was 36 000 tons in 2021.
In Norwegian waters, the abundance of BFT has been increasing during the past 5 years and a fishing quota has been allocated since 2016. The Norwegian BFT quota was 315 tons in 2021. The increasing abundance and fishing activity on BFT in Norwegian waters (Nøttestad et al. 2020 a, b), requires that the Institute of Marine Research, IMR, provides updated scientific knowledge and advice to national authorities and the International Commission for the Conservation of Atlantic Tunas, ICCAT.

The survey is part of a larger scientific initiative at IMR that aims to investigate and evaluate methods for the detection and identification of BFT in Norwegian waters with a long-term ambition of efficient and robust fisheries independent stock monitoring. The objectives of the survey were to:

- Investigate and evaluate use of sonar and echo sounder for detection of BFT
- Evaluate acoustic methods to discriminate BFT from other pelagic species
- Obtain basic knowledge about BFT swimming behavior, horizontal migration and potential diel vertical migration
- Quantify BFT school size

In this report we present preliminary results from the survey. The complete results willbe published in a scientific publication currently under preparation.

2 - Methods

2.1 - Survey time, area and vessel

The survey period was from the 4^{th} to 15^{th} of October. The survey design was a non-systematic search from the coast to 10 nm miles offshore, between Bergen and Molde. Both time and area were based on bluefin tuna observations and catches in 2020 and 2021 and advice and discussions with bluefin tuna fisherman. The combined purse seiner and pelagic trawler M. Ytterstad (75m long) was hired for the survey.

2.2 - Acoustic instrumentation

The following sonars from Kongsberg Maritime AS were used during the survey: i) Long range and low frequency (20-30 kHz) Simrad SU90, ii) medium range and medium frequency (70-120 kHz) Simrad CS90, iii) medium range and medium frequency (70-120 kHz) Simrad SN90, and iv) short range and high frequency (500 kHz) Kongsberg M3. In addition, a multifrequency (18, 38, 70, 120 and 200 kHz) echo sounder, Simrad EK80 (Kongsberg Maritime AS) was used, where the frequencies 70, 120 and 200 kHz were broadband. During operation the SU90 and CS90 omnidirectional sonar transceivers were lowered 1.6 m below the vessel hull. The SN90 flat (160° sector) transducer was mounted on the vessel hull in the starboard side. The M3 sonar was mounted in a retractable pole 2 m below surface in the starboard side and attached to a remote-controlled hydraulic system which allow the tilt of the sonar head from 0 to 45 degrees (Annex 1). The M3 sonar was used only during selected periods when fish were near the vessel and vessel speed was below 4 knots (risk for damaging the pole in higher speeds).

The echosounder and sonars were calibrated on the 4^{th} and 5^{th} of October in Bergen harbor. The echosounder was calibrated using the reference target method (Demer et al., 2015). All frequencies were calibrated in continuous wave (CW) and the broadband frequencies were also calibrated in frequency modulated (FM) pulse transmission. The SU90, CS90 and SN90 sonars were calibrated following the Macaulay et al. (2016) protocol. The M3 multibeam sonar was not calibrated.

The sonars were synchronized to avoid acoustic interference, using CS90 as master of the SU90 and SN90. The echosounder was not synchronized. In addition, transmission frequencies of the sonars (horizontal, vertical and inspection beams) were carefully selected to avoid or reduce interference of main frequencies and harmonics (Table 1).

Sonar data were processed in the Profos module for scrutinizing sonar data in the Large Scale Survey system (LSSS, Korneliussen et al., 2016). School echoes were extracted from the background (“school growing”) using dB thresholding and other criteria for school acceptance (e.g. size and shape). The software then calculates school position, depth, area, average volume backscattering strength (S_v, dB re $1m^{-1}$, MacLennan et al., 2002), swimming speed and heading for the extracted schools.

Table 1 . Transmission modes used for horizontal and vertical fans and inspection beams of the different sonars. Transmission mode includes center frequency (kHz), type of pulse (LFM for linear FM or HFM for hyperbolic FM), length of the pulse (short, medium or long), and bandwidth (kHz).

Sonar	Horizontal fan	Vertical fan	Inspection beam
SU90	26 kHz (LFM medium, 5 kHz)	22 kHz (LFM short, 0.5 kHz)	28 kHz (LFM short, 3 kHz)
CS90	72 kHz (HFH medium, 1 kHz)	80 kHz (HFH medium, 1 kHz)	82 kHz (HFM medium, 2 kHz)
SN90	85 kHz (LFM medium, 5 kHz)	90 kHz (HFM long, 5 kHz)	100 kHz (LFM medium, 5 kHz)

2.3 - Detection of BFT schools

The long-term aim of the project is to be able to detect BFT schools at a range that can be used during surveying following a systematic survey design for abundance estimation. Acoustic detection of BFT schools was investigated with the two omni directional sonars, Simrad SU90 and CS90. The low frequency SU90 was initially set to a range of 1000-1200 m and a tilt angle of 3°to target the schools close to sea surface. The medium frequency sonar was set to an intermediate range of 400-500 m and a tilt angle of 5-7°.

2.4 - Characteristics of BFT schools

Detection and identifying BFT schools require knowledge of school characteristics, behaviour and vertical distribution. This information is currently lacking for BFT in Norwegian waters. To collect school behavioural data, many of the detected BFT schools were tracked continuously over long time periods, keeping a distance between 200-300 m and adjusting the sonar range and tilt to keep the school in the center of the beams. Schools were monitored with the CS, SU and SN90 sonars. The flat SN90 transducer is attached to the boat hull and is closer to sea surface compared with the CS and SU sonars on the hull unit. In rough seas the SN90 is therefore affected by waves and schools close to surface can be difficult to detect. After monitoring the schools for some time, we tried to approach and maintain the school close to vessel side for data logging with the M3 sonar.

The sonar data provide information about school swimming direction and speed, school size, depth and fish density at different times of the day. In addition, information about feeding behavior on schools of juvenile mackerel, and other pelagic species was collected. When BFT schools were observed deeper than 20 m, attempts were made to cross over them and measure the fish with the multibeam echosounders mounted in the vessel hull. Also, on some occasions when following a school, fish swam under the vessel. The echosounder data will be used to investigate the target strength and frequency response of BFT between 18 and 200 kHz. The echosounder data could also provide information of the prey species in the area.

2.5 - BFT species identification

In the survey area other pelagic schooling species, such as mackerel, herring and horse mackerel are also present and there is a need to distinguish BFT from these other species. Before the survey and based on available literature and experience we identified the following characteristics that may be used to distinguish BFT from other species:

School speed ; it is expected that BFT schools move at a higher speed than other pelagic species when migrating, however, when actively feeding, schools are not expected to move at high speed

Fish observed at sea surface ; BFT force its prey towards the sea surface, and when feeding, they can be observed visually when breaking at the sea surface

School echo strength (S_v) ; because the large fish size, the acoustic backscatter of a tuna school is expected to be significantly stronger than other small pelagic species

Acoustic frequency response ; by using high and low frequency sonars it is possible to investigate if the relative acoustic response of BFT at different frequencies is different from that of other species

Single fish detection ; because of the large fish size and larger between-fish distances, it is possible to acoustically detect single fish at long range (previous experience indicates up to 600 m with medium frequency omni sonar).

2.6 - Quantification of BFT school size

Two methods for estimating school biomass will be evaluated. The first method is based on the school echo strength (converted to fish density) and volume (Peña et al., 2021). The second method is based on counting individuals detected with the sonar.

School biomass estimated based on fish density and school volume

To estimate BFT school biomass, the swimming direction and speed of the school need to be determined first. Then the vessel will be positioned at a fixed distance from the school, between 200 to 300 m to starboard side. The initial plan of circling around the school was not followed because of strong fish reaction to the approaching vessel, and a strategy to sail along the school following predominant fish heading was used.

Calibrated volume backscattering strength (S_v, dB re 1 m^{-1}) values will be obtained by ping and aggregated by school. The biomass will be computed following procedure developed during the Crisp project and includes the computation of fish density and school volume (Peña et al., 2021). For fish density, lateral aspect target strength is required, and will be collected using the inspection beams in the SN90 sonar. If not possible, reference values from literature will be used. School volume will be calculated using the area from the horizontal beams and the vertical extension from the vertical beams.

Due to problems with the calibration files, it was not possible to obtain calibrated S_v values yet. Instead, as a preliminary exercise, the number of fish in a school was subjectively estimated using information from the sonar images, visual detections, and discussions with the skipper. School diameter estimated from the sonar was then related to number of fish and used to convert school size to number of fish. Average fish weight was obtained from landed catches and use to convert number of fish in a school to biomass.

Counting individuals

Because of the size of the BFT and the relatively high resolution of the sonars we expect it to be possible to visually identify individuals in the sonar data. The SN90 sonar data will be used to evaluate fish counting using manual and automatic image analyses. We will also consider the M3 sonar for counting individuals. The M3 sonar has a better resolution than the SN90 sonar but requires that fish can be maintained at close range (maximum 150 m) and vessel speed cannot exceed 4 knots risking that the pole bends or instruments are damaged.

2.7 - Estimating fish size with echosounder

The high range resolution broadband echosounders can be used to estimate fish size if single individuals can be detected. This is done by measuring the distance between volume backscattering strength (Sv) peak values by depth in a single ping, representing the upper and lower boundaries of the fish (Kubilius et al., 2020). Based in literature values of the ratio between body height and length this value can be converted to body length.

2.8 - Visual observations

Dedicated observers on the vessel roof made visual observations of tuna in the surface. The observations were communicated via VHF to the bridge, where time, number of tunas and distance and bearing relative to vessel bow were registered. The observations were made continuously during light hours (ca. 08:00 to 19:00 hrs.) with 2 observers on 2-hour watches. The observers also reported sea state at the end of each watch based on a scale from 1 (calm sea) to 5 (too rough sea for detections).

3 - Results

The surveyed area extended from Molde to Bergen from the coast to about 10 nmi offshore (Figure 1). Most of the tuna observed were concentrated in two regions; off Fedje on the 6th and 13th October and off Ålesund from 8th to 10th October. So far sonar data from the 6th (CS90), 8th and 12th (SN90) of October have been analyzed and will be presented here.

The preliminary results show that the abundance of BFT in the survey area was higher than observed in the 2020 survey. So far, we have identified and analyzed 41 schools with the medium frequency sonar on the 6th of October in the coastal region off Fedje and 25 schools with the SN90 on the 8th and 12th of October. In many cases several BFT schools were simultaneously observed in the sonar in a radius of 500 m (Figure 2).

The weather conditions were optimal for visual detections in the surface on the 6th of October (wind strength < 5 ms^{-1},Figure 3). The other days, wind was higher reaching up to 20 ms^{-1}, but with periods below 10 ms^{-1} . Sea state followed a similar pattern as wind speed, with a value varying mainly between 3 and 5 (value 1 is calm seas, and 5 high waves and whitecaps). Despite the poorer weather conditions, we had periods with many BFT detections both visually at surface and with the sonars. This indicates that BFT can be detected also in poorer conditions. In these days the fishing boats remained in the harbor.

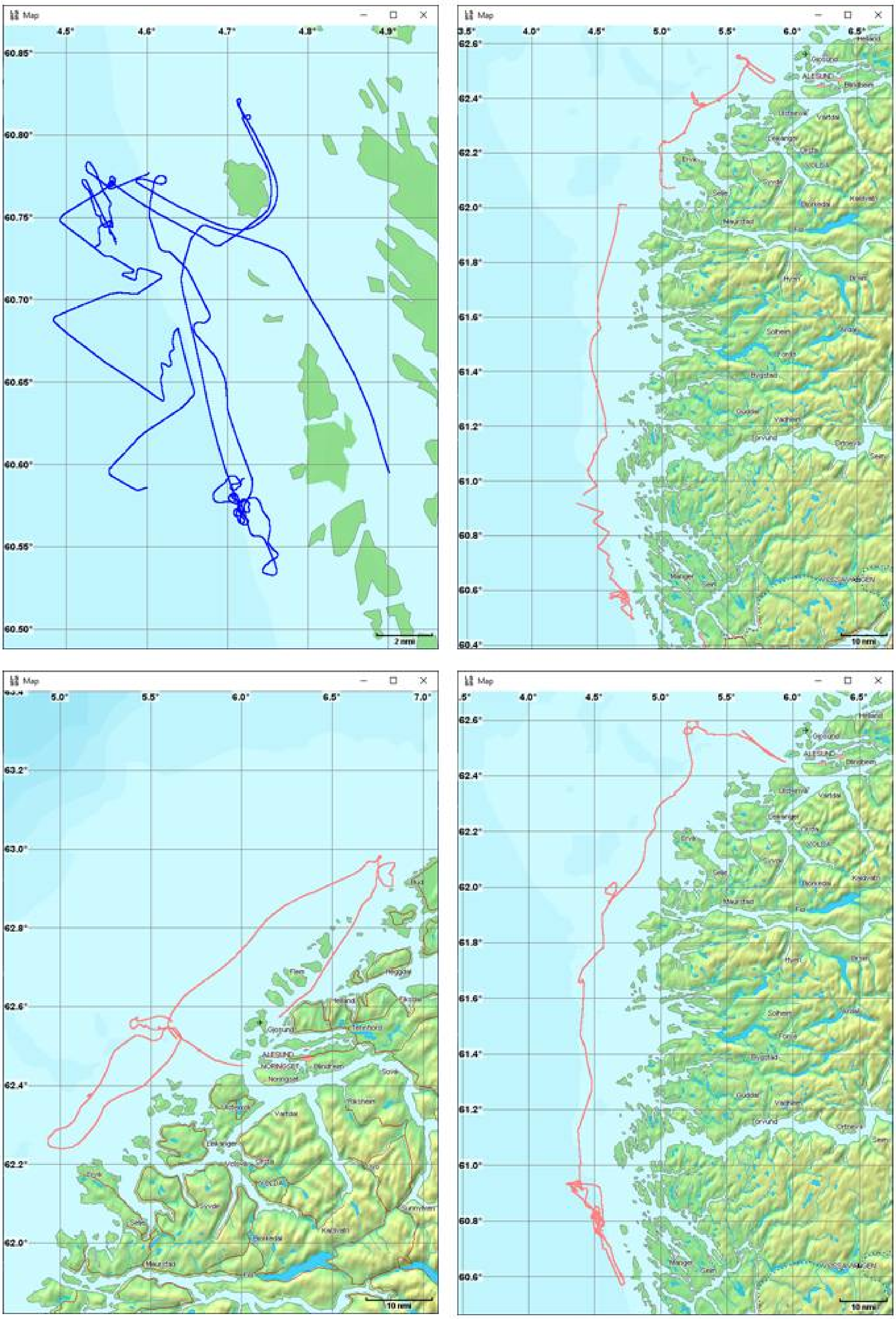


Figure 1 . Survey track from M. Ytterstad during 05 to 06 (top left), 07 to 08 (top right), 09 to 10 (bottom left) and 11 to 13 (bottom right) October 2021.

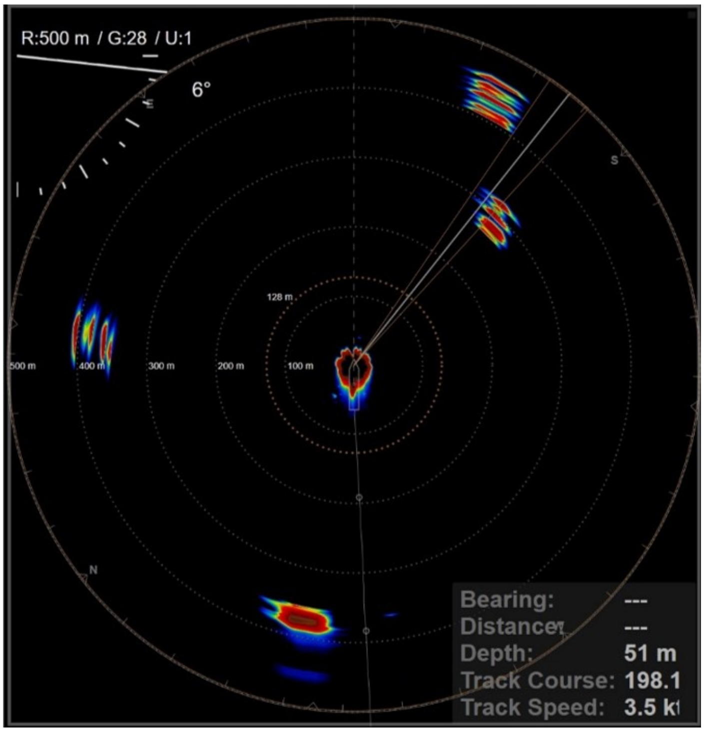
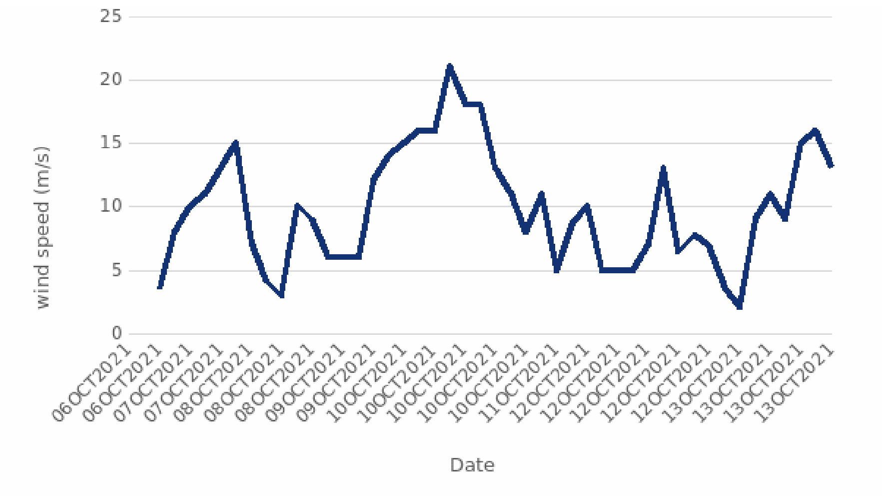


Figure 2. Image of the medium frequency sonar showing 3 BFT aggregations; port side at 350 m, starboard bow at 300 and 450 m.



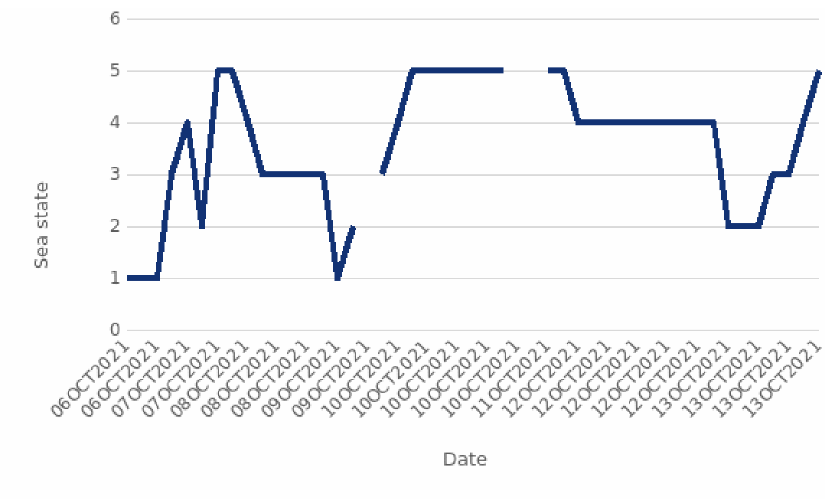


Figure 3 . Wind speed and sea state (value 1 is calm seas, and 5 high waves and whitecaps).

3.1 - Detection of BFT schools

3.1.1 - Sonar settings

One week before the survey start, one scientist joined FV “Vestbris” for tuna fishing in the Måløy region with the objective to gain experience with sonar settings and the BFT fishing grounds prior to the survey onboard M. Ytterstad. The skipper used a range of 900 m and a tilt of 3 degrees for fish search using the Simrad SU90. For the medium frequency sonar, Furuno FSV-85, a range of 400 m with 7 degrees tilt was used. This information was used for the initial set-up of the sonars onboard M. Ytterstad. The final settings used for the search during most of the survey was 800 m range and 3 deg tilt in the SU90 low frequency and 400 m range and 7 deg tilt in the CS90 medium frequency sonar.

Search speed was set to 7 - 9 knots. At this speed sonar detection of schools seemed to be good and it was possible to discriminate BFT from the background and other species. It was observed that at normal survey speed of 10-11 knots, small groups of fish swimming at high speed were difficult to detect.

3.1.2 - Characteristics of BFT aggregations

In the medium frequency sonar, at 400-600 m range, the schools were generally observed as strong echoes of ca. 50-200 m diameter composed by individuals or groups of targets (Figure 4). The detections differed from small pelagic schools (e.g. mackerel and herring) that usually appear as patches with a more uniform echo intensity.

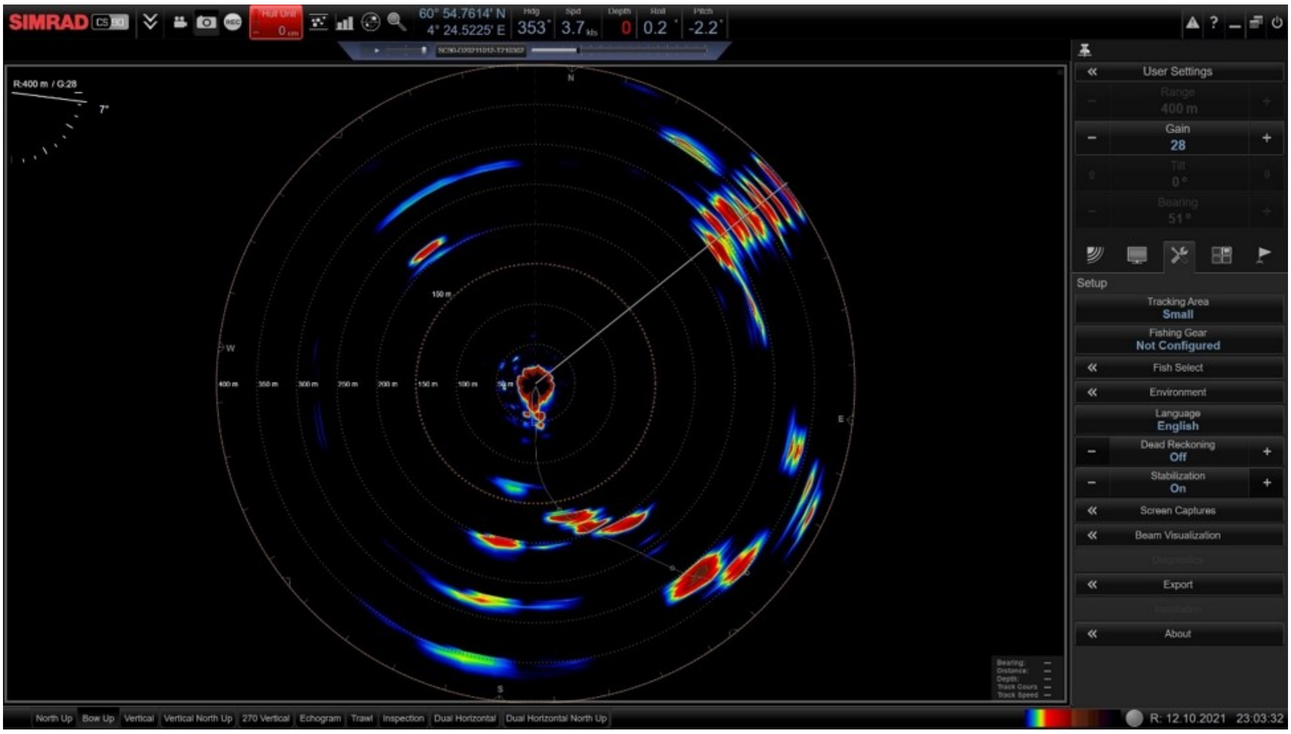


Figure 4. School of 30-50 tuna observed with the medium frequency sonar at a range of 300 m and 7 degrees tilt to the starboard bow side (vessel in the center of the image).

In general, two types of aggregations were identified;

1. Actively feeding in the sea surface (surface and down to 20 m). Chaotic behavior with fish jumping out from the water, slow displacement of the aggregations (< 1.5 ms^{-1}), without a clear direction and large numbers of fish in order of hundreds. This behavior was observed on the 6th of October and was associated with ocean surface fronts. These could be regions where prey species for tuna aggregate. This behavior was observed visually and in the sonars (Figure 5).

2. Fish in soldier formation, following a steady direction and speed. Mean depths between 20 and 50 m (Figure 6). Number of individuals varied from 5 to 50 fish (Figure 3 and 4). The aggregations were observed during day and night hours. On some occasions, fish were observed jumping in the sea surface. Schools did not seem to react strongly to the approaching vessel but followed the same swimming direction until the boat was very close to the fish (<30 m).

The data from the SU90 sonar on the 6th of October show that schools were swimming at a speed between 0 and 3.5 ms^{-1} in varying directions (Figure 6).

It was not possible to distinguish the schools close to surface with the SN90 sonar with a transducer close to sea surface. However, schools deeper down where clearly detected with the sonar (Figure 7). Data processed from the 8th and 12th of October show that the schools were on average at a depth between 10 and 50 m and the average swimming speed was mainly between 1 and 2 ms^{-1} (Table 3). School area varied from 20 to more than 2000 m^2. Uncalibrated average S_v values varied between -37 and -61 dB and were affected by the chosen dB threshold and other school criteria used.

The schools were dynamic and rapidly changed swimming depth from the surface and down to 30 m (Figure 8). School sizes were also dynamic and small aggregations were observed to merge into larger schools and large schools were observed to split into smaller aggregations. The schools generally reacted to the boat and avoided by diving under the boat when approached closer than about 30 - 50 m.

It was also noted that when schools were in soldier formation and monitored using a fixed tilt angle, the echoes from the same individual fish fluctuated in intensity. This indicates that the fish changed its depth and moved between the edges (weak echoes) and the center of the vertical beam (strong echoes) (Figure 8). Analysis of the changes in the acoustic strength of individual fish may give clues of the swimming behavior of tuna when in soldier formation.

On the 10th and 11th of October several medium sized schools (30-50 fish) were observed west of Ålesund at sunset in a shallow region with complex bathymetry. The schools were swimming at speeds between 2 and 4 knots with a predominant westerly direction. On 11th October, a school was followed for more than 2 hours (20:26 to 22:38 UTC) until it had completed a full circular trajectory in a 2 by 2 nautical mile region, changing constantly its depth (Figure 9). Before the survey we expected to observe mostly migrating aggregations, but this suggests that schools may remain in the same area and following a school only for a short period may give a false indication of a migrating school.

In the coastal and shallow region off Ålesund (50 m depth) a group of fish was observed actively changing its depth, what was interpreted as a possible feeding strategy (Figure 10 , top panel). This hypothesis was supported by echosounder measurements of smaller individual fish in the same region that presented a different frequency response and lower target strength values than the tuna, and could correspond to saithe (Figure 10 , bottom panel).

Although information available prior the survey indicated presence of juvenile mackerel in the stomach content of captured tuna, no mackerel schools were observed during the survey, neither from the acoustic equipment (echo sounders and sonars) or from visual observations. However, some small schools (ca. 5 m diameter) moving at low speed (< 0.5 ms^{-1}) close to the surface were observed in some areas, especially in the middle frequency sonar. We were not able to measure these targets with the vessel echo sounder, which would have helped in the identification. It would have been convenient to have available a small trawl for targeting this type of aggregations for species identification. The trawl could also have been used to catch the potentially more dispersed prey fish found in the Ålesund region.

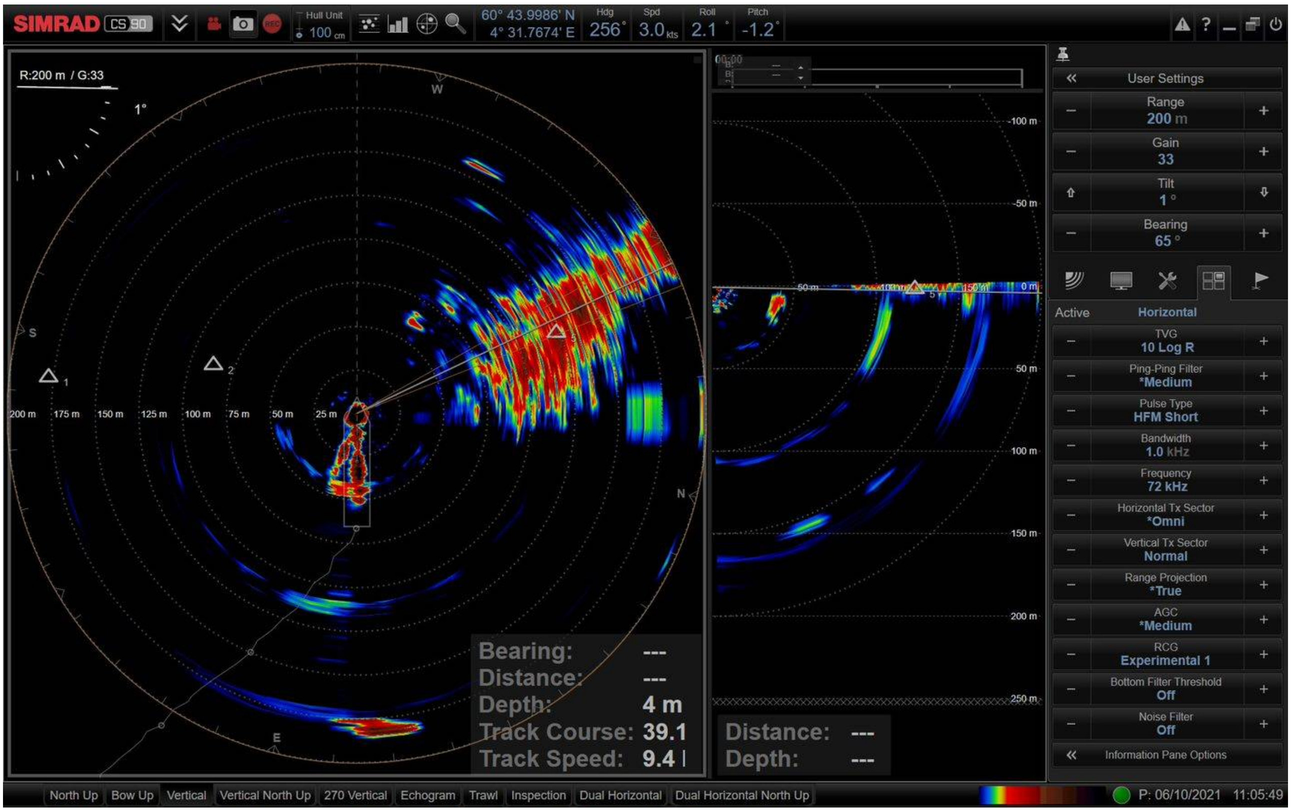


Figure 5. School BFT actively feeding in the surface during 6th October observed with the medium frequency sonar at a range of 200 m and 1 degree tilt to the starboard bow side (vessel in the center of the image).

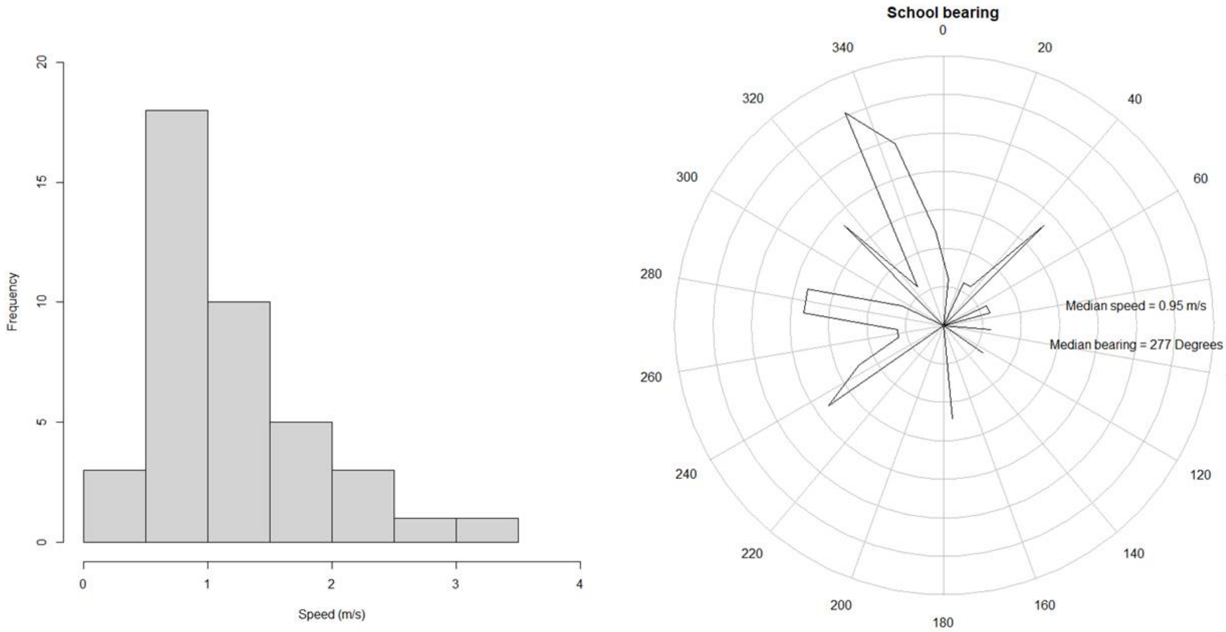


Figure 6. Bluefin tuna swimming speed and direction measured by medium frequency sonar on day 6 th October.

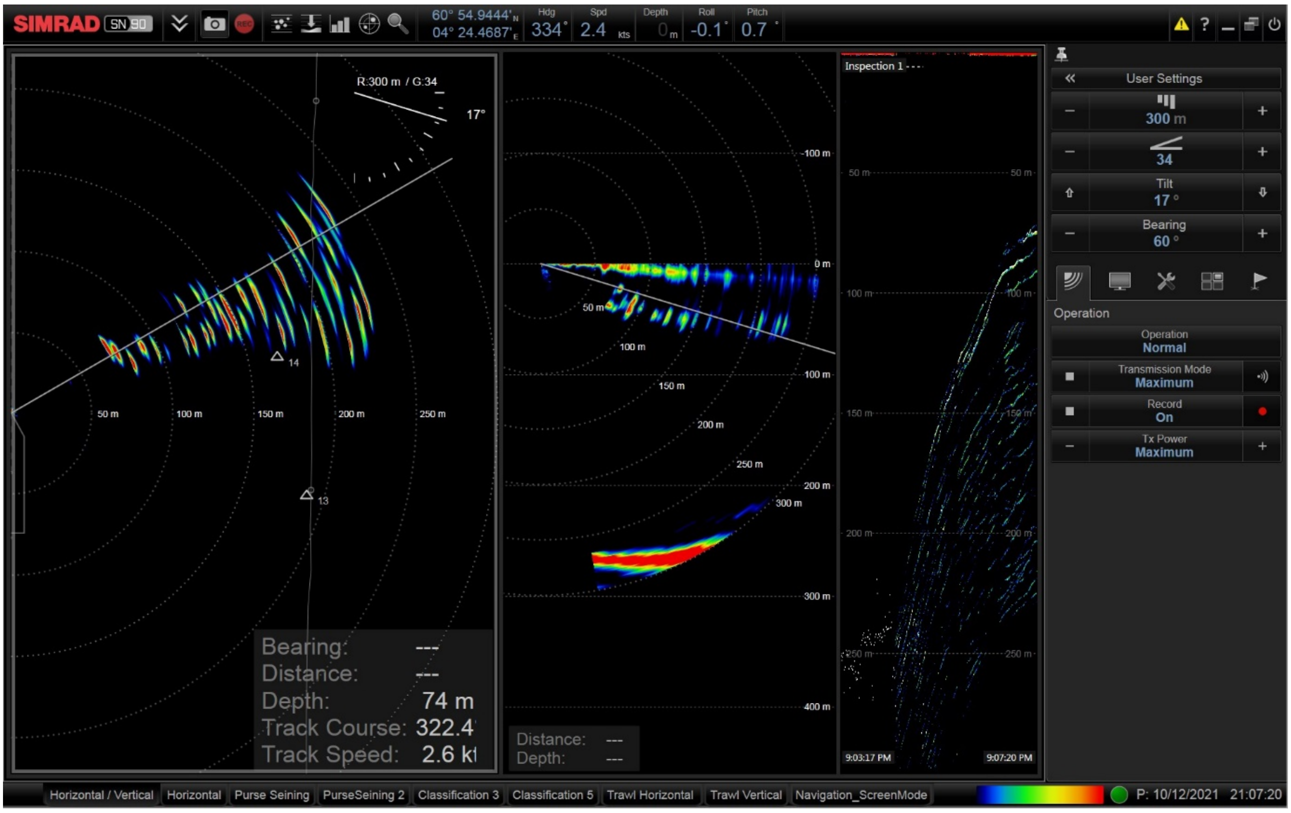


Figure 7. Example of screen image from the SN90. On the left fish are seen in a horizontal cross section, in the middle the same fish are seen in a vertical cross section and in the right inspection beam data is presented.

Table 3. SN90 raw data have so far been processed for two of the survey days (8th and 12th of October). In this table the school characteristics are presented including date and time and how long the school was monitored, average school depth, average school volume backscattering strength (Sv, dB re 1 m-1), average area (m2), average swimming speed (ms-1) and the average swimming direction as heading in degrees.

School nr.	Date	Time (UTC)	Monitoring duration	Depth (m)	S_v (dB)	Area (m^2)	Speed (ms^{-1})	Heading (°)
1	08.10.2021	13:16:13	00:02:06	25	-37.41	84	1.25	294
2	08.10.2021	13:20:54	00:11:46	26	-39.58	191	1.55	280
3	08.10.2021	13:43:23	00:01:36	22	-40.34	22	1.59	333
4	08.10.2021	16:40:07	00:00:30	13	-42.89	670	0.39	46
5	08.10.2021	16:54:47	00:05:22	12	-42.27	205	0.04	207
6	08.10.2021	18:56:29	00:02:54	13	-44.15	39	1.40	328
7	08.10.2021	19:15:43	00:06:22	15	-38.41	179	1.22	309
8	08.10.2021	19:25:35	00:05:10	17	-38.78	132	1.22	316
9	08.10.2021	19:44:19	00:02:40	15	-44.83	2483	1.03	256
10	12.10.2021	20:04:33	00:07:33	37	-40.07	112	1.26	212
11	12.10.2021	21:09:31	00:17:11	38	-43.20	268	1.32	300

School nr.	Date	Time (UTC)	Monitoring duration	Depth (m)	S (dB)	Area (m)	Speed (ms)	Heading (°)
12	12.10.2021	21:30:11	00:10:40	48	-48.62	998	1.54	9
13	12.10.2021	22:14:20	00:00:40	35	-61.24	1505	1.51	275
14	12.10.2021	22:17:08	00:07:19	33	-48.84	192	1.48	309
15	12.10.2021	22:29:42	00:02:33	30	-51.49	166	1.57	228
16	12.10.2021	22:35:06	00:04:51	22	-39.42	175	1.42	266
17	12.10.2021	22:44:27	00:01:31	11	-60.44	1332	1.09	244
18	12.10.2021	22:47:44	00:01:56	39	-44.58	62	1.64	252
19	12.10.2021	22:54:39	00:06:53	43	-47.99	357	1.63	271
20	12.10.2021	23:19:13	00:00:38	44	-52.12	156	1.64	199
21	12.10.2021	23:22:59	00:00:37	40	-53.25	293	0.73	170
22	12.10.2021	23:26:06	00:02:09	39	-49.55	448	0.56	116
23	12.10.2021	23:46:46	00:09:57	42	-52.15	530	1.22	295
24	12.10.2021	08:21:28	00:02:17	30	-45.42	118	1.63	352
25	12.10.2021	21:48:07	00:02:43	53	-52.98	557	1.74	304

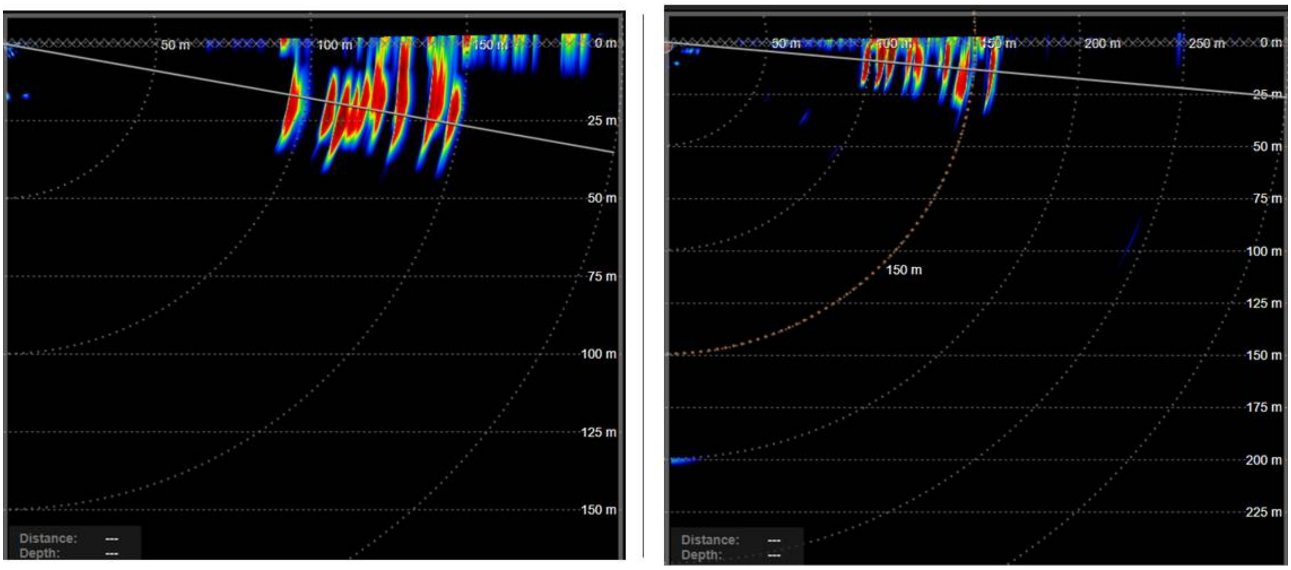


Figure 8. Changes in the mean school depth in a period of 14 minutes, from 25-30 m (left panel) to ca. 10 m (right panel). Fish school had a mean depth of about 25-30 m when observed with a 10-degree tilt (02:02 UTC), and 14 minutes later (02:16 UTC) fish were closer to the surface at ca. 10 m depth using the sonar with 5-degree tilt.

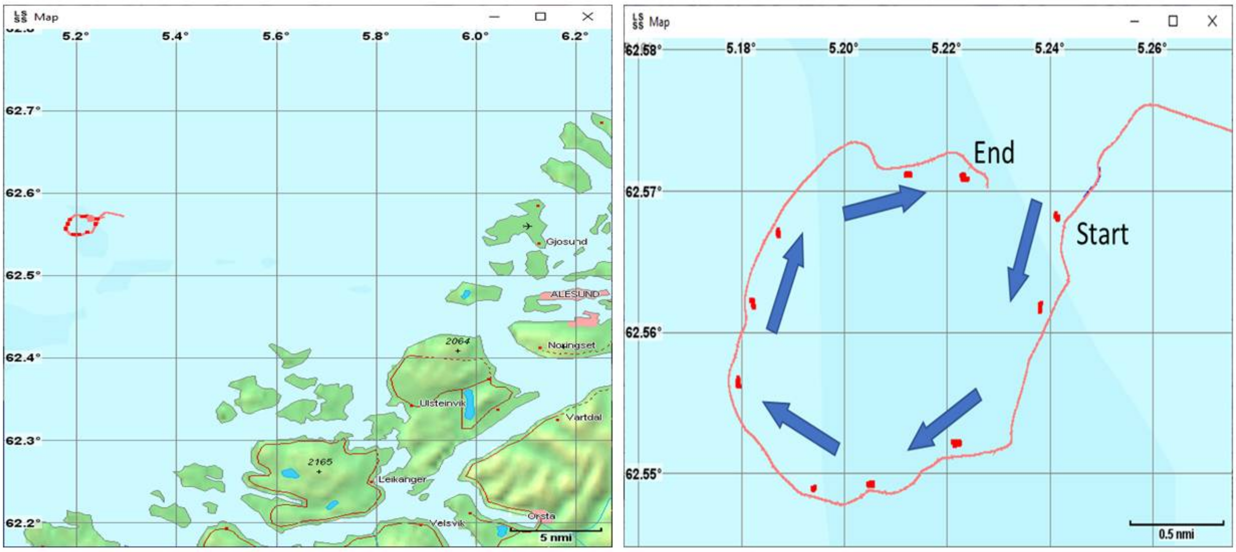
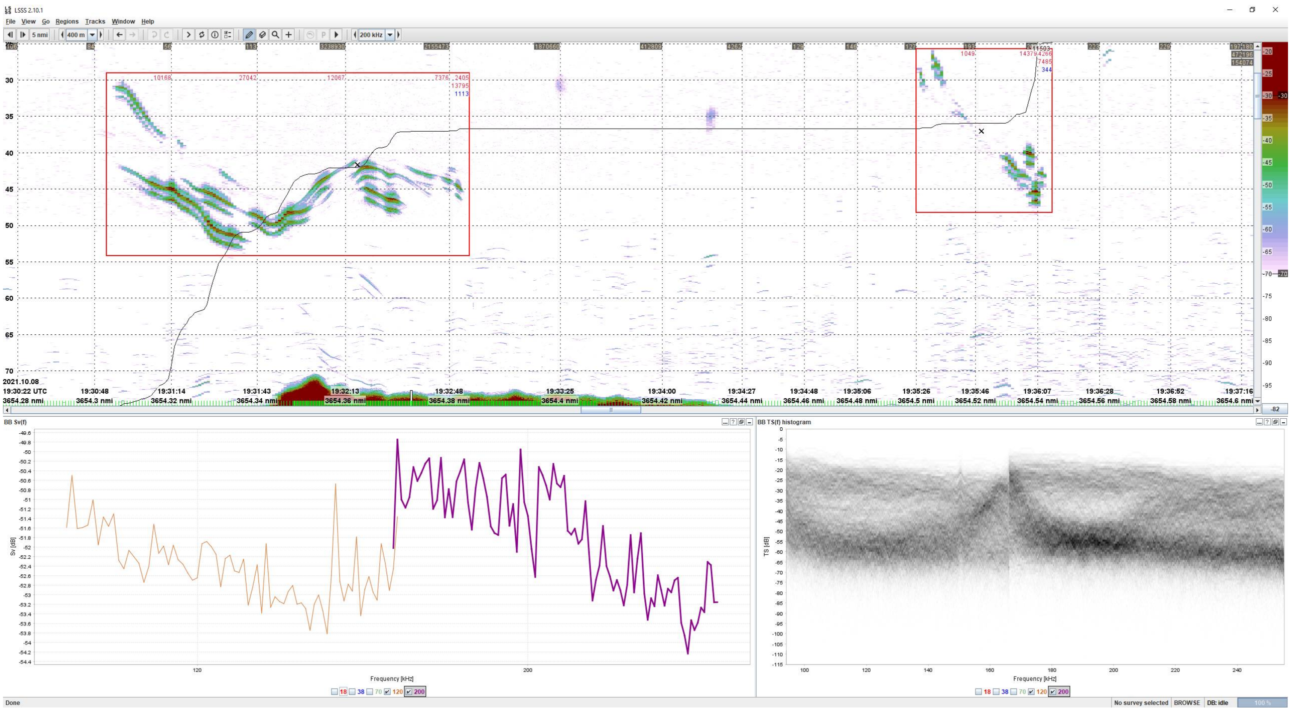


Figure 9. Behaviour of bluefin tuna observed with sonar off Ålesund on 11th October. Vessel track in pink line and school detections as red dots at starboard side of the vessel path.



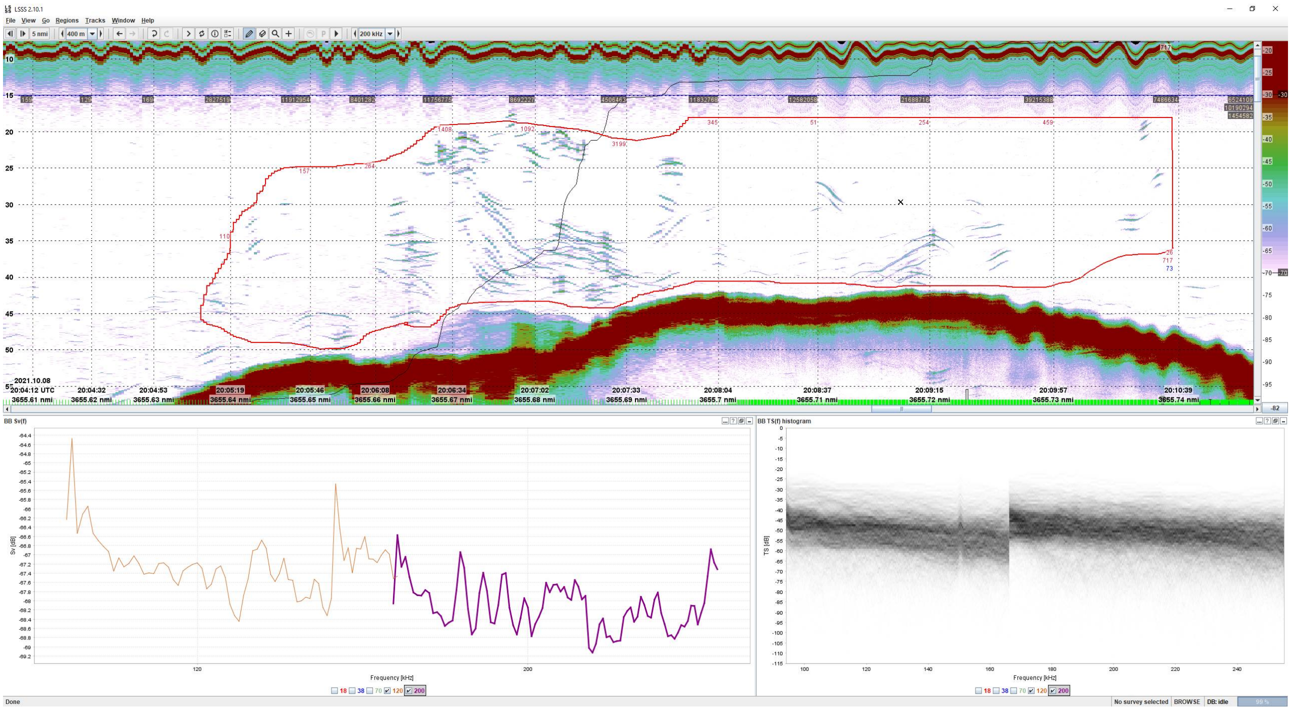


Figure 10. EK80 echo sounder recordings of bluefin tuna (top panel) and possible prey fish (bottom panel). In each figure an echogram of 200 kHz is displayed in the upper panel, the volume backscattering strength (Sv) for the broadband frequencies of 120 and 200 kHz (bottom left panel) and histogram of target strength detections in the same frequency range (bottom right panel).

3.2 - Species identification of BFT schools

Out of the suggested characteristics (appearance on sonar, swimming speed, visual detection, echo strength and frequency response) for distinguishing BFT from other species, appearance on the sonar was maybe the best characteristic. As described in the previous section, bluefin tuna schools were generally observed in the sonar as a group of individual targets rather than a compact school with homogeneous backscatter common for small pelagic species (Figure 2).

In general, the swimming speed of BFT schools was faster than that of small pelagic species. The swimming speed of the tuna schools was mainly higher than 1 ms^{-1} and generally between 0.5-1.5 ms^{-1}, with maximum speed of ca. 3.5 ms^{-1} (Figure 5 ; Table 3). Swimming speed may thereby also be a useful indicator when trying to distinguish BFT from other species.

Observing the BFT visually at the surface is naturally the most secure way to identify BFT. In a meeting before the survey tuna fishermen explained how they follow the targeted fish before catching until they appear at the surface and they can verify that it is tuna. Visual detections are highly useful but only under some conditions, i.e. day light and when fish are close to surface. Many of the schools observed in the survey were deeper in the water and at night-time and no visual detections were obtained.

Average school S_v measured by the sonar depend on the dB threshold used, based on the preliminary results the uncalibrated average S_v values ranged between -37 and -61 dB (SN90, Table 3) and are not different from other pelagic schools.

3.3 - Acoustic estimates of fish size

Echo sounder measurements of BFT were generally made after finishing the sonar sampling of a target school. The vessel was maneuvered carefully to sail on top of the tuna and make it accessible to the echosounders mounted in the scientific keel. On some occasions, when following a tuna school, some of the individuals were swimming under the vessel allowing for echo sounder measurements.

Using the high range resolution of the broadband echosounder, preliminary measurements of the dorsal and ventral fish boundaries of an individual bluefin tuna fish were done. Using volume backscattering strength (S_V) values by depth for a single ping, the distance between S_V peaks was measured with a resulting fish height of 70 cm (1, top right panel, following method described by Kubilius et al., 2020). Using the ratio of 0.27 between the maximum body height and fish fork length (Ticina et al., 2011), we can compute a fork length of 259 cm for this specimen, which agrees with the fish size from catches during the fishing season.

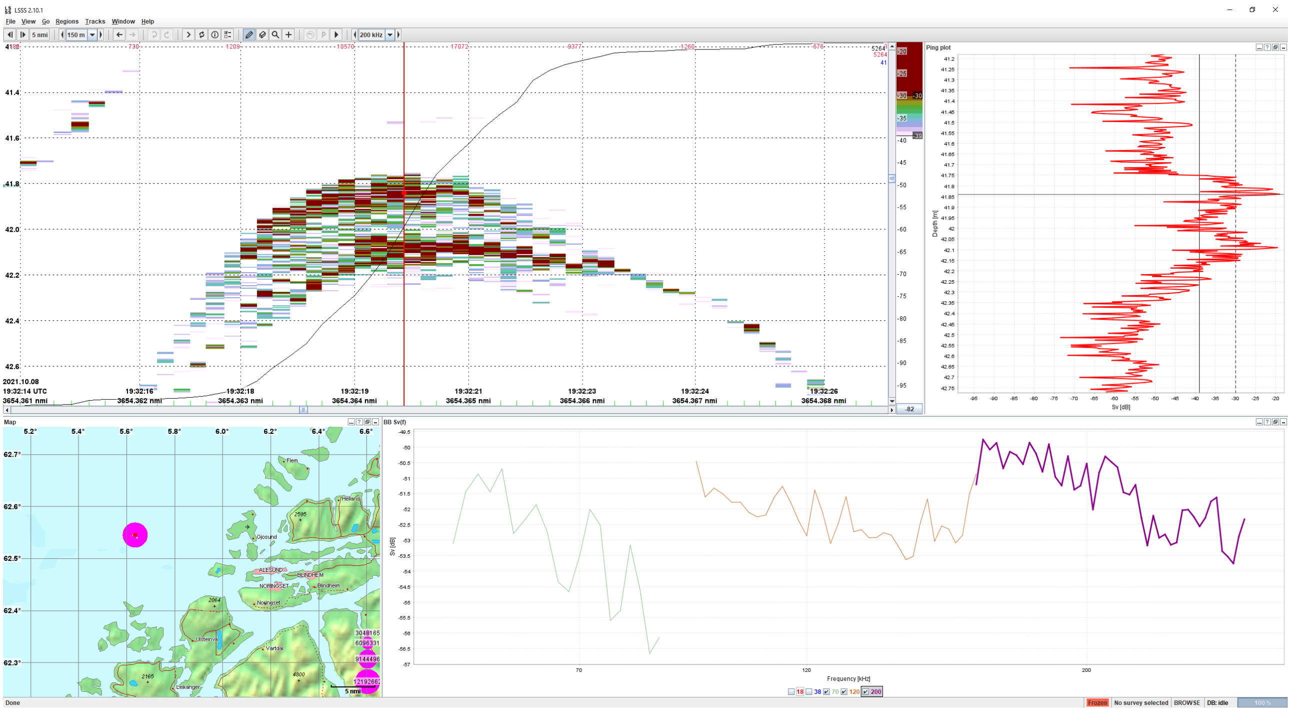


Figure 11 . 200 kHz echogram of a single bluefin tuna recorded, with stronger scattering from dorsal and ventral fish boundaries (upper left). Plot showing the echo strength (Sv) in a single ping (top right) and broadband frequency response from 70 to 200 kHz (bottom right).

3.4 - Quantification of BFT schools' size

3.4.1 - Biomass estimation based on fish density and school volume

Results from the scrutinizing of the 41 schools observed with the medium frequency sonar on the 6th October are shown in Figure 12 and Table 4), where volume backscattering strength (S_V, dB re 1 m^{-1}) values are uncalibrated. Due to some problems with the calibration files, we have not yet been able to obtain calibrated S_V values and can therefore not convert S_V values to fish density. Instead, as a preliminary exercise the estimated number of fish in a school based on sonar image, visual detections and discussions with the skipper were related to the school diameter (Table 5). The school biomass was estimated using this conversion from school diameter to number of individuals and assuming a mean fish weight of 240 kg, based on reports from the fishing fleet during the season. Large fluctuations were found in all parameters related to school size, e.g. school horizontal diameter ranged from 6 meters to over 150 m and the estimated school biomass varied between 5 and 150 fish and a biomass of 1.2 to 36 tonnes (Table 4).

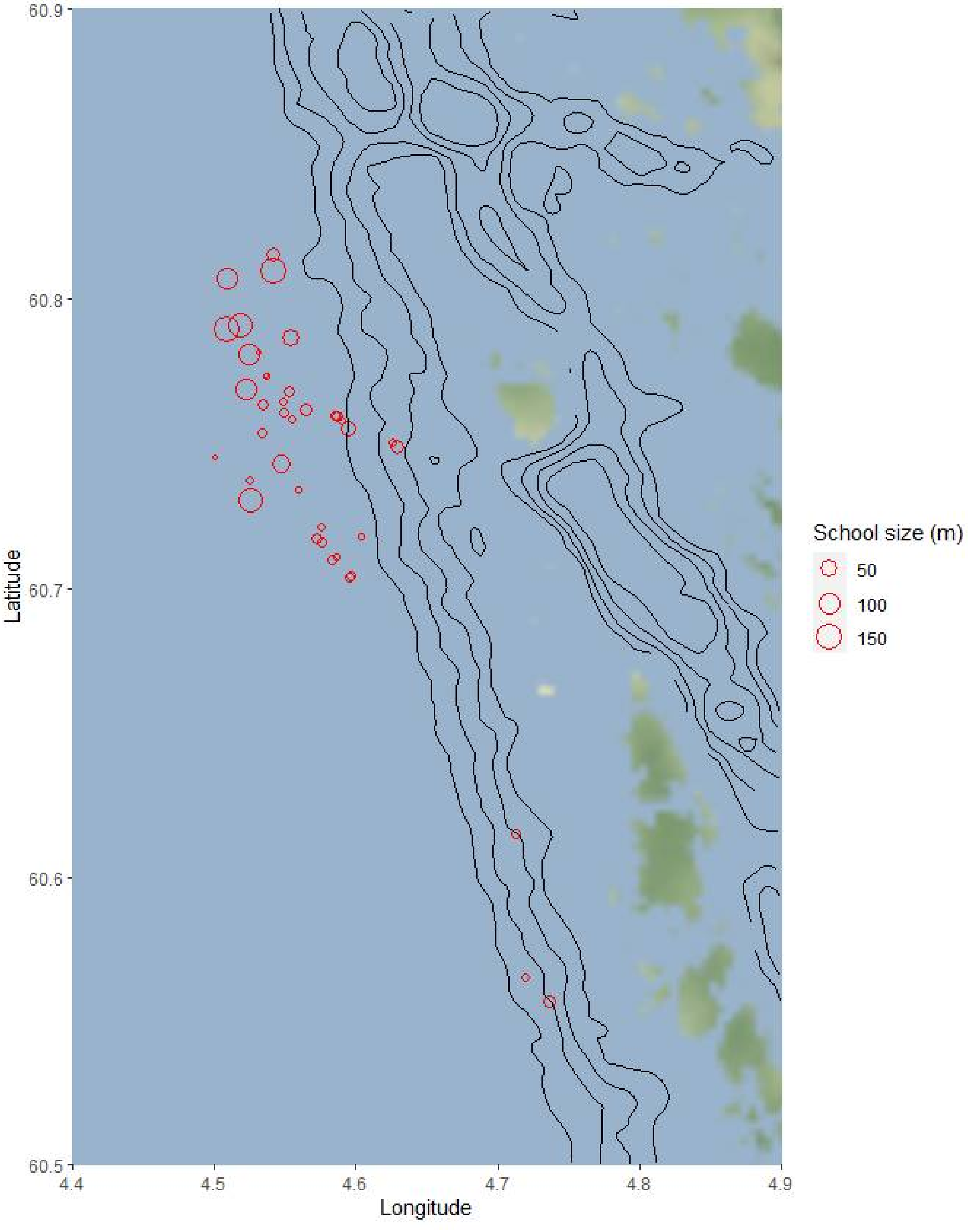


Figure 12. Location of bluefin tuna schools measured with medium frequency sonar CS90 during 6th October. Symbol size proportional to the diameter the school measured along the sonar beams. Bathymetric curves are also shown in black.

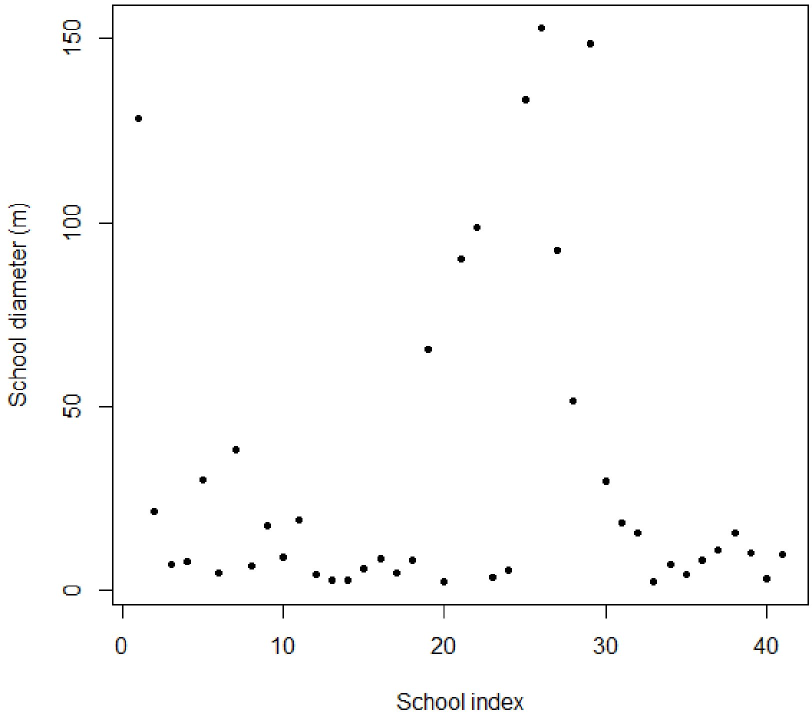


Figure 13. Bluefin tuna school horizontal diameter measured with medium frequency sonar on 6th October.

Table 4. School parameters from schools measured on 6th October using medium frequency sonar.

	Mean Sv (dB)	Mean area (m^2)	Diameter (m)	Biomass (t)
Minimum	-70.9	55	6	1.2
1st quantile	-63.6	137	6	1.2
Median	-57.6	236	10	1.2
3rd quantile	-55.5	1 328	30	2.4
Maximum	-48.6	22 767	153	36

Table 5 . Number of bluefin tuna by school diameter based in sonar measurements and visual observations.

School diameter (m)	Number of fish
<10	5
10-50	10
50-100	40
>100	150

3.4.2 - Abundance estimation based on counting individuals

An alternative method to extracting school echoes and using that for abundance estimation is to count individuals, ideally using automatic image analyses. The higher the resolution of the sonar, the better the chances to detect individuals. A preliminary attempt was also made to count individuals from the SN90 sonar data. First, by counting individuals manually every 10 seconds (Figure 14). The 31 counts made from one school ranged between 5 and 15 fish. The challenge was to determine at what echo strength (colour) the mark should be defined as a tuna and how to distinguish one fish from a group of several fish. When using only a slice through the school all fish will not be captured and the school abundance will be underestimated in larger schools. A simple automatic thresholding was made in image J for the same school (Figure 15). The same challenges face the automatic method as the manual counting (threshold level and how to separate fish in groups), but this method is objective.

All sonars used in the survey detected individual fish at times, but the high resolution M3 sonar provided the best data (Figure 16). Preliminary results from the measurements with the M3 multibeam sonar indicate good detection of single fish which will allow fish counting in selected periods. Results from fish counting with this sonar will be compared with estimates from CS90 and SN90 sonars.

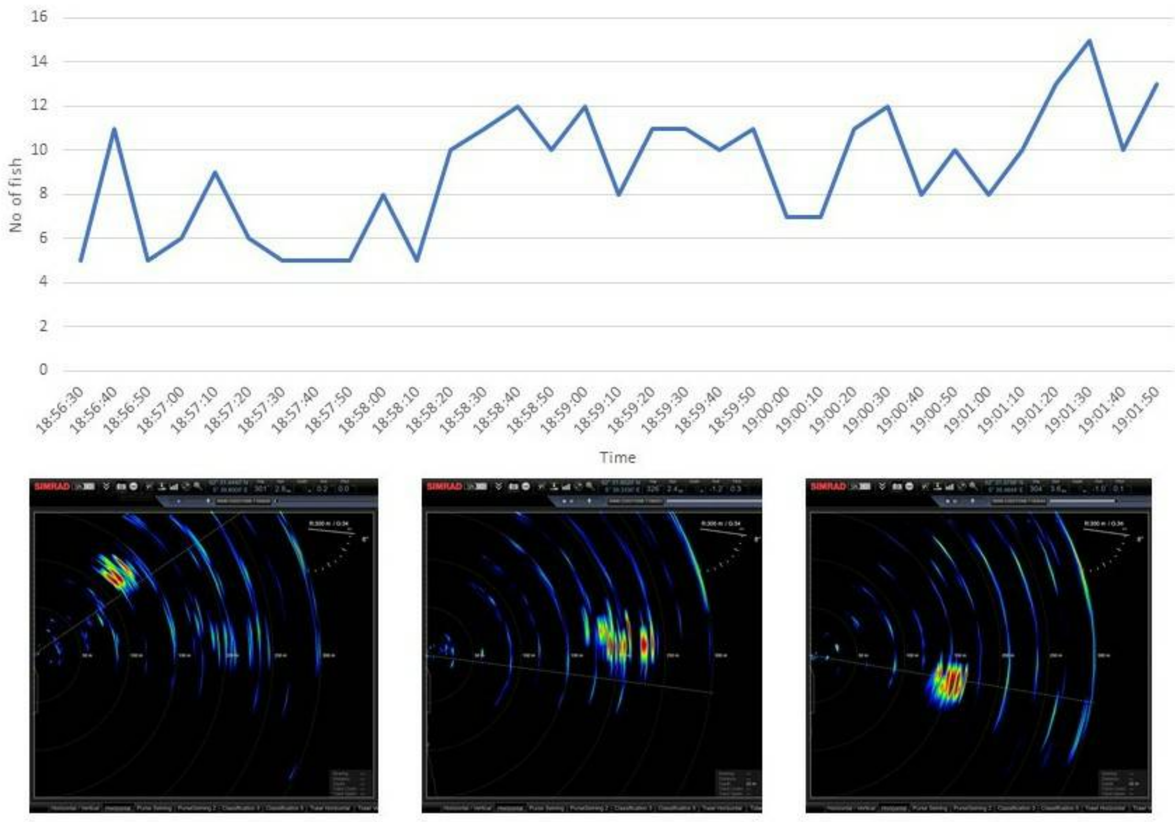


Figure 14 . Manual fish count from SN90 screen images. Fish in the same school were counted 31 times with 10s intervals. Examples of screen images used are shown below the chart.

Figure 15. Example of using autothresholding in image J to automatically detect and extract BFT echoes and count the number of individuals. The image is first converted to binary, then a threshold is applied and finally borders of the thresholded parts are detected and the number of shapes counted.

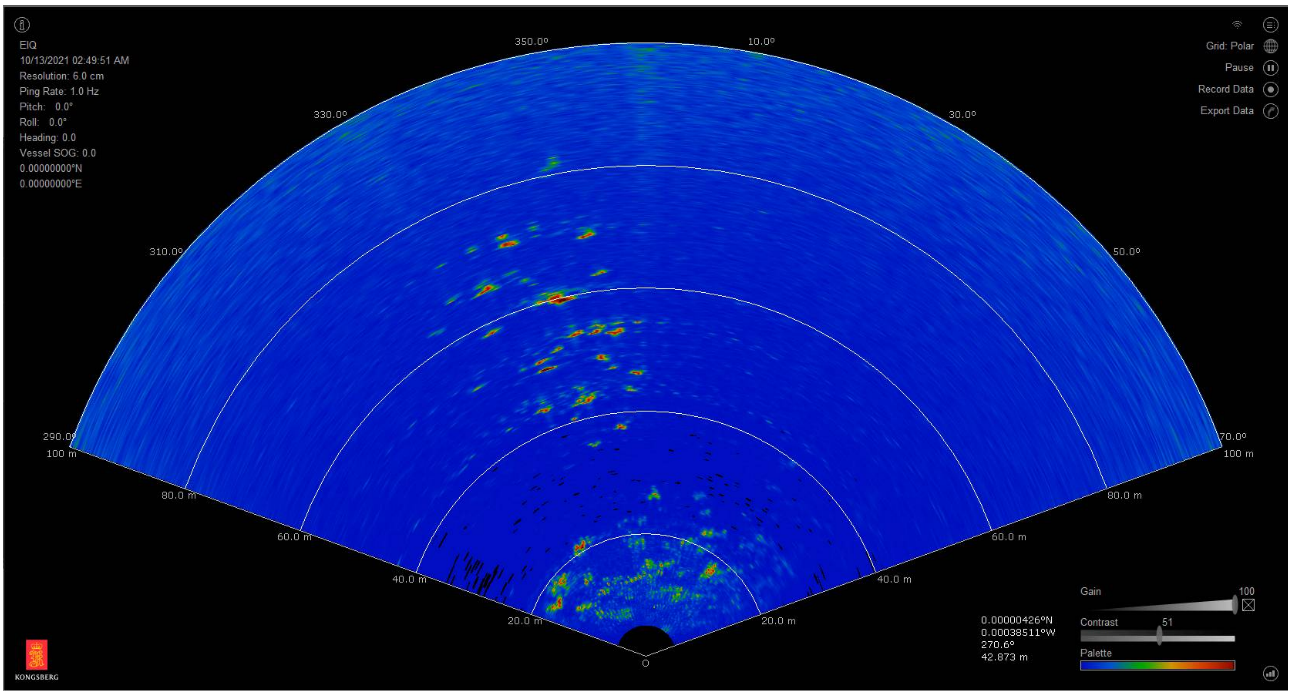


Figure 16. Image of M3 multibeam sonar (mounted pointing starboard) showing individual bluefin tuna (as orange/yellow dots) at ranges between 40 to 80 m from the vessel.

3.5 - Challenges with scrutinizing

During the scrutinizing of the medium frequency (CS90) and hull mounted (SN90) sonar data, the following challenges were faced:

- In medium and small size schools, individual fish are registered as individual targets and not a single compact unit, which makes the segmentation algorithms implemented in PROFOS post processing system inefficient. In most cases it was necessary to extract individuals or small groups of tuna separately and then merging these into a single school. This was time consuming and alternative ways of extracting fish echoes from background noise should be considered

- In many schools, vertical school extension from the vertical beam fan do not reflect the height of the school because of the low resolution of the acoustic beam and the more extended horizontal than vertical distribution of the fish in the aggregations, i.e. a layer of 1 or 2 fish

3.6 - Visual observations

Most of the Bluefin tuna observations were made on the 6th and 8th of October (Figure 17). Some observations were also made on the 12th and 13th of October. In total 51 visual observations were made during the survey. The number of observations is likely related to sea conditions as well as the presence of BFT in the area. In general, more schools were observed with the sonars compared with visual observations. The data also indicate that different conditions are preferable for the different methods. Visual detections require light and calm seas and fish close to surface. While sonars are not dependent on daylight and detect fish deeper in the water column but may struggle detecting fish close to surface.

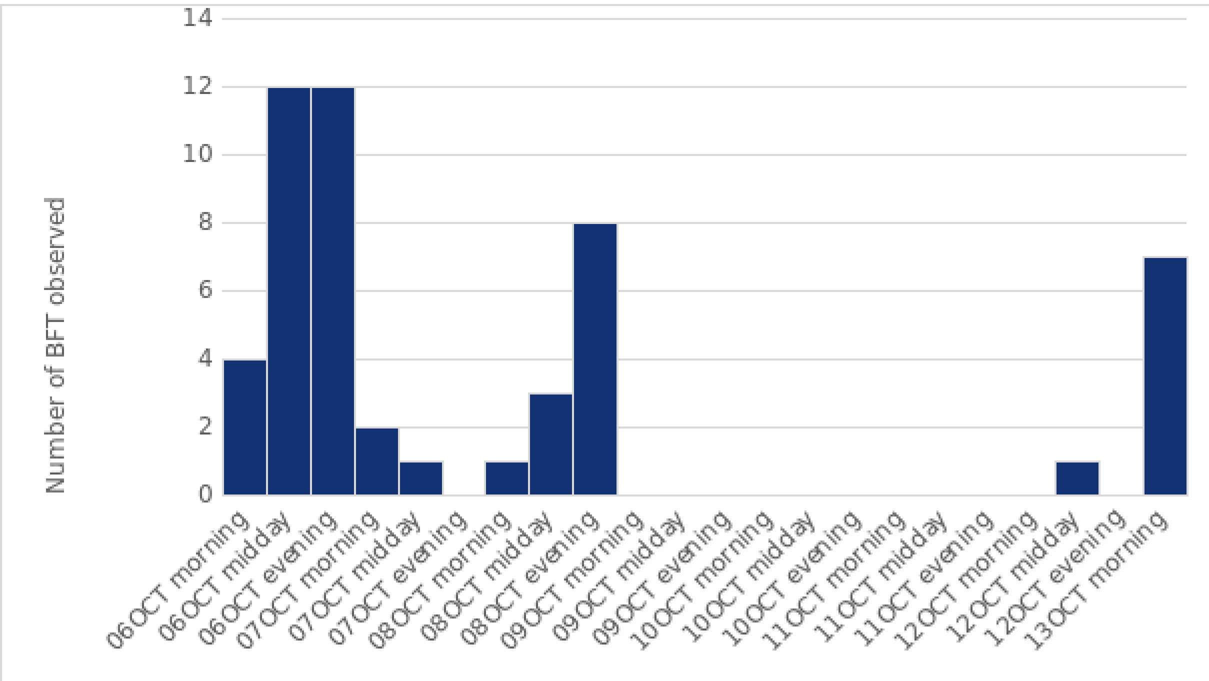


Figure 17. Number of BFT visually observed at sea surface.

4 - Concluding remarks and the way forward

The survey has given promising preliminary results for using acoustic methods for monitoring the distribution, abundance and behaviour of bluefin tuna in Norwegian waters. The advantages and disadvantages of the different sonars used are summarized in the below table.

Table 6. Summary of the main findings from the use of the different sonars for monitoring BFT.

Sonar	Pro	Cons
Simrad SU90 - Low frequency (26 kHz) - Omni (360deg)	Good for long range detection (800 -1000 m)	Not suitable for fish counting (except few fish in soldier formation), not best for identifying BFT schools
Simrad CS90 - Medium frequency (82 kHz) - Omni (360 deg)	Good for long range detection (800 m), good for identifying BFT school, suitable for fish counting in medium and small size schools	
Simrad SN90 - Medium frequency (75 kHz) - Sector (160 deg)	Good medium range detection (400 m), good for identifying BFT school, suitable for fish counting in medium and small size schools	Limited sampling volume compared with omni medium frequency
Kongsberg M3 - High frequency (500 kHz) - Sector (120 deg)	Best for fish counting	Only short range (< 100 m) detection and small sampling volume. Only operational at low vessel speed < 5 knots

The results indicate that the omnidirectional medium frequency sonar was the best sonar for detecting and inspecting the schools out of the sonars used in the survey. This is a type of sonar that most fishing vessels have and would thereby be a practical monitoring tool for future surveys. We also identified and describe optimal sonar settings for detecting BFT and school characteristics that can be used to distinguish BFT from other species. Our results show that it is possible to identify bluefin tuna schools based on the sonar signature and swimming speed at a range up to 800 m. It was further clear that visual monitoring provides useful extra information but is inefficient in monitoring the stock in a routine survey as daylight, good weather conditions and fish close to surface are required.

The Simrad SN90 sonar with its high resolution, showed good results for counting individuals in schools. We are currently investigating automatic and objective methods for counting individual fish in acoustic data as an alternative or complementary to school biomass estimates based on echo strength. Promising results were also achieved of BFT sizing using broad band echosounders and we obtained the broadband frequency spectrum (from 55 to 250 kHz) from single bluefin tuna. Being able to detect and measure individuals is highly valuable for obtaining in situ target strength measurements. This will be especially important for BFT where trawl sampling is not an option. Once the problems with the sonar calibration files are solved, we will measure lateral target strength and quantify school biomass from the echo strengths and school volumes. Some problems were also encountered when extracting school echoes from the background in the profos software as the processing method is designed for uniform small pelagic schools. However, this should be relatively easily solved by doing some modifications to the school growing algorithm in the Profos software.

During the survey we observed large amounts of bluefin tuna in two main areas; off Fedje on the 6^{th} and 13^{th}

October and off Ålesund from 8th to 10th October. This agrees with indications of an increasing part of the stock feeding in Norwegian waters in the autumn. School sizes varied from a few fish to several hundred individuals. The mean depth of the schools fluctuated from surface to 50 m and schools were detected both during the day and night. Some schools were monitored for several hours and despite a relatively fast swimming speed and same swimming direction the schools were observed to make large circles and stayed in the same area, most likely feeding. Such behaviour needs to be considered when designing a survey for estimating stock size. There is a need for better understanding of the feeding behaviour of the BFT in the Norwegian waters. It would have been useful with a sampling trawl to capture prey species.

The most challenging task is to design a survey that covers appropriately the distribution area of this highly dynamic stock. While we were close to the coast, we got reports from the mackerel fishing grounds 100 nm from the coast that large amounts of BFT were encountered. Still, acoustic and visual monitoring of the size and distribution and understanding the behaviour, including the predator-prey interactions, of BFT in Norwegian waters will be increasingly important as the number of fish, fishing quotas, challenges related to unwanted bycatch of BFT in other pelagic fisheries as well as ecosystem impact may increase in Norwegian waters.

5 - Annex 1

Pole used for mounting high frequency sonar Kongsberg M3

Mounting the pole on starboard side of M Ytterstad. Hinge attached with bolts to the vessel side ladder (left) and detail of the tilt adjustable platform where the sonar head was mounted (right).

6 - References

Demer, D.A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D., Domokos, R. et al. 2015. Calibration of acoustic instruments. ICES Cooperative Research Report No. 326, 133pp. DOI: http://dx.doi.org/10.25607/OBP-185

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., and Ona, E. 2020. Remote sizing of fish-like targets using broadband acoustics. Fisheries Research. Volume 228, 105568, ISSN 0165-7836.

Macaulay, G. J., Vatnehol, S., Gammelsæter, O. B., Peña, H., and Ona, E. 2016. Practical calibration of ship-mounted omni-directional fisheries sonars. Methods in Oceanography, 17: 206–220.

MacLennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365–369.

Nøttestad, L. Boge, E., Ferter K. 2020a. Comeback at Atlantic bluefin tuna (Thunnus thynnus) to Norwegian waters. Fisheries Research 231, November 2020, https://doi.org/10.1016/j.fishres.2020.105689.

Nøttestad, L., Boge. E, Mjørlund R.B. 2020b. Fishing capacity on Atlantic bluefin tuna (Thunnus thynnus) by purse seine vessels fishing in the Norwegian Exclusive Economic Zone from 2014 to 2019. Col. Vol. Sci. Pap. ICCAT, 77: 215-225.

Peña, H., Macaulay, G. J., Ona, E., Vatnehol, S., and Holmin, A. J. 2021. Estimating individual fish school biomass using digital omnidirectional sonars, applied to mackerel and herring. ICES Journal of Marine Science, doi:10.1093/icesjms/fsaa237

Tičina, V., Grubišić, L., Šegvić, T., and Katavic, I. 2011. Biometric characteristics of small Atlantic bluefin tuna (Thunnus thynnus, Linnaeus, 1758) of Mediterranean Sea origin. Journal of Applied Ichthyology. 27. 971 - 976. 10.1111/j.1439-0426.2011.01752.x.

VFORSKNINGSINSTITUTTET

stboks 1870 Nordnes

.7 Bergen

55 23 85 00

ost: post@hi.no

w.hi.no

HAVFORSKNINGSINSTITUTTET

Postboks 1870 Nordnes
5817 Bergen
Tlf: 55 23 85 00
E-post: post@hi.no
www.hi.no