# Silent research vessels are not quiet

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**Abstract:** Behavior of herring (*Clupea harengus*) is stimulated by two ocean-going research vessels; respectively designed with and without regard to radiated-noise-standards. Both vessels generate a reaction pattern, but, contrary to expectations, the reaction initiated by the silent vessel is stronger and more prolonged than the one initiated by the conventional vessel. The recommendations from the scientific community on noise-reduced designs were motivated by the expectation of minimizing bias on survey results caused by vessel-induced fish behavior. In conclusion, the candidate stimuli for vessel avoidance remain obscure. Noise reduction might be necessary but is insufficient to obtain stealth vessel assets during surveys.

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## 1. Introduction

Vessel-induced fish behavior during acoustic density estimation[1,2] and trawl sampling[3,4] may bias survey estimates of stock abundance. As noise has been considered a major stimulus, fisheries research institutions worldwide are investing in new silent research vessels[5] in accordance with recommendations from the International Council for the Exploration of the Sea (ICES).[6] The lack of fish avoidance observed from a stealth vessel[7] has been considered a result of reducing vessel noise,[7,8] but no direct comparison with a traditional research vessel has demonstrated this. Nevertheless, the scientific community has tacitly accepted that the major avoidance stimulus originates from the sound characteristics of the vessels, which is also the basis for the ICES recommendations.[1,6,9]

In 2003 the new Norwegian diesel-electric propulsioned research vessel “G. O. Sars” (GS) [Gross Registered Tonnage (GRT) 4067 tons, Length Overall (LOA) 77,5 m], fulfilling the ICES demands for a silent vessel, was put into operation. Several earlier reports have documented vessel avoidance of Norwegian spring spawning herring (*Clupea harengus*), showing that this stock is underestimated acoustically when distributed in the upper 100 m of the water column.[1,2] Currently the acoustic observations are used to establish an abundance index. Assuming similar or randomly varying conditions for observation among years, the time series of indices gives a relative change in abundance from one year to the next that is utilized in the stock evaluation. A vessel comparison was therefore an absolute necessity before the new GS could be used in data collection for the official annual stock assessments. Vessel comparison experiments were carried out in December 2004 in the Ofotfjord in northern Norway between GS and the previous standard vessel “Johan Hjort” (JH) (GRT 1828 tons, LOA 64,4 m). JH is a traditional research vessel with sound emission above the ICES standard[6] and thus far noisier than GS.

## 2. Methods

The two vessels followed each other at standard cruising speed and maximum distance along the exact same triangular cruise track [Fig. 1(a)]. Both vessels collected acoustic data according to the standard protocol for acoustic surveys, and, along the pursue track, an upward-looking echosounder and an acoustic Doppler current profiler (ADCP) were placed. This allowed us to record herring density by depth as well as the mean swimming velocity of the fish layer during

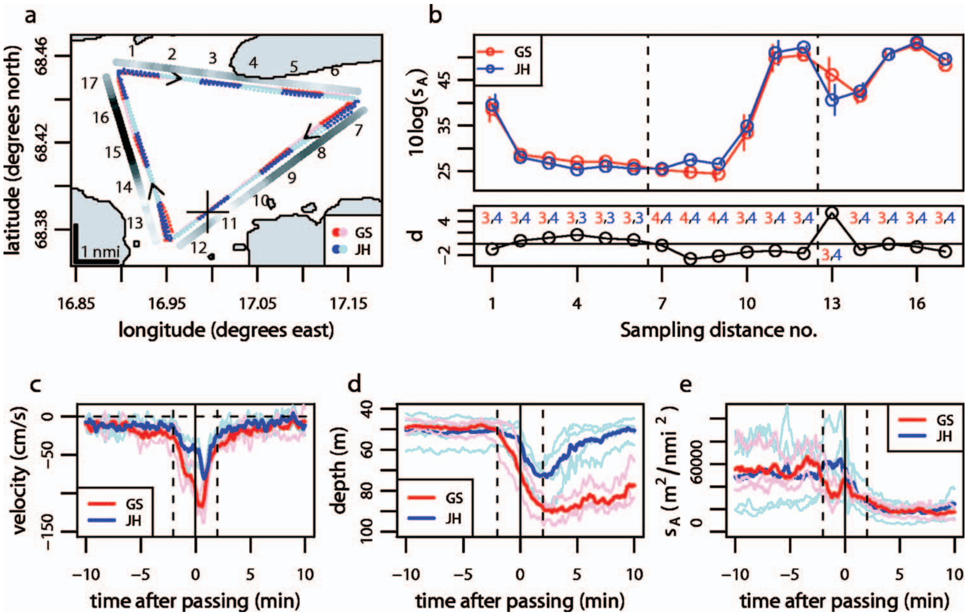

Fig. 1. Results from the pursuit experiment and mooring passages. (a) The numerical-density vessel-transects integrated over intervals of 1 nmi, shown as numbered light and dark sequences of points. Each point indicates the start of a 0.1 nmi sampling distance. Gray points indicate bottom depth (lightest: about 60 m, darkest: about 520 m). The cross at sampling distance no. 11 indicates the position of the moored platforms. Arrows indicate cruising direction. (b), upper panel. Numerical density along the transects. Each point represents the average of the log-transformed numerical densities for one vessel at one interval. The error bars show ±2 standard errors of the averages. (b) lower panel: The corresponding vessel differences in numerical density, and the number of passages for each vessel. Dashed vertical lines indicate the corners of the triangle in (a). (c) Vertical swimming velocity component when GS (red curves) or JH (blue curves) passed the moored ADCP. Thin lines denote single passages, and thick lines denote the averages over all passages. Vertical dotted lines are drawn 2 min before and after the point of passage. (d) Vertical fish distribution (median depth) when GS (red curves) or JH (blue curves) passed the moored echosounder. Thin lines denote single passages and thick lines denote the averages over all passages. Vertical dashed lines are drawn 2 min before and after the point of passage. (e) Average $s_A$ when GS (red curves) or JH (blue curves) passed the moored echosounder. Thin lines denote single passages and thick lines denote the averages over all passages. Vertical dotted lines are drawn 2 min before and after the point of passage.

and between passages of the two vessels. The mooring was passed four times by JH and three times by GS at moderately dense recordings of herring at 40–80-m depth during the night. The two vessels were completely darkened during the experiments. First, we present the method and protocol for collecting and analyzing the data from the vessel-mounted echosounders. Then, the method to collect and analyze the data from the bottom-mounted platforms is presented, including noise level confirmation for the vessels.

Raw echosounder data were recorded using the Simrad EK500 (Kongsberg Gruppen, Kongsberg, Norway), 18 kHz on JH, and the Simrad EK60, 18 kHz on GS. The calibrated raw data were directly transferred to the format of the postprocessing system BEI, and scrutinized by standard procedures for herring surveys by the same two operators. In fjord surveys with high densities, this basically involves the removal of bottom detection errors and isolating the herring layers by integration boundaries. The processed herring density data were stored in a database with 0.1 nmi × 10-m depth bins in absolute, linear units for the "nautical area scattering coefficient," $s_A$ ($m^2/nmi^2$), a standard unit in fisheries acoustics.[10]

The $s_A$ values from the two vessels were compared using a standard method,[11] slightly modified since the method is designed for two vessels following parallel transects, whereas in our experiment each part of the survey transect was traversed 3–4 times by each vessel. Also, we have chosen to replace ln($x$) in the published method with 10 log($x$). The modified method is as

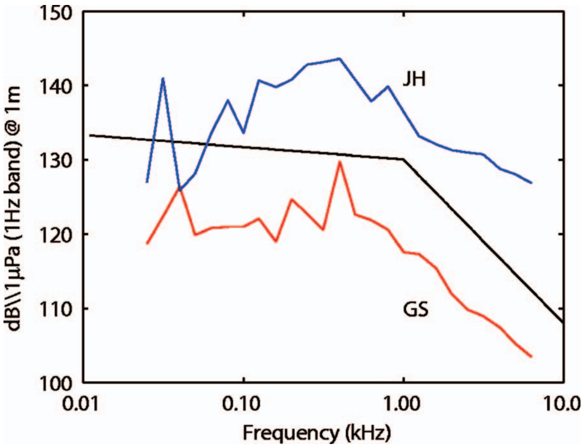

Fig. 2. Noise signatures of JH (blue) and GS (red), respectively, measured in the keel aspect of both ships using the Naxys hydrophone. The maximum recommended levels of noise from a free-running survey vessel at any speed up to and including 11 knots according to ICES CRR 209[6] is also included in the figure (black curve). Due to a possible inaccuracy in the hydrophone positioning, the absolute levels may be 3 dB off. This does not affect the relative difference between the vessels.

follows: Let $\rho_i$ be the true fish density at elementary sampling distance unit $i$, and $x_{ij} = \alpha_j \rho_i 10^{\sigma \varepsilon_{ij}}$ the density measured at sampling distance $i$ by vessel $j$, $j = \{1,2\}$, averaged over all passages (there is no visible trend in the measured densities over the time period used in the analysis). Here, $\alpha_j$ is a vessel-dependent bias, $\sigma^2$ is the variance, and $\varepsilon_{ij}$ is random noise. Defining $d_i = 10\log(x_{i1}) - 10\log(x_{i2})$, we have $d_i = \delta + \sigma\varepsilon_i'$, where $\delta = 10\log(\alpha_1/\alpha_2)$ and $\varepsilon_i' = 10(\varepsilon_{i1} - \varepsilon_{i2})$. Testing the null hypothesis that $H_0: \alpha_1 = \alpha_2$ is equivalent with testing $H_0: \delta = 0$, and if the $d_i$ are independent, this can be done using a two-sided $t$-test. The ratio $\alpha_1/\alpha_2$ is estimated by $10^{\bar{d}/10}$, where $\bar{d} = \Sigma_i d_i$.

The horizontal resolution of the data is 0.1 nmi, but using this resolution in the analysis would yield autocorrelated $d_i$, and the $t$-test could not be used. We have therefore aggregated the data so that each sampling distance is 1.0 nmi [Fig. 1(a)]. This has another advantage as well: the sampling distances for the two vessels do not match exactly, but the mismatch is smaller relative to the sampling length when this is increased (or resolution is decreased).

At a selected position in both surveys [Fig. 1(a)], the vessels passed directly above a bottom-moored platform, carrying a calibrated, upward-looking EK60, 38 kHz echosounder, and a calibrated underwater hydrophone (Naxys A/S, Bergen, Norway) with a computer for digital sound recordings. The hydrophone was used to verify the noise levels from the two vessels [Fig. 2]. An upward-looking bottom-moored 75-kHz acoustic Doppler current profiler (Teledyne RD Instruments, San Diego) 50 m perpendicular to the track line was used to measure the swimming speed of the herring layer. The raw backscattering data from all of the four ADCP beams were used to create a mask to isolate the herring layers from the surrounding water, and to calculate the resulting vertical and horizontal velocity components.

Avoidance reactions were analyzed using data from seven vessel passages over the moored platforms, four by JH and three by GS, including data from 10 min before each passage to 10 min after. The acoustic backscatter from the moored echosounder was integrated over the fish layer and is presented in $s_A$ units. Herring depth distribution and $s_A$ were available with a resolution of about 3 pings per second, and ADCP data with one recording every fifth second. To remove some of the random noise, the depth and $s_A$ data were smoothed using a moving average with a window of 10 s. The ADCP data were smoothed using a window of 15 s for the vertical component and 25 s for the horizontal component. Vessel differences and effects of vessel passages were tested for using two-sided $t$-tests with $n = 3$ (JH), 4 (GS), or $3+4$ (both

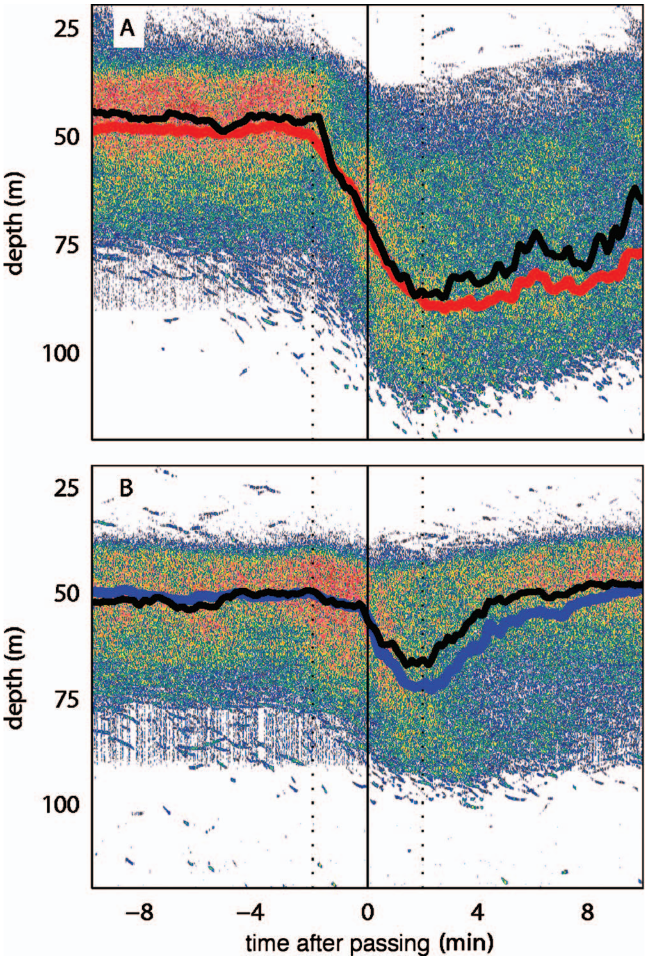

Fig. 3. The echogram for a single passage over the moored echosounder when passed by GS (a) and JH (b), respectively. The black line is the median depth distribution for this passage, and the blue and red lines are the means of the median depth distributions for all passages for JH and GS, respectively.

vessels). For example, when testing for a vessel difference in vertical displacement, the difference $D_{\mathrm{JH},i}=\bar{q}_{50,i,\mathrm{before}}-\bar{q}_{50,i,\mathrm{after}}$ between the median depths averaged over the time periods 5–2 min before and 2–5 min after passage $i$, $i=\{1,\ldots,4\}$, was calculated for JH, and similarly, $D_{\mathrm{GS},j}$, $j=\{1,\ldots,3\}$ was calculated for GS. A difference between $D_{\mathrm{JH}}$ and $D_{\mathrm{GS}}$ was then tested for using a standard $t$-test with $n=3+4$, not assuming equal variance.

## 3. Results and discussion

First, we show that the herring numerical densities measured from the two vessels were similar. The average numerical density recorded by GS during the pursuit experiment was 97% of the average recorded by JH, which is a nonsignificant difference ($p=0.75$ under the null hypothesis of no vessel differences).

Next, we show that GS initiated a more intense and prolonged avoidance reaction than JH by analyzing the results from the moored instrumentation. The vertical mean swimming velocity as estimated by the ADCP during the period of passage (from 2 min before to 2 min after) was significantly higher for GS (−70.5 cm/s) than for JH (−42.7 cm/s) [$t$-test, $p=0.009$, $n=3+4$, Fig. 1(c)]. For GS the mean vertical velocity of the fish layer corresponds to

2–3 bl $s^{-1}$ (body lengths per second), while the maximum recorded corresponds to about 4 bl $s^{-1}$. Since the horizontal velocity component is not taken into account, and as variation is expected for individuals over the depth range of the layer, this is a strong reaction compared to the maximum individual swimming speed for herring of 6–7 bl $s^{-1}$.[12] The horizontal swimming speed in the same period was similar for the two vessels.

From the moored echosounder (Fig. 3), the diving is observed as a vertical displacement of the herring layer [Fig. 1(d)]. From about 2 min before passage and to 2 min after passage a median displacement of about 20 and 40 m is seen for JH and GS, respectively [Fig. 1(d) and Fig. 3]. The difference between the vessels in terms of change in median depth distribution from 5–2 min before passage to 2–5 min after passage is significant on a 1% level ($t$-test, $n=3+4$, $p=0.003$). The fish also needed more time to return to its original distribution after being disturbed by GS [Fig. 1(d)].

The numerical density when passing the mooring was on average similar to that before vessel passage [Fig. 1(e)]. The variability in numerical density was large during the experiment, and it is difficult to separate vessel-induced effects from natural variations on a detailed level based on only seven passages. Nevertheless, there was a clear decrease in numerical density after the vessels had passed. Comparing the intervals 2–5 min before passage and 2–5 min after passage, the decrease is significant on a 5% level both for GS ($t$-test, $p=0.022$, $n=3$) and JH ($t$-test, $p=0.045$, $n=4$).

## 4. Conclusion

Although the moored echosounder did not record any significant difference in numerical density before and during passage for any vessel, the fish reaction pattern is strong and clearly vessel dependent. The differences in behavioral response and the magnitude of the response demonstrate the potential to cause severe bias, particularly seen in the perspective of earlier experience.[1,2] This illustrates the complexity of the vessel avoidance behavior, but more important, the results show that a stimulus other than noise, as defined by ICES, must be responsible for the reaction. Silent vessels have many advantages for reliable acoustic surveys, e.g., improving signal-to-noise ratio. Reducing the vessel noise may be necessary but is not a sufficient measure, and as long as influential candidate stimuli for fish avoidance remain obscure, the ICES goal of a establishing a stealth vessel design appears unrealistic.

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