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Measuring herring densities with one real and several phantom research vessels

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Vessel-induced avoidance can potentially cause a large bias in acoustic estimates of schooling, pelagic-fish biomass. This paper presents a method for quantifying this uncertainty. Volume-backscattering strength (S_v) from a horizontally projecting, multibeam sonar (Simrad MS70) is resampled to form synthetic, vertical, echosounder beams to the side of the survey vessel. These data are analysed as if they were collected from phantom vessels surveying parallel transects at fixed ranges from the real vessel. The nautical-area-backscattering coefficients (s_A) from the synthetic echograms are compared with those measured by conventional 70 and 120 kHz echosounders (Simrad EK60) on the real vessel. Data collected in 2006 from schools of Norwegian spring-spawning herring are used to illustrate the method and explore its limitations. Potential effects of vessel-induced avoidance are evaluated by comparing the mean s_A values observed from the phantom vessels with those observed from the real vessel. The technique also allows direct estimates of the mean lateral-aspect target strength of *in situ* herring.

Keywords: acoustics, echosounder, herring, Simrad EK60, Simrad MS70, three-dimensional sonar.

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Introduction

Vessel avoidance is a well-known source of bias in acoustic abundance-estimation surveys (Olsen, 1979; Olsen *et al.*, 1983; Gerlotto and Fréon, 1992; Mitson, 1995). This is especially true for schools of pelagic fish, like herring (*Clupea harengus*), when they are aggregated in dense schools located near the sea surface. Such avoidance reactions were noted by comparing observations made concurrently using a sonar and an echosounder (Misund *et al.*, 1996; Soria *et al.*, 1996; Gerlotto *et al.*, 2004). However, Fernandes *et al.* (2000) reported an absence of avoidance behaviour when herring were observed concurrently from an autonomous underwater vehicle and a noise-reduced vessel (RV "Scotia"). The lack of reaction was attributed to the noise-reduced vessel design. However, that survey was conducted at a speed well below typical survey speeds.

When comparing reactions of herring layers to noise-reduced and conventional research vessels surveying at normal speed, Ona *et al.* (2007a) observed significant avoidance from both vessels. They concluded that modern, noise-reduced research vessels still produce stimuli that may provoke avoidance reactions by herring to the measurement platform. In bad weather, with elevated background noise levels, however, Ona *et al.* (2007b) measured no reaction by herring in layers at depths of 30–40 m. Clearly, the avoidance reaction by herring to an approaching vessel is variable and therefore difficult to account for in acoustic abundance estimates.

Studies of avoidance by Norwegian spring-spawning herring (Hjellvik *et al.*, 2008) demonstrated that their reactions varied between research vessels, survey areas, and seasons. A modelled correction factor for vessel avoidance, as suggested by Løland *et al.* (2007) and Hjellvik *et al.* (2008), will therefore include much uncertainty. In this paper, a simple method is explored for estimating herring densities at different ranges to the side of a research vessel. Such data could be used to compute a survey-specific avoidance index.

The assessment of the Norwegian spring-spawning herring stock, now estimated to contain an adult component of $\sim 12 \times 10^6$ t, includes catch data and eight surveys (six acoustic surveys of adults and juveniles, a larval survey, and a 0-group survey). The acoustic-survey data are used as relative indices of abundance (ICES, 2007). These surveys were very important during the stock-rebuilding phase from 1983 to 2002, but, in recent years, summer surveys on the feeding grounds in the Norwegian Sea have been more crucial in the assessments of this stock (ICES, 2007). During summer surveys, feeding herring schools are often observed very close to the sea surface, where the sampling volume of a conventional echosounder beam is very small (conical diameter 2–10 m). In some instances, the herring can be seen at the sea surface. Considering the small sampling volumes at depths shallower than 20 m, horizontal avoidance of the approaching vessel by herring need not be large for the schools to be missed completely.

Løland *et al.* (2007) estimated the relative contributions of various sources of random error in a bias-corrected abundance estimate and concluded that avoidance contributes a significant part of the total uncertainty for surveys of herring in the wintering area. Note, however, that often more than half of the herring biomass is measured at depths >150 m, where avoidance should be insignificant (Vabø *et al.*, 2002).

Judging from published experiments on fish avoidance of survey vessels, the expected "avoidance zone" around the steaming vessel can be defined by a circle with a radius of 100 m. The Simrad MS70 multibeam sonar outputs calibrated data (Ona *et al.*, 2007a), which can be used to measure fish schools quantitatively at ranges >200 m from the surveying vessel. In this study, data from the MS70 are resampled to form seven, synthetic-echosounder beams at various ranges to the side of the surveying vessel that are compared with the data from the EK60 echosounder with transducers mounted in the ship's keel. The synthetic-echosounder data are considered to come from phantom vessels steaming parallel to the real ship. Avoidance reactions by herring to the real survey vessel are quantified by comparing the herring densities measured with the real and phantom vessels. A similar measurement scheme, using echosounder and sonar data, was suggested earlier by Fernandes *et al.* (1998).

Methods

Acoustic data were collected aboard RV "G. O. Sars" in the Røst area from 25 to 26 January 2006, using a multifrequency split-beam echosounder system (Simrad EK60) and a multibeam sonar (Simrad MS70). The transducers of both systems were mounted in retractable keels. During surveying, the keels were lowered to ~10 m below the sea surface, or 3.5 m below the vessel's hull. The vessel's speed varied between 1.3 and 4.4 m s^{-1} (2.5–8.5 knots) and the seabed depth varied between 160 and 206 m. A 24-kHz omnidirectional sonar (Simrad SP72) was used for long-range school detection. Interference between the systems was minimized by synchronous triggering of the MS70 and EK60 transmissions. Both systems were calibrated before the survey using the standard-sphere method.

The MS70 projected horizontally to the port side of the ship. For each ping, a large volume of water was sampled, and data forming a three-dimensional image were stored in a bin. The sonar was operated in the calibrated "survey mode" using Frequency Rotated Directional Transmission (Ona and Andersen, 2008). In this mode, 500 beams comprised 20 layered horizontal fans, each containing 25 beams. Each horizontal fan used a portion of the 75–112 kHz bandwidth, i.e. the uppermost fan was at 75 kHz and the lowermost fan was at 112 kHz, and the intermediate fans were at intermediate frequencies. The frequency response of adult herring is flat (<0.5 dB) within this bandwidth (Korneliussen and Ona, 2003).

Data were collected at a pulse repetition frequency of 0.25 Hz. At different times throughout the survey, different pulse durations and signals were transmitted: 0.001 s CW (continuous wave), 0.002 s CW, and 0.003 s FM (frequency modulated). The effects of different pulse durations and signals were considered negligible because the MS70 was calibrated at all settings. In all, 2107 data bins were collected at a data rate of 1 Gb h^{-1}, mostly with 2 ms CW pulses.

The EK60 had a vertical, downward-projecting, split-beam transducer. For each ping, the water column directly beneath the ship was sampled and stored in one data bin. RV "G. O. Sars" had a multifrequency EK60 system with six channels: 18, 38, 70, 120, 200, and 333 kHz. This analysis only considers data from the 70 and 120 kHz channels because they were most comparable with the MS70 frequencies. Data were collected at a pulse-repetition frequency of 1 Hz. The pulse length and signal were 0.001 s and CW, respectively. In all, 32 133 data bins were collected at a data rate of 188 MB h^{-1}.

To compare EK60 and MS70 data, the latter were resampled vertically at ranges (R) of 150, 160, 170, 180, 190, 200, and 250 m from the vessel, to a depth of 100 m, i.e. the depth of the lower fan at a range of 150 m. Herring schools deeper than 100 m were better observed with the EK60, and avoidance at that depth was assumed insignificant.

The EK60 beam was roughly conical and its sampling volume was small near the transducer and increased with range. In contrast, the synthetic beams displayed a nominally constant volume from the surface to the seabed. The observation volumes were taken into account when computing volume-backscattering strength (S_v) for both systems. The sampling volumes of the synthetic beams depended on the sampled depth. In general, the maximum sampling volumes of the synthetic beams were smaller than those of the EK60.

The MS70 data were resampled by considering data along vertical lines representing each imaginary acoustic axis (Figure 1). Samples with the shortest Euclidean distances to points at 0.2 m intervals along each line were chosen. The sample resolution was

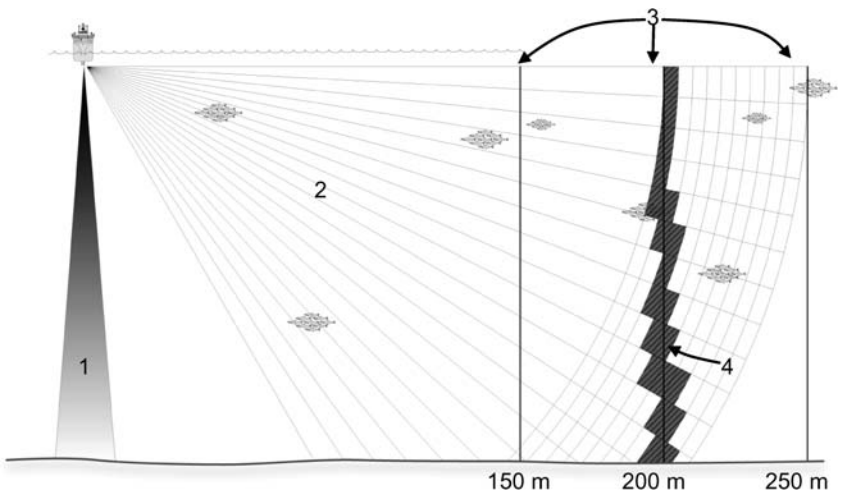

Figure 1. Echosounder sampling from a real ship and phantom vessels. (1) Echosounder beam. (2) MS70 beams. (3) Axes of three of the seven synthetic beams. (4) Samples selected from the MS70 data to create the virtual echograms.

therefore the same as for the EK60. This nearest-neighbour resampling strategy was chosen because of its simple implementation and good performance with respect to data-processing speed. The algorithm was originally programmed in MatLab (The Mathworks, USA) and in 2008 was implemented as a module in PROMUS, a MS70 post-processing system (Korneliussen and Heggelund, 2007).

The S_v data from the ship and the phantom vessels were evaluated using the large-scale survey system (Korneliussen *et al.*, 2006). Because of scattering from the sea surface in the uppermost MS70 beams, data in the upper 25 m were excluded from the analysis of the synthetic echograms. Usable data in the EK60 echograms began at 13 m below the sea surface when the keel was fully extended. The dataset for the phantom vessel at a range of 250 m from the vessel had the highest noise level. A threshold of $S_v = -50$ dB was therefore used to suppress this noise, thereby clearly isolating school echoes from other backscatter. Because echoes from schools are being considered in this analysis, this threshold should not significantly affect the results. For comparisons of weak scattering layers, another strategy may be warranted. Some noise spikes were also removed from the synthetic echogram data. For all the echograms, nautical-area-backscattering coefficient (s_A) values were calculated for depths from 25 to 100 m and distances of 0.1 nautical mile.

Because of the spatial separation of the observations and the patchiness of the fish schools, there was seldom good correlation between the s_A values from the real vessel and the phantom vessels. At best, the two systems simultaneously measured different parts of the same herring school or parts of different, but neighbouring schools. Therefore, the dataset had to be compared statistically on a large spatial scale. To do so, s_A values were randomly sampled from the phantom- and real-vessel datasets, and their means were calculated. The resulting mean s_A values from the phantom-vessel data were each divided by those obtained from the real-vessel data. An overall mean s_A ratio was calculated by randomly sampling data from all the phantom vessels. To estimate the mean s_A ratio vs. R, 1000 random samples were picked 1000 times from each dataset.

Results

Typical three-dimensional data from the MS70 are displayed in Figure 2. Depicted are three synthetic-sampling volumes corresponding to samples from three phantom ships. The herring school imaged by the MS70 was observed by two of the phantom ships. Synthetic echograms from the phantom vessels and real echograms from the 70- and 120-kHz EK60s are presented in Figure 3. Discrete schools appeared at different times on the MS70 and EK60 echograms. This can be observed at 15:38 and 15:41 UTC. However, some of the larger schools were measured simultaneously by both instruments, exemplified at 15:44 UTC. The variation in background noise in the phantom echograms probably results from the different sample ranges used.

Figure 4a shows mean s_A values measured from the phantom ships. Figure 4b shows mean s_A values from the 70- and 120-kHz EK60 data. Figure 4c and d shows a box plot of the ratios between the s_A values from the phantom vessel and the real ship, respectively. The mean s_A ratio was 3.02 for the 120 kHz and 3.83 for the 70 kHz, resulting in an overall mean s_A ratio of 3.43.

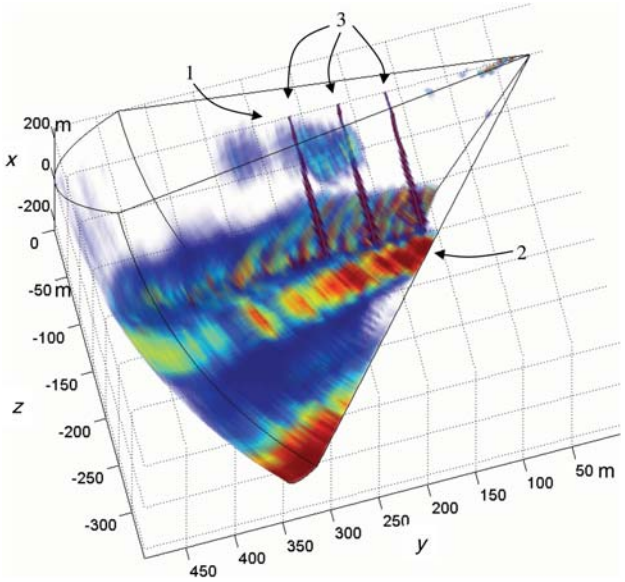

Figure 2. Three-dimensional volume imaged by the MS70 displaying the seabed, a herring school, and the selected samples for three of the seven synthetic beams. The axes' units are metres. The *x*-, *y*-, and *z*-axes correspond to the athwartship, alongship, and depth directions, respectively. Labelled are (1) a herring school, (2) the seabed, and (3) the synthetic echosounder beams from phantom vessels.

Discussion

It is difficult to compare samples from patchy distributions collected along parallel transects directly. As illustrated in Figure 2, even when an entire school was enveloped by the MS70-sampling volume, only two of the phantom vessels sampled the schools. The distance between the phantom track lines was 50 m, and the distance between the nearest phantom vessel and the real ship was 150 m.

For the synthesized echograms, the mean s_A generally increased with observation range, but there was a slight decrease at a phantom-vessel range of 250 m relative to that at 200 m. It is tempting to interpret the increased mean s_A values vs. observation range as vessel avoidance. In this particular case, however, the schools were targeted, and the data are therefore not appropriate for avoidance estimation. However, if data were collected along random transects during standard herring surveys, the method could allow quantification of bias that results from avoidance behaviours. Such data could be used to study the effects of vertical migrations of schools on the survey results. However, this potential bias might be quantified more accurately using data from an omnidirectional sonar. The SP72, for example, can track the movements of individual schools over longer periods and ranges than the MS70.

On average, the backscattering from adult herring was roughly 0.5 dB greater at 70 than at 120 kHz. The mean s_A ratio and its standard error (s.e.) were both lower at 70 than at 120 kHz, probably because of the frequency response of herring schools (Korneliussen and Ona, 2003). The scattering directivity of an adult herring is less at 70 than at 120 kHz, so the effects of fish orientation in both vertical and horizontal planes were probably less at 70 kHz.

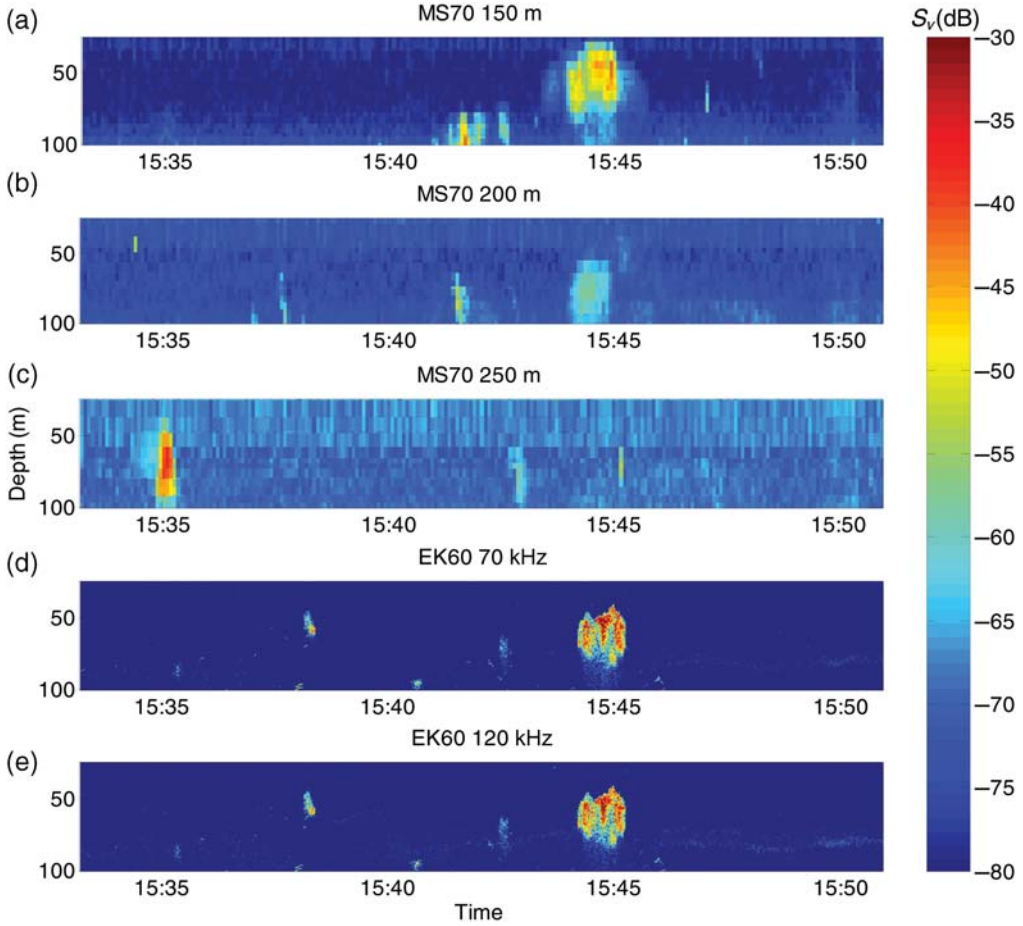

Figure 3. Echograms derived from the MS70 sonar data at multiple ranges (R) from the real ship and echograms from the EK60 echosounder data at two frequencies (f): (a) MS70, $R = 150$ m; (b) MS70, $R = 200$ m; (c) MS70, $R = 250$ m; (d) EK60, $f = 70$ kHz; and (e) EK60, $f = 120$ kHz. The colour scale is for volume-backscattering strength (S_v) in dB.

The s_A values from the phantom vessels were 3.43 times higher than those from the real ship. This is extremely interesting because the measurements from the phantom vessel were made of the fish in horizontal or nearly horizontal aspect, at mean vertical angles $<15^\circ$. The mean s_A ratio is therefore a direct measure of the mean ratio of mean σ_{bs} for herring in nominally lateral and dorsal aspects. If the s_A from each ME70 fan were considered independently, especially at moderate ranges, the scattering directivity of herring could be measured over precise angular increments (Handegard *et al.*, 2009).

The lateral-aspect target strength (*TS*) of adult herring is quite variable because of its scattering directivity and unknown angle of incidence. Although swimming herring can assume angles relative to the horizontal that can be described with a Gaussian distribution with a mean of 0° and s.d. of 10° (Foote, 1980), they could have been swimming in any direction relative to the ME70's horizontal beams. That is, swimming herring could assume, on average, a uniform distribution of yaw angles ranging from 0° (head towards the transducer) to 180° (tail towards the transducer). Consequently, depending on the frequency-dependent scattering directivity, the mean lateral-aspect *TS* could vary by 10–20 dB (Haslett, 1973; Nakken and Olsen, 1973). However, the range of yaw angles is expected to be fewer for individual schools.

It is difficult to measure schools close to the sea surface with an echosounder because the insonified volume is small at close ranges, and any horizontal movements of fish in response to the vessel will bias the biomass estimates. The dorsal-aspect *TS* should be stable, at least if the fish do not change their orientations in response to the vessel. Conversely, for sonar surveys, the observation volume is large; therefore, bias caused by avoidance could be mitigated by selecting an appropriate sampling distance from the vessel. As a result, the number of schools and their mean s_A values could be measured more accurately. The lateral-aspect *TS* is more variable, however, resulting in larger confidence bounds on the estimates of fish abundance. Consequently, if the s_A ratio for lateral- and dorsal-aspect observations is averaged over a large number of observations, it could be used to offset the limitations mentioned earlier of both the EK60 and MS70 observations and improve the collectively derived biomass estimates. For this reason, estimation of herring abundance during a composite sonar-echosounder survey might be a realistic goal for the future. In addition, the statistics and cross-correlations of the EK60 and MS70 data

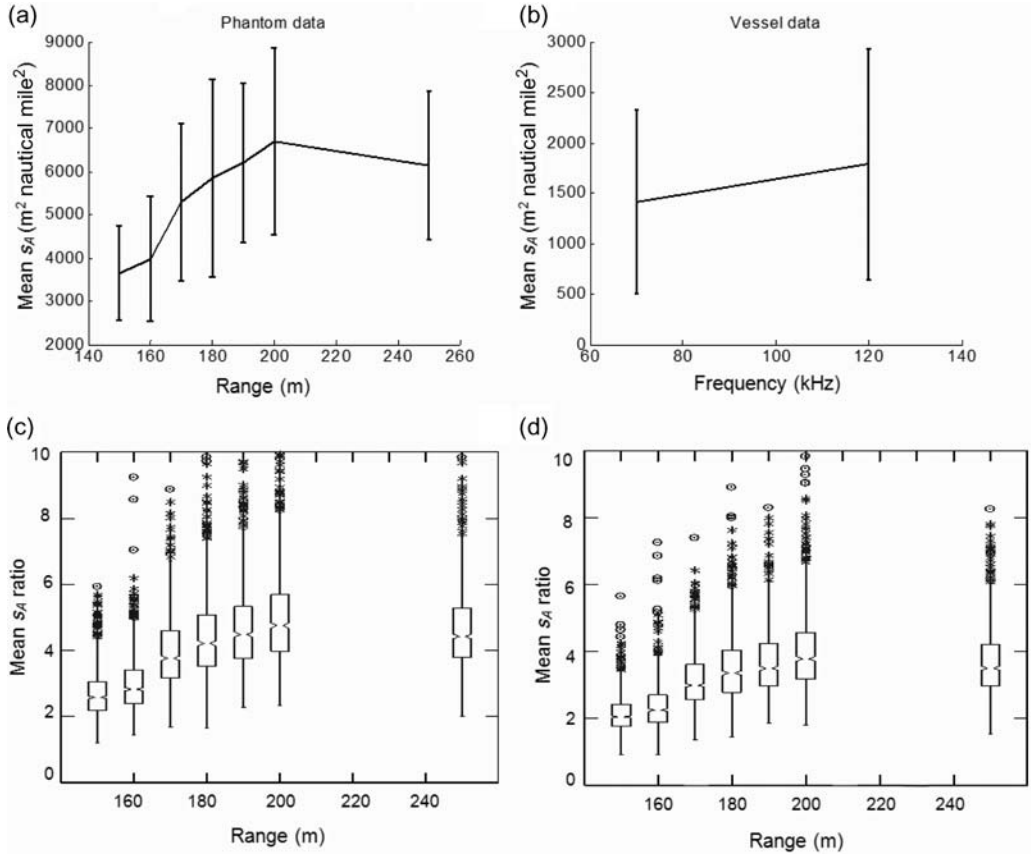

Figure 4. (a) Mean and s.e. of s_A vs. range (R) from the ship. (b) Mean and s.e. of s_A vs. frequency measured by the EK60s aboard the ship. (c) Ratio of mean s_A values observed from the phantom vessel and the real-ship data at 70 kHz and (d) 120 kHz. Indicated in (c) and (d) are 50% of the samples (box), the mode (notch), the first and third quartiles (bars), the nominal ranges (whiskers), extreme values (asterisks), and outliers (open circles) (McGill *et al.,* 1978).

could be used to describe the swimming behaviours of fish schools (Godø *et al.*, 2004). Several findings in this paper therefore warrant further investigation, but, for this to happen, appropriate datasets must be collected concurrently with the EK60 and MS70 systems during pelagic-fish surveys.

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