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# Robust Daytime In Situ Target Strength Estimation of Pacific Hake (*Merluccius productus*) over a Wide Size Range

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**Abstract**

Accurate determination of the target strength (TS) of a fish species is essential for estimating the biomass of fish stocks using acoustic technology. This study estimated the daytime in situ target strength of Pacific hake (*Merluccius productus*) at 38 kHz using echosounder data collected during hake biomass acoustic-trawl surveys and research cruises conducted from 2009 to 2019 by U.S. and Canadian scientists. The intercept term for the 20-log TS regression over fish length at 38 kHz, $b_{20}$ was found to be −67.9 dB re 1 m$^2$ (CI: −68.09, −67.72), closely aligning with the currently used value of −68 dB in biomass assessments. Applying the revised $b_{20}$ value of −67.9 dB in past stock assessments suggests that biomass estimates would be underestimated by less than 3%, which is well within the typical uncertainty range of fish stock assessments.

**Keywords:** hake; echosounder; in situ target strength; biomass estimate

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## 1. Introduction

Effective management of fisheries and ecosystems requires marine scientists to take on substantial responsibilities, including monitoring, assessing, and researching marine resource distributions. Pacific hake (*Merluccius productus*), hereafter referred to as hake, is a commercially important marine fish found off the west coast of North America [1]. Over the past decade (2014–23), coastwide annual harvests averaged 338,606 metric tons [2], with U.S. and Canadian catches averaging 275,957 metric tons and 62,648 metric tons, respectively. In 2023, the coastwide catch reached 263,981 metric tons [2]. The U.S. West Coast's hake fishery, including non-tribal at-sea and shoreside operations, supported 4450 jobs and generated an income of USD 335 million in 2021 when considering revenue (including production values and exports) and jobs.

Beyond its commercial significance, hake is a key trophic species and the most abundant groundfish in the California Current Large Marine Ecosystem [3]. Given its prominent economic and ecological value, integrated acoustic-trawl (IAT) surveys have been conducted to assess hake's abundance, spatial and temporal distributions, and additional biological characteristics along the west coasts of the United States and Canada [4]. These surveys began in 1977, with the Alaska Fisheries Science Center (AFSC) conducting triennial IAT surveys in U.S. and Canadian waters. In 1990, Fisheries and Oceans Canada (DFO) initiated annual IAT surveys in Canadian waters. After the 2001 survey, responsibility for the U.S. portion of the IAT survey transitioned to the Northwest Fisheries Science Center (NWFSC), and the survey frequency increased from triennial to biennial. Since 1995, the United States and Canada have collaborated on hake assessments. The triennial IAT surveys of 1995, 1998, and 2001 were conducted jointly by AFSC and DFO, while surveys since 2003 have been conducted by NWFSC and DFO. The joint hake surveys normally began at Point Conception, California (the current southern extent of the survey area) and proceeded north along the west coast of the U.S. and Canada, surveying Queen Charlotte Sound, Hecate Strait (above Port Hardy in Figure 1), Dixon Entrance (the northern extent of the survey area, straddling the Canada and Alaska border), and the west side of Haida Gwaii, which was surveyed from north to south (Figure 1, with the actual 2019 survey transects).

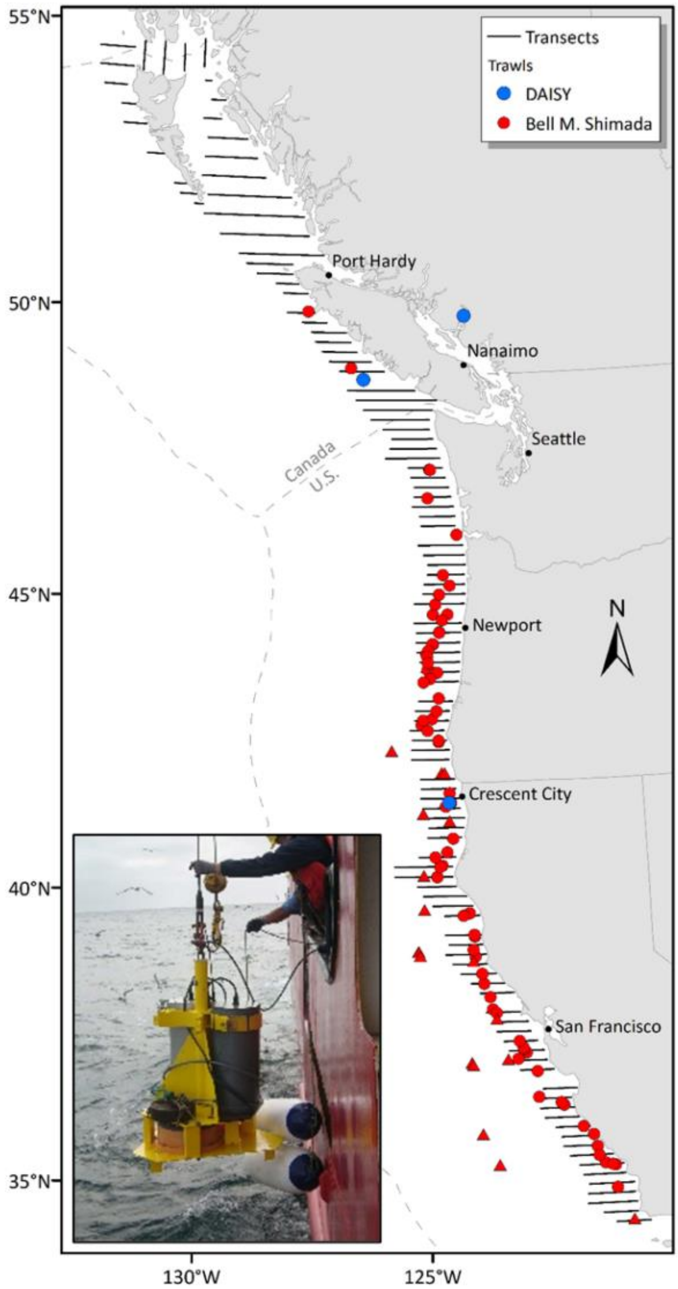


**Figure 1.** Survey area map and the locations of the biological trawls associated with the TS samples from individual hake used in this study (circles for summer trawls, triangles for winter trawls). The survey transects are for the actual 2019 hake survey, and the inset is the photo of the DAISY deployed off the Canadian Coast Guard Ship (CCGS) W. E. Ricker.

Acoustic-trawl surveys are widely used for assessing stocks of pelagic and semi-pelagic fish species worldwide [5]. Methods and instruments have significantly improved over the years and the technology has become a recognized tool in ecological studies and the application of the ecosystem approach to fisheries management [6,7]. Estimating the abundance or biomass of fish stocks using acoustic technology requires accurate measurements of an acoustic property known as target strength (TS). TS is directly tied to biomass estimates, which are based on echo integration theory [8]. Conceptually, TS measures the acoustic energy scattered (typically in the backward direction) from an object relative to the source intensity [9].

Three common methods are used to estimate the TS of fish: in situ field data [10–14], ex situ data [15–17], and theoretical model predictions [18–21]. The target strength currently used by NWFSC and DFO to estimate hake biomass was originally published by Traynor [22]. This value was derived from in situ hake echosounder data at 38 kHz using a widely accepted 20-log regression formula based on the theoretical relationship between the differential backscattering cross-section ($\sigma_{bs}$) and fish length ($L$) $\sigma_{bs} \propto L^2$. In the case of Pacific hake, $L$ represents the fork length. The TS is commonly expressed logarithmically as

$$TS = 10\log_{10}\ \sigma_{bs} = 20\log_{10} L\ + b_{20} \quad (1)$$

where the fish length is measured in centimeters, and the intercept term $b_{20}$ is in dB re 1 $m^2$. The $b_{20}$ that has been used by NWFSC/DFO for Pacific hake biomass estimates has been historically set to −68 dB based on in situ target strength values reported by Traynor [22]. However, this intercept value was questioned by Henderson and Horne [16], where a much smaller $b_{20}$ was suggested (by 4–6 dB).

To address discrepancies in $b_{20}$ estimates and evaluate the validity of the currently used $b_{20}$, we analyzed in situ echosounder TS data from single targets collected between 2009 and 2019 during hake biomass surveys and research cruises. In contrast to Henderson and Horne [16], who used a combination of ex situ and nighttime in situ methods (similar to Traynor [22]) to estimate target strength, this study focused on daytime in situ methods as being more representative of fish encountered during the daytime survey used for stock assessment, and also provided estimates of accuracy and robustness. Daytime estimates of TS are considered more representative since the fish would be in the same orientation, distribution, and conditions (both physiologically and behaviorally) as when they are assessed for acoustic estimates of biomass. To account for bias due to multiple target scattering and a low signal-to-noise ratio (SNR) typically encountered during daytime surveys (when fish are found in denser aggregations at greater depth), we have used a stepwise approach for selecting valid targets and further introduced a pulse energy filtering method. Our specific objectives for this study were to (1) introduce a new approach based on target pulse energy to improve the selection of single targets under high-fish-density conditions, (2) to provide in situ estimates of Pacific hake target strength over a wide range of survey conditions and fish sizes, and (3) to validate and compare the TS-L relationship obtained from these measurements to the one currently used for stock assessment purposes.

## 2. Materials and Methods

### *2.1. Data Description*

Acoustic data were collected between 2009 and 2019 using Simrad EK60 split-beam echosounders manufactured by Kongsberg (Horten, Norway). This study focused on data collected at 38 kHz, the primary frequency used for hake biomass estimation and widely recognized for fish biomass assessments globally [5]. Single-fish TS estimates were collected from the vessel's echosounder during midwater trawl verification tows conducted at an average vessel speed of approximately 3 knots (~1.5 m/s) using the NOAA Fisheries Survey Vessel (FSV) Bell M. Shimada. This ensured that the TS measurements were made on individual fish just prior to their capture from the trawl net behind the vessel. Only trawls in which hake exceeded 95% of the total catch composition (by weight) were selected for TS analysis, minimizing any misidentification. All trawls were monitored with a Simrad FS70 third wire trawl sonar equipped with a depth sensor. The path of the trawl was overlayed on the echogram to only select acoustic targets that were vertically within 50 m of the trawl path. Thus, mean fish fork lengths from each selected trawl were assigned to the selected individual acoustic targets from the same corresponding trawl event.

In addition, a Dropped Acoustic Information SYstem (DAISY), a deployable instrument, was used to collect echosounder data off the Canadian Coast Guard Ship (CCGS) W. E. Ricker (Inset in Figure 1). DAISY consisted of 38 kHz and 120 kHz split-beam EK60 echosounders connected to a power supply inside a pressure housing. The unit was equipped with 200 m of cable for deployment at depth using a relay for topside control and included a heading, pitch, and roll sensor. The CCGS W. E. Ricker drifted while the DAISY was deployed to collect data. Each deployment of DAISY was associated with midwater verification trawl. Catches of hake from these trawls comprised 80%, 82%, and 99% of the total catch for 7 September 2014, 14 September 2014, and 23 March 2016, respectively. An in-trawl camera system indicated that the other species caught in 2014 (mostly opalescent inshore squid, *Dorytheutis opalescens*) were in different depth layers than the hake. The geographic locations of all selected trawls used for hake in situ target strength estimation are shown in Figure 1. Echosounders from the Shimada and DAISY transmitted narrowband pulses with a duration of 1.024 ms. All echosounders were calibrated using the standard sphere method [23] prior to each survey, including the deployment of a calibration sphere at depth for DAISY measurements.

### *2.2. Data Analysis*

To correctly obtain single-target TS data, the single-target detection algorithm of Echoview (version 13.1, Hobart, Tasmania) was used (Table 1). The single targets that fell within these parameters only served as a foundation for further analysis. Originally, we used the fish-tracking algorithm provided within Echoview (Table 2), based on the Alpha-Beta tracking algorithm described by Blackman [24], but inspections revealed a high number of erroneous tracks, which required substantial manual corrections, despite several attempts at fine-tuning the tracking parameters. To better ensure the TS samples in the selected fish tracks were from individual fish, we manually selected candidates from these fish tracks, following stringent guidelines to guarantee the quality of the samples for final TS analysis. A single analyst (co-author Steve de Blois) made the selection of candidate tracks to ensure consistency throughout the dataset. The guidelines for single targets based on initial fish track analysis were the following:

1. Fish tracks were selected throughout the depth range of aggregations but primarily from the outskirts of fish aggregations away from regions of highest densities (generally the center of aggregations) to minimize potential biases from multiple targets.
2. Each fish track had to contain at least five contiguous echoes.
3. Following track selection, only targets that were within 2° of the acoustic beam axis were retained for further analyses.
4. Sample TS values greater than −30 dB were excluded to eliminate larger, non-hake targets or potential multiple targets.

**Table 1.** EK60 echosounder parameters for single-target detection.

| Single-Target Detection | |
|---|---|
| **General Parameter** | **Parameter Value** |
| TS threshold (dB) | −60 |
| Pulse length determination level (dB) | 6.0 |
| Minimum normalized pulse length | 0.2 |
| Maximum normalized pulse length | 1.8 |
| **Beam compensation** | |
| Beam compensation model | Simrad LOBE |
| Maximum beam compensation (dB) | 12.0 |
| **Exclusion** | |
| Maximum standard deviation of | |
| Minor-axis angles (deg) | 2.0 |
| Major-axis angles (deg) | 2.0 |

**Table 2.** EK60 initial target tracking parameters.

| Direction on a 3D Orthogonal Frame | Major Axis | Minor Axis | Depth |
|---|---|---|---|
| A | 0.7 | 0.7 | 0.7 |
| B | 0.5 | 0.5 | 0.5 |
| Exclusion distance (m) | 4.0 | 4.0 | 0.4 |
| Weights | 30 | 30 | 40 |
| Minimum number of single targets | | 3 | |
| Minimum number of pings | | 3 | |
| Maximum gap (pings) | | 1 | |

Following the selection of the TS samples satisfying these criteria, additional filtering was applied using a pulse-energy detection range on each single target. The reasoning of using this pulse-energy criterion was based on the concept that if the echoes from two targets (or multiple targets) were either in or out of phase but arrived at slightly different times, the resultant echo would be either elongated or shortened, respectively, but still within the single-target detection pulse duration window specified in Table 1. As a result, the combined and normalized pulse energy over a time window of the transmit pulse duration would likely be either greater or less than the normalized transmit pulse energy over the duration of the transmit pulse (1.024 ms in this study). The pulse energy ($E_{pulse}$) was calculated as

$$E_{pulse} = \int_0^T I(i)dt \tag{2}$$

where $I(t)$ is the echo intensity, which is proportional to the volume backscattering coefficient, $s_v = 10^{S_v/10}$, where $S_v$ is the volume backscattering strength. Since the absolute value of $s_v$ depends on the target, we used a normalized $s_v$ and the normalized pulse energy in the actual algorithm:

$$\hat{E}_{pulse} = \sum_{i=1}^{N_p} \hat{s}_v(i) \tag{3}$$

where $N_p$ is the number of samples in each transmitted pulse (4 in the case of Simrad EK60 system) and $\hat{s}_v = \frac{s_v(i)}{\max\limits_{i=1,\ldots,N_p}\{s_v(i)\}}$ is the normalized $s_v$ of the pulse of interest. TS samples were retained if their pulse energy satisfied the following relation:

$$\overline{E}_{theo} - 3\,\sigma_{st} \; < \hat{E}_{pulse} \; < \overline{E}_{theo} + 3\,\sigma_{st} \tag{4}$$

where $\overline{E}_{theo}$ and $\sigma_{st}$ are the theoretical mean and the standard deviation of the normalized echo energy, respectively, and were estimated based on the recorded waveform of the

EK60 transmit pulse presented in Figure 2.30 of Demer et al. [25]. Since each pulse in the EK60 has four samples, the start of a (theoretical) echo was randomized within the first 256 µs time window of the pulse (equivalent to 1/4 of a 1024 µs pulse length). We used 10,000 realizations of this randomized start time in estimating the theoretical $\overline{E}_{theo}$ and $\sigma_{st}$ with values of 3.56 and 0.14, respectively.

Biological catch data were matched with acoustic data by assigning the mean fork length from each trawl to corresponding single-fish TS samples. Only trawls in which the fork length distribution of hake was relatively unimodal and had a standard deviation of less than 5 cm were retained for analyses to ensure that each estimate of in situ target strength was representative of a relatively narrow fish size (e.g., representative of the fish length at the trawl location). Unimodality was assessed visually on each length distribution to ensure that only one clear single peak was present.

Representative echograms illustrating single-target detections are shown in Figure 2, where the trawl traces were superimposed onto the echogram (Figure 2a) and the chosen TS samples from single fish were away from the center of the fish aggregation, the region with the highest fish density. The single-fish TS were much easier to determine from the echograms collected with DAISY due to the slow vessel speed (Figure 2b). As a result, the detected single-fish TS echo traces were much longer than those collected when trawling at a ship speed of about 3 kts (~1.5 m/s). Since all of the data for these analyses were collected on natural aggregations of fish (prior to trawl sampling), we assumed that the orientation (tilt, pitch, and roll) of the retained targets was representative of the orientation and distribution of free swimming fish. The Pacific hake population is acoustically assessed during daytime acoustic-trawl surveys under the same conditions as their target strength was estimated.

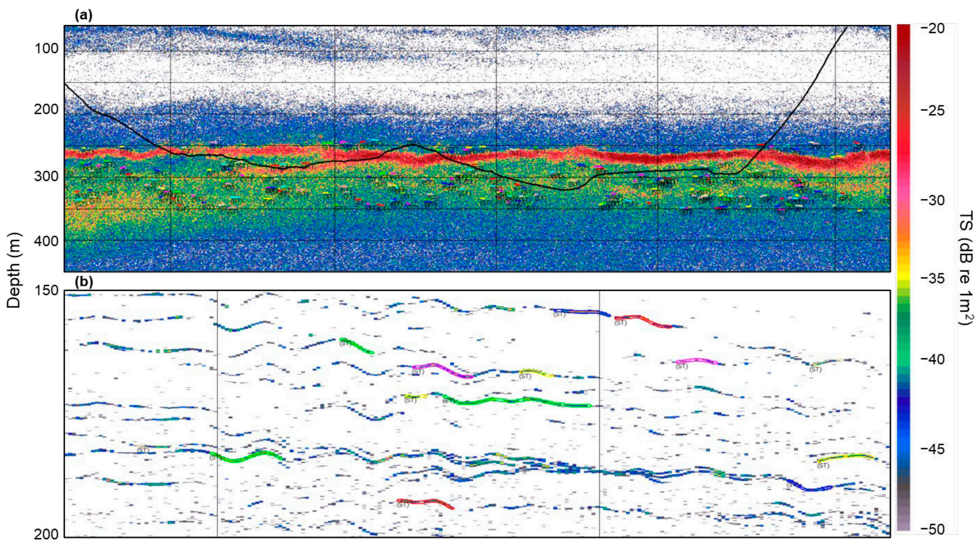


**Figure 2.** Examples of the target strength echograms from assumed individual hake, where each colored line (polygons) indicates an individual track. (**a**) Collected from the U.S. Fisheries Survey Vessel (FSV) *Bell M. Shimada* during a trawl (trawl path is indicated by the thick black line). Each vertical bar indicates 0.5 NM (**b**) DAISY drift TS echogram deployed from the *CCGS W. E. Ricker*, each vertical line representing 100 pings. Depth (in m) is indicated on the left side.

### 2.3. Estimation of $b_{20}$

To obtain an optimized estimate of the intercept, $b_{20}$, we used the least-square fit to the TS data using Equation (1), a 20-log form of the TS-length regression relation. The mean fork length (from trawl samples) was categorized in 1 cm length bins. Since the only unknown is the intercept term $b_{20}$, it is straightforward to show that using the standard least-square approach, $b_{20}$ can be estimated by

$$b_{20} = \frac{\sum_{i=1}^{n_L} \sum_{j=1}^{n_{i_L}} \left( TS_{ij} - 20 \log_{10} L_{ij} \right)}{\sum_{i=1}^{n_L} n_{i_L}} \quad (5)$$

where $n_L$ is the total number of length bins and $n_{i_L}$ is the number of length samples in each length bin (which may have included more than one trawl when their mean length was within the same 1 cm bin). $TS_{ij}$ and $L_{ij}$ are the measured TS (dB) value and the corresponding hake fork length (cm) for the *i*th length bin and *j*th TS sample in the *i*th length bin, respectively. For comparison, the TS-length regression was also assessed empirically with a free slope parameter in the form of

$$TS = a \log_{10} L\,(\text{cm}) + b_a \quad (6)$$

where $a$ is the slope parameter and $b_\text{a}$ its associated intercept.

*2.4. Statistical Analysis*

To evaluate the variability and robustness of the $b_{20}$ estimate, three statistical methods were applied and compared. Each method provides a slightly different perspective on the sampled data and their reliability:

1. Resampling: All TS data were randomly resampled with non-replacement, using 95%, 90%, and down to 5% of the original data, with 1000 realizations for each percentage bracket. This addresses the sensitivity of the data to marginally high or low TS samples (or specific to trawl hauls) by assessing significant divergence in slope estimates as the TS sample size is gradually reduced down to a small fraction of all available data. This resampling approach also helps in identifying potential bias due to outliers, or disproportionate weight to sample values that are at the tail end of the distribution (e.g., hauls with the smallest and largest mean fork lengths).
2. Bootstrapping: The bootstrap method estimated the sampling distribution of $b_{20}$ by resampling the original data using all (100%) data samples with replacement [26,27], also with 1000 realizations.
3. Jackknife: The jackknife cross-validation technique, a leave-one-out resampling method with replacement, was used for bias and variance estimation [28].

## 3. Results and Discussion

*3.1. Target Strength (TS) Data Processing and Acceptance*

After applying the single-target detection and tracking criteria specified in Tables 1 and 2, the manual selection guidelines, and a pulse-energy filter, the processed TS samples were analyzed. The accepted TS samples from assumed single targets associated with the selected hauls across different years are summarized in Table 3. The dataset comprises a total of 92 hauls from 13 surveys conducted between 2009 and 2019, with an overall acceptance rate of single targets less than 2%. This was largely due to the pulse energy filter, which we found necessary to analyze targets at a long range in low signal-to-noise ratio conditions, because of the relatively high density of hake (and other scatterers) at depth during daytime surveys. The average biological catch per haul was approximately 380 kg, with an average hake catch composition of 98%, confirming that the samples were representative of hake-dominated areas. Exceptions were two hauls in 2014 that were associated with the DAISY data, where hake catch proportions were slightly above 80% (Appendix A, Table A1). Although the hake catches were lower for these DAISY data, the non-hake catches were primarily squids (no gas inclusions) and small lanternfish (~5-cm), whose TSs were believed to be much less than those of hake ($L \geq 17$cm). Furthermore, in-trawl camera footage indicated that these non-hake animals were caught at different depths from hake, as explained in Section 2.1.

**Table 3.** Information on target strength (TS) samples from the targets associated with the chosen midwater trawl hauls. The average catch weight per haul was 377 kg and the average hake catch was 97%.

| Dataset | No. of Hauls | TS Samples (Original) | TS Samples (Pulse-Energy Filtered’) |
|---|---|---|---|
| 2009 | 8 | 6891 | 150 |
| 2011 | 7 | 4875 | 98 |
| 2013 | 12 | 14,103 | 241 |
| 2014 | 2 | 1898 | 6 |
| 2015 | 9 | 1915 | 48 |
| 2016 Winter | 13 | 9922 | 218 |
| 2017 Winter | 9 | 4158 | 92 |
| 2017 Summer | 5 | 3365 | 61 |
| 2018 | 2 | 216 | 5 |
| 2019 | 22 | 16,829 | 481 |
| DAISY 7 September 2014 | 1 | 3722 | 40 |
| DAISY 12 September 2014 | 1 | 3788 | 47 |
| DAISY 23 March 2016 | 1 | 5372 | 23 |
| Sum | 92 | 77,054 | 1510 |

*3.2. TS Distribution and Depth Analysis*

The histogram of the TS samples from detected single targets is shown in Figure 3. The TS distribution was not symmetric around the mean or mode, approximately at −37.5 dB. A small portion of the TS samples had very low TS values, indicating the TS samples were either from smaller hake individuals, from hake that had larger tilt angles, or from small non-hake targets. Although the lower limit of the single-target detection algorithm was specified at −60 dB re 1 $m^2$, the actual accepted TS samples following the filtering processes were all greater than −55 dB re 1 $m^2$.

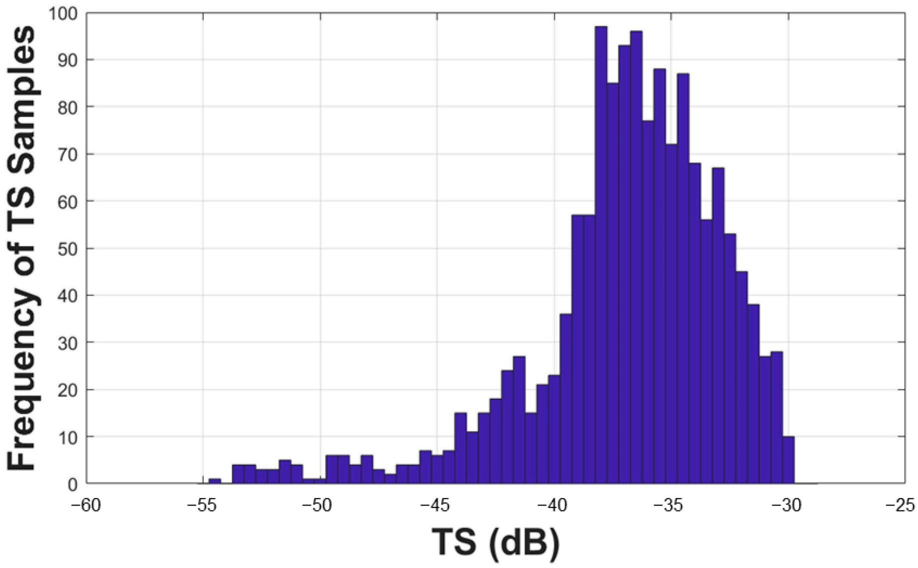


**Figure 3.** Histogram of the TS from single targets.

TS samples distributed between 150 and 400 m represented about 80% of the total accepted TS values (Figure 4). There were few samples detected in very shallow water, i.e., shallower than 100 m depth, but their corresponding TS values were mostly lower than $-45$ dB re 1 m$^2$, significantly lower than the mean TS value of $-36.8$ dB re 1 m$^2$, or the median value of $-36.3$ dB re 1 m$^2$ (Figure 5), likely from smaller age-1 juvenile hake, or even age-0 young-of-year (YOY) hake. The left side of Figure 5 illustrates the lower target strength values observed in shallower water, associated with smaller juvenile fish that are typically found at those depths. There was no trend observed in target strength with depth beyond 175 m. Since Pacific hake are a physioclist species, where the amount of gas inside the closed swimbladder is controlled internally by the rete mirabile [29], we assumed that the volume of their swimbladder was constant since they were acclimated for the depth at which they were sampled.

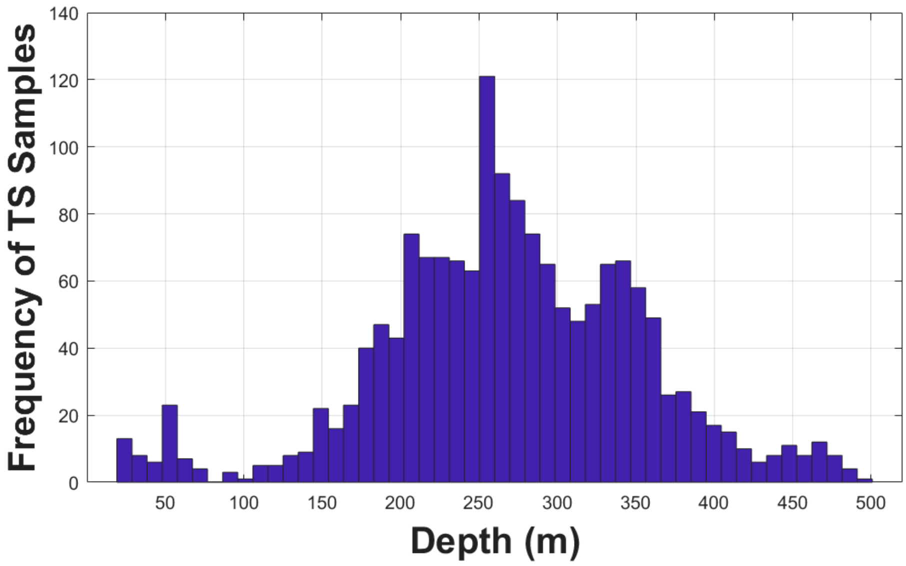


**Figure 4.** Histogram of the TS from single targets as a function of target depth.

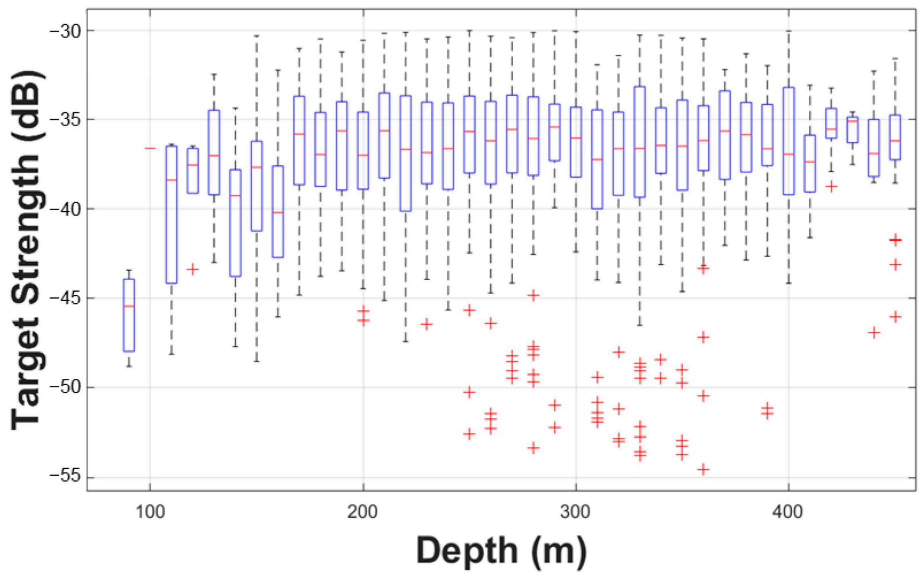


**Figure 5.** Target strength (TS) from single targets as a function of depth, where the central mark (red line) is the median, the edges of the box (blue) are the 25th and 75th percentiles, the whiskers (black dashed line) extend to the most extreme data points (red plus) that the algorithm considers to be not outliers, and these outliers are plotted individually.

### 3.3. Spatial Variability and Fork Length Association

Except for TS samples around lat 43.5° N, where the TS values were lower and more spread out, all TS samples had median values close to the overall median of −36.9 dB re 1 $m^2$ (Figure 6). These low TS values at lat 43.5° N possibly correspond to the smaller hake fork length at the same latitude (Figure 7), as stated in Section 3.2. Some trawls at the median length were at the higher end of the 75th percentile (lat 36.5° N, 38.5° N, 39° N, 41° N, and 43.5° N), or at the lower end of the 25th percentile (lat 37.5° N, 42° N, 42.5° N, and 44° N). At some latitudes, the 25th and 75th percentiles and the median were identical (lat 41.5° N and 45.5° N), indicating that the catches were uniform in length distribution. The smallest fork length of Pacific hake for this study was just over 16 cm. A resonance peak for these fish would be expected well below 38 kHz [18,30,31].

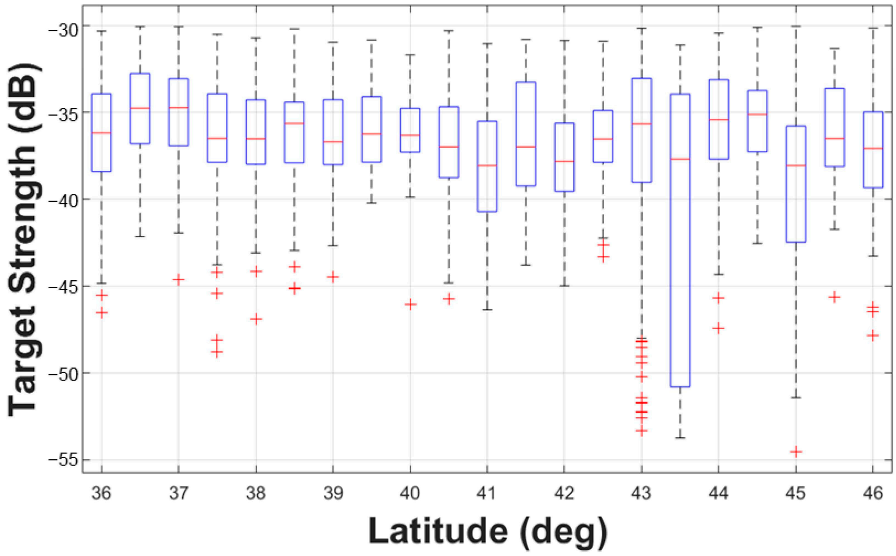


**Figure 6.** Target strength (TS) from single targets as a function of latitude. The central mark (red line) is the median, the edges of the box (blue) are the 25th and 75th percentiles, the whiskers (black dashed line) extend to the most extreme data points that are not considered outliers (red plus).

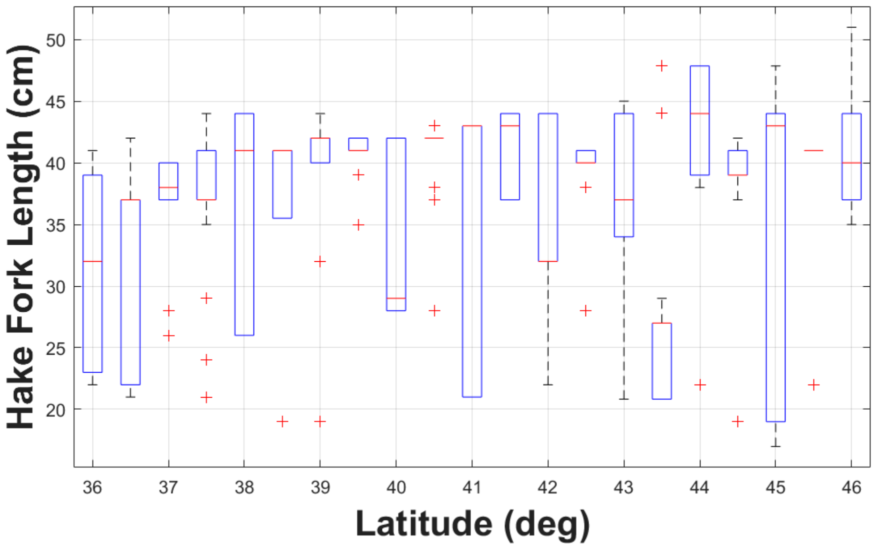


**Figure 7.** Hake fork length from biological haul catches as a function of length. The central mark (red line) is the median, the edges of the box (blue) are the 25th and 75th percentiles, the whiskers (black dashed line) extend to the most extreme data points that are not considered outliers (red plus).

### 3.4. TS-Length Regression

One of the most important results of this study is the regression of TS versus length. The regression was performed in the logarithmic domain for TS (dB) and linear domain for the length (cm) (Section 2.3). The boxplot of the TS values of the accepted samples as a function of length is presented in Figure 8. Mean lengths from trawls were categorized in 1 cm length bins, which may include samples from more than one trawl (when their mean length was similar). The forced slope of 20 for the model provided an estimated slope of −67.9 dB ($p < 0.001$, with a residual standard error of 3.73). This value is only 0.1 dB larger than the value derived from Traynor et al. [22] currently used for biomass estimates of Pacific hake. The areal acoustic scattering coefficient (NASC) is used for converting the acoustic quantity to biological quantity, i.e., the number of fish,

$$N = \frac{NASC}{\sigma_{bs}} \tag{7}$$

where $\sigma_{bs}$ is the differential scattering cross-section defined in Equation (1), or $\sigma_{ba} = 10^{TS/10}$. For a fixed $NASC$ value, the difference in $\sigma_{bs}$ will result in a change in the number of fish, $N$:

$$\Delta N = -\frac{NASC}{\sigma_{bs}^2}\Delta\sigma_{bs} \tag{8}$$

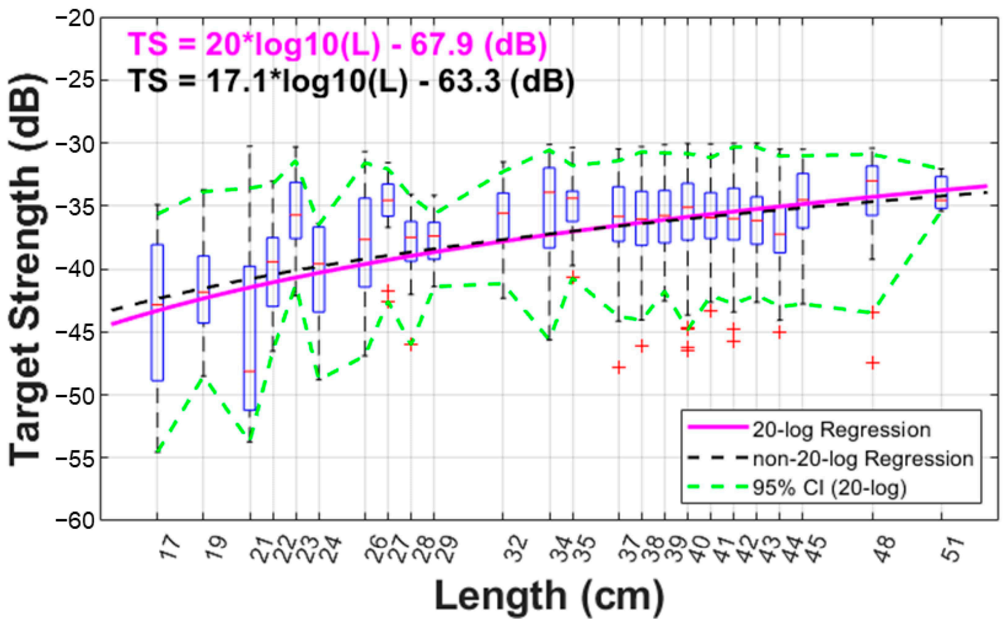


**Figure 8.** Target strength (TS) from single targets as a function of length. The $x$-axis is marked and labelled at the mean fork length of the samples. The fitted TS-length regression (solid magenta line) is superimposed onto the plot, and the upper and lower 95% confidence intervals of the sample values in each length category are plotted with a dashed line (dashed green line). A non-20-log regression (dashed black) is also superimposed to the plot.

A relative change in the estimated fish number is expressed as the ratio of (8) to (7):

$$\frac{\Delta N}{N} = -\frac{\Delta\sigma_{bs}}{\sigma_{bs}} = -\Delta TS\frac{\log_e 10}{10} \approx -0.23\Delta TS \tag{9}$$

As a result, a 0.1 dB increase in TS would lead to a change of less than 3% $\left(\frac{\Delta N}{N} \approx -0.23 < 3\%\right)$ in the estimated fish number. Applying this revised value and assuming that the fish weight is proportional to the fish number, the estimated biomass would have been less than 3% higher than the acoustic biomass estimates reported from previous Joint U.S.-Canada IAT Surveys [2].

For comparison, a linear regression where slope was estimated was also performed, resulting in a slope of 17.1 and the intercept of −63.3 dB ($p < 0.001$, adjusted $R^2$ of 0.21). This regression curve is also shown in Figure 8 (dashed black line), which is not very different from the 20-log regression curve (solid magenta line) and well within the sample confidence interval that includes the slope of 20. This non-20-log regression relation was an empirical data fit comparison. For gadoids, which have large spheroid-shape swimbladders, the relationship is justified to follow a 20-log relationship [32]. Scattering physics reveals that the differential backscattering cross-section in the farfield (i.e., plane wave incidence) should be proportional to the squared length of the target of finite size (i.e., smaller than the first Fresnel zone) [33–35]. There have been debates in the literature about whether the relationship of target strength to length does not always necessarily follow a 20-log regression [36,37], perhaps due to complexity in fish body types and swimbladder morphologies.

### 3.5. Statistical Robustness of $b_{20}$

To assess the robustness and the variability of the value of $b_{20}$ in the TS-length regression, we performed the three statistical processes as described in Section 2.2, i.e., partial, bootstrapping, and jackknife resampling methods, all with 1000 iterations.

a. Partial sampling: For the partial sampling, we resampled the whole data population with 95% down to 5% in 5% increments, and at each percentage value, we performed the resampling with replacement 1000 times or realizations. The results are tabulated in Table 4, and their graphic representation is shown in Figure 9. All distributions from the resampling can be well described by Gaussian or normal distributions. A representative example at 90% resampling is illustrated in Figure 10, where a Gaussian Probability Density Function (PDF) with a mean of −67.9 dB and standard deviation of 0.03 dB is superimposed onto the plot of the raw resampled values. Note that even with a substantially low number of selected TS samples at 5% of the original data, the estimated mean value of the in situ TS was only 0.003 dB lower than −67.9 dB.
b. Bootstrapping: Bootstrapping yielded a $b_{20}$ mean of −67.9 dB with a 95% confidence interval of [−68.09, −67.72]
c. Jackknife analysis also resulted in a $b_{20}$ mean of −67.9 dB with a standard deviation of 0.002 dB.

**Table 4.** Results from the partial resampling with replacement.

| Resample Percentage | Mean (dB) | Standard Deviation (dB) |
|---|---|---|
| 5% | −67.9 | 0.42 |
| 10% | −67.9 | 0.29 |
| 20% | −67.9 | 0.19 |
| 30% | −67.9 | 0.15 |
| 40% | −67.9 | 0.12 |
| 50% | −67.9 | 0.10 |
| 60% | −67.9 | 0.08 |
| 70% | −67.9 | 0.06 |
| 80% | −67.9 | 0.05 |
| 85% | −67.9 | 0.04 |
| 90% | −67.9 | 0.03 |
| 95% | −67.9 | 0.02 |

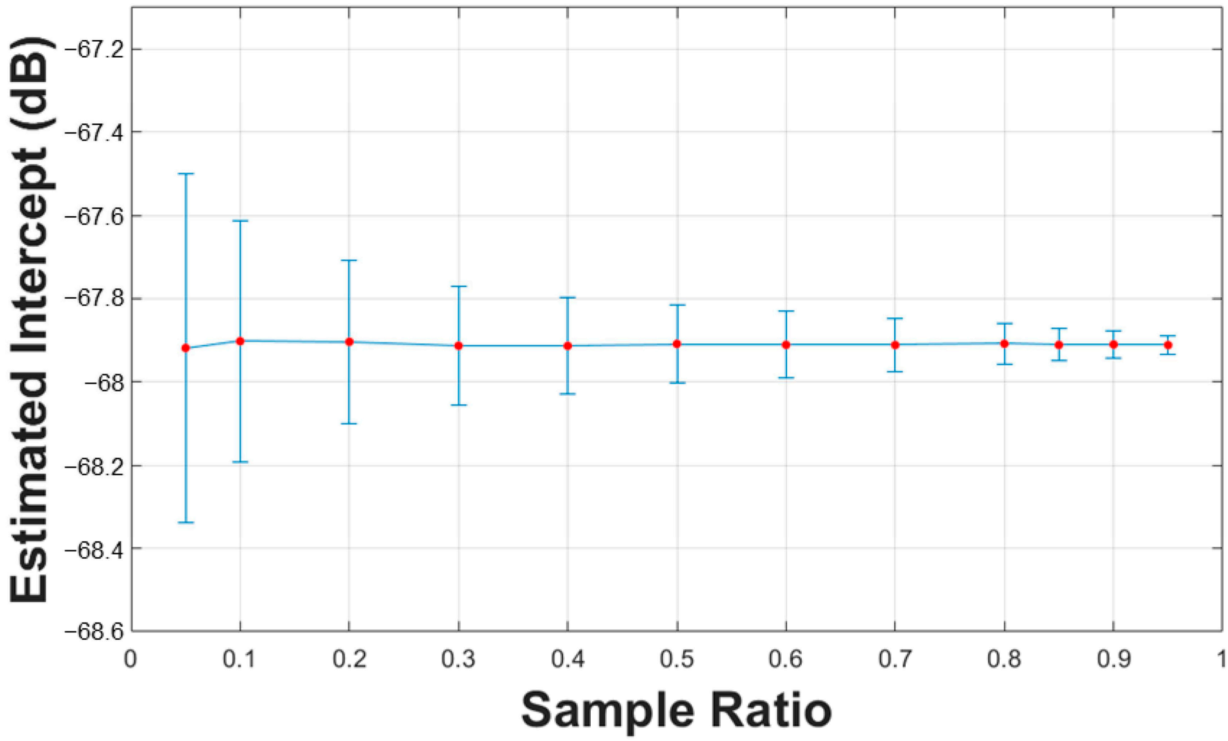


**Figure 9.** $b_{20}$ estimates from bootstrapping resampling with 5% to 95% of original TS samples, where 1000 realizations were used. Red circles are the mean with standard deviations in blue.

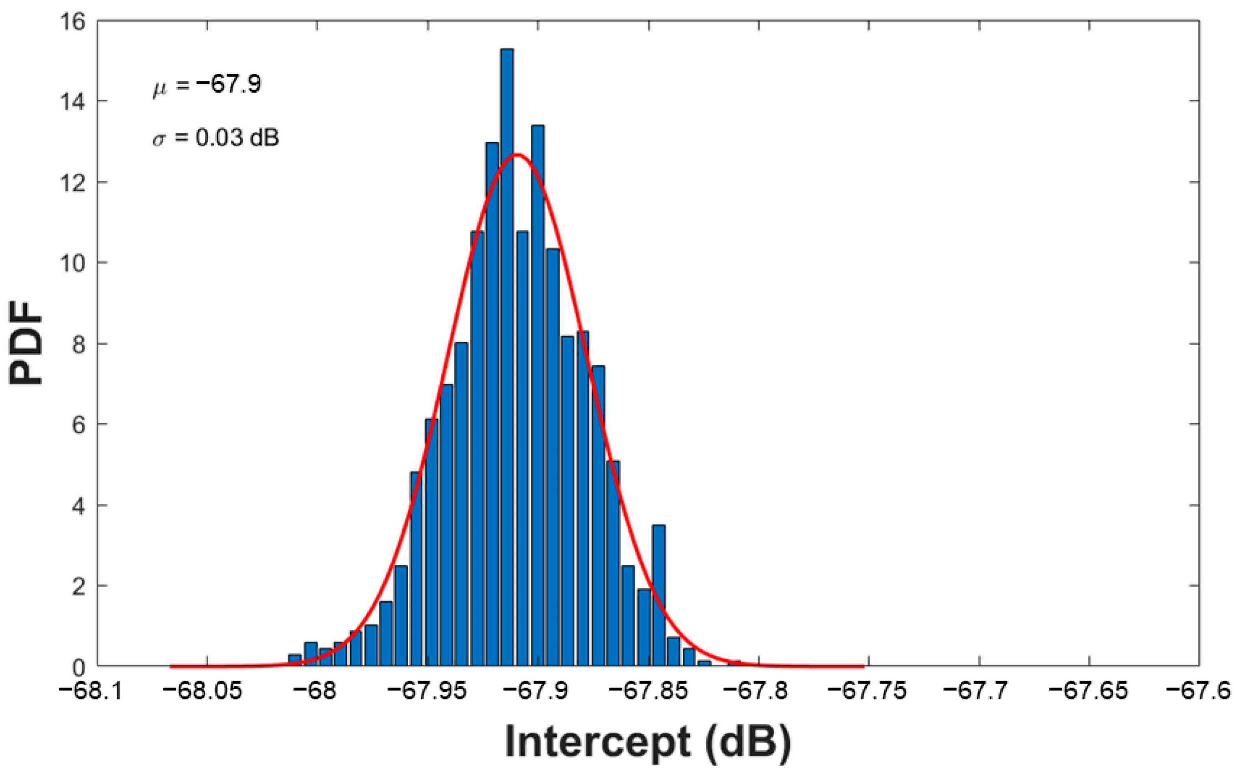


**Figure 10.** $b_{20}$ estimate from partial resampling with 90% of the whole TS sample population, where 1000 realizations were used. The parameters $\mu$ and $\sigma$ are the mean and standard deviation of the Gaussian PDF (red solid line).

These analyses all confirm the robustness of the $b_{20}$ estimate, with minimal variability, well within the tolerance for uncertainty in the stock assessment [2]. The low variability observed in the data indicates consistency in TS measurements, likely the result of the extensive filtering of data, primarily based on the last step involving the pulse energy filter.

### 3.6. Comparison with Previous Studies

Although the $b_{20}$ value reported here is similar to that of Traynor [22], it was 4–6 dB higher than that reported by Henderson and Horne [16]. Several factors may explain this discrepancy:

a. Data Collection Conditions: Previous studies on Pacific hake used TS data collected at night, while all of the data presented in this paper were collected during the daytime, i.e., consistent with the hake survey time from sunrise to sunset [38]. Hake TS measurements during daylight are more representative for biomass estimation as hake aggregate at depth during the day, but tend to scatter at night when there are fewer visual cues. As hake scatter and spread out through the water column at night, they could present increased tilt angles, resulting in reduced TS values.
b. Length Range and Regression Consistency: Henderson and Horne's ex situ TS data spanned a narrow fork length range (44–53 cm), with TS values spread over an 8 dB range [16], potentially reducing regression reliability and robustness.
c. Backscatter Model Discrepancies: The Kirchhoff Ray-Mode (KRM) [30] backscatter model used by Henderson and Horne, with X-ray images of fish bodies and the swimbladders of live fish captured at sea, showed predictions 4–6 dB higher than their ex situ TS measurements [16], indicating inconsistencies between model predictions and the ex situ measurements, but consistent with the findings from this study. It has been shown that when the fish body and swimbladder morphology are known, the KRM model is appropriate and suitable for single fish [39].

Results from these in situ measurements are consistent with the findings of Traynor despite their relatively small dataset of target strength measurements. The intercept value of −67.9 dB is in line, but lower by ~2 dB than reported for other gadoids [22,32,40,41]. Recent broadband measurements on Atlantic cod yielded a $b_{20}$ of −65.6 dB, consistent with narrowband measurements and also about ~2 dB higher than for Pacific hake [42]. Interestingly, early target strength measurements reported a $b_{20}$ of −67.4 dB for physioclists (which include Pacific hake), which is only 0.5 dB higher than our estimate [43]. Consistency and low variability in TS measurement values observed over nine surveys (spanning 10 years) provide confidence in the use of the −68 dB intercept value currently used for Pacific hake biomass estimates obtained from acoustic surveys. This consistency and low variability were likely the result of using the same methodology over a wide range of conditions across several years. Because of the uneven distribution of samples across survey years, it was not possible to investigate the effect of interannual environmental or biological factors that might affect TS—however, the consistency of results over the span of this study indicates that these trends would likely be small compared to the natural variability observed in target strength measurements.

### 3.7. Limitations of the Study

Collection of Pacific hake in situ target strength data during the day is problematic because these fish tend to aggregate at high densities in relatively deep waters (often mixed with other smaller mesopelagic scatterers), making collection of ship-based data prone to multiple target bias. Collection made at shorter range, for example, using the DAISY system, partially addresses this issue, but is resource-demanding (requiring dedicated time and equipment). On the other hand, data collected during assessment and research surveys provide large volumes of data that can be mined afterward (see [32] for another example). Because of the low signal-to-noise ratio conditions encountered in relatively deep Pacific hake aggregations, selection of targets based on fish or target density metrics [44,45], even at reduced survey speeds, was not used in this study (as very little data would be preserved). Rather, a stepwise approach to the selection of targets was adopted, with the addition of a novel filter based on pulse energy used on the final dataset. The consistency of TS values obtained (especially when compared to closer measurements made with DAISY) provides further evidence for the validity of this approach. It is also important to note that ship-based target strength measurements in this study were all made during midwater trawling operations (because of the reduced vessel speed). There is evidence that trawling affects fish behavior [46]. Acoustic data collection from the centerboard of the vessel was performed prior to the trawl going through the aggregation, but increased vessel and trawling gear noise may have an impact on the orientation and swimming behavior of fish. There is, however, little evidence of a change in aggregation characteristics and depth distribution prior compared to during trawling, so we are assuming that these measurements of target strength data were made on fish representative of those encountered during routine acoustic surveys.

## 4. Conclusions

Single-fish TS data of Pacific hake at 38 kHz from more than ten surveys and research cruises spanning ten years were analyzed. These data were processed with a number of filters and criteria to ensure data quality so that all accepted TS samples were expected to be from individual hake. All echosounder datasets were verified by biological trawl catches with an average hake composition of more than 95% by weight to ensure the echoes were most likely from hake. The TS-length regression of 20-log linear representation, i.e., Equation (1), suggests an intercept term, $b_{20}$ of $-67.9$ dB, only 0.1 dB larger than the value currently used in acoustic biomass estimates. The updated $b_{20}$ aligns closely with current biomass estimation practices, ensuring an accuracy well within acceptable uncertainty limits. The results from three statistical validation methods, i.e., partial, bootstrapping, and jackknife resampling procedures, were used to assess the variability of the estimated $b_{20}$, ensuring accuracy within acceptable uncertainty limits while addressing discrepancies with earlier studies. These findings emphasize the importance of standardized sampling protocols and robust methods for advancing acoustic biomass assessment. Our methodology and new filtering of single-target data based on pulse-energy information may be useful for a wide range of pelagic and semi-pelagic species assessed using acoustic methods.

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**Data Availability Statement:** The data presented in this study are openly available in [NCEI NOAA] [https://www.ncei.noaa.gov/products/acoustics]. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

# Appendix A

**Table A1.** Detailed catch information of all hauls used in this study.

| Year | Haul Number | Latitude (Deg North) | Longitude (Deg West) | Mean Fork Length (cm) | Standard Deviation of Fork Length (cm) | CV (%) | # of Length Samples | Total Catch (kg) | % of Hake by Weight |
|---|---|---|---|---|---|---|---|---|---|
| Shimada | | | | | | | | | |
| 2009 | 8 | 37.0401 | 122.6764 | 40 | 3.76 | 9.4 | 324 | 321 | 95 |
| 2009 | 22 | 39.0280 | 123.9685 | 40 | 2.58 | 6.5 | 347 | 1426 | 100 |
| 2009 | 39 | 42.7018 | 124.7260 | 38 | 2.34 | 6.2 | 437 | 4590 | 100 |
| 2009 | 56 | 44.2032 | 124.9930 | 42 | 2.12 | 5.0 | 301 | 1100 | 99 |
| 2009 | 57 | 44.3706 | 124.8315 | 41 | 2.5 | 6.1 | 288 | 446 | 100 |
| 2009 | 62 | 44.8783 | 124.4680 | 19 | 1.64 | 8.6 | 336 | 1749 | 100 |
| 2009 | 64 | 44.8796 | 124.8209 | 43 | 2.52 | 5.9 | 248 | 128 | 99 |
| 2009 | 66 | 45.3749 | 124.4020 | 41 | 2.48 | 6.0 | 339 | 268 | 100 |
| 2011 | 2 | 35.3790 | 121.0993 | 22 | 1.25 | 5.7 | 242 | 82 | 99 |
| 2011 | 4 | 35.7137 | 121.4605 | 23 | 1.13 | 4.9 | 280 | 941 | 100 |
| 2011 | 9 | 37.3658 | 122.9050 | 24 | 1.88 | 7.8 | 208 | 18 | 100 |
| 2011 | 18 | 39.3728 | 123.9755 | 35 | 2.00 | 5.7 | 276 | 116 | 100 |
| 2011 | 27 | 44.3747 | 124.8392 | 39 | 2.96 | 7.6 | 307 | 216 | 99 |
| 2011 | 40 | 46.8773 | 124.9192 | 37 | 1.83 | 5.0 | 264 | 259 | 100 |
| 2011 | 44 | 47.3707 | 124.8633 | 38 | 1.93 | 5.1 | 325 | 140 | 100 |
| 2013 | 5 | 35.4248 | 121.3085 | 35 | 1.00 | 2.9 | 118 | 33 | 99 |
| 2013 | 10 | 35.9212 | 121.5310 | 26 | 1.42 | 5.5 | 317 | 463 | 100 |
| 2013 | 13 | 36.5982 | 122.6653 | 37 | 1.56 | 4.2 | 308 | 181 | 100 |
| 2013 | 16 | 37.2632 | 123.0873 | 37 | 1.72 | 4.7 | 536 | 177 | 99 |
| 2013 | 18 | 37.4207 | 122.9600 | 37 | 1.54 | 4.2 | 333 | 495 | 100 |
| 2013 | 33 | 40.5868 | 124.6773 | 38 | 2.24 | 5.9 | 556 | 198 | 98 |
| 2013 | 38 | 41.5960 | 124.5763 | 37 | 1.56 | 4.2 | 414 | 369 | 100 |
| 2013 | 42 | 43.0928 | 124.8732 | 37 | 1.94 | 5.2 | 397 | 259 | 98 |
| 2013 | 45 | 43.9313 | 124.9667 | 38 | 2.15 | 5.7 | 345 | 446 | 100 |
| 2013 | 48 | 44.2608 | 124.9428 | 39 | 2.69 | 6.9 | 230 | 86 | 100 |
| 2013 | 56 | 46.2453 | 124.2052 | 40 | 2.97 | 7.4 | 353 | 318 | 97 |
| 2013 | 76 | 50.0928 | 128.0172 | 51 | 3.62 | 7.1 | 537 | 522 | 89 |
| 2014 | 15 | 43.8840 | 124.7910 | 43 | 3.16 | 7.3 | 237 | 642 | 100 |
| 2014 | 16 | 43.8858 | 124.7343 | 44 | 3.35 | 7.6 | 200 | 192 | 100 |
| 2015 | 9 | 36.4460 | 122.1363 | 23 | 2.22 | 9.7 | 373 | 49 | 98 |
| 2015 | 13 | 37.4495 | 122.9712 | 22 | 1.46 | 6.6 | 285 | 431 | 88 |
| 2015 | 15 | 38.1177 | 123.6143 | 24 | 1.06 | 4.4 | 375 | 69 | 94 |
| 2015 | 21 | 39.7728 | 124.0748 | 35 | 3.40 | 9.7 | 418 | 166 | 100 |
| 2015 | 39 | 43.4477 | 124.7072 | 24 | 1.36 | 5.7 | 323 | 1316 | 100 |
| 2015 | 42 | 43.7828 | 124.9052 | 42 | 1.56 | 3.7 | 62 | 34 | 96 |
| 2015 | 46 | 44.7827 | 124.6060 | 21 | 1.23 | 5.9 | 481 | 290 | 100 |
| 2015 | 60 | 47.3663 | 124.8485 | 23 | 2.02 | 8.8 | 237 | 314 | 99 |
| 2015 | 73 | 49.1188 | 126.8678 | 44 | 2.37 | 5.4 | 288 | 156 | 100 |
| 2016 Winter | 2 | 42.1750 | 124.6632 | 29 | 2.74 | 9.4 | 235 | 35 | 92 |
| 2016 Winter | 4 | 41.3485 | 124.4978 | 27 | 1.58 | 5.9 | 474 | 440 | 93 |
| 2016 Winter | 7 | 41.4722 | 125.0988 | 44 | 2.72 | 6.2 | 195 | 234 | 96 |
| 2016 Winter | 8 | 40.4218 | 125.0995 | 44 | 3.04 | 6.9 | 221 | 460 | 100 |
| 2016 Winter | 9 | 39.8428 | 125.0960 | 44 | 3.02 | 6.9 | 123 | 61 | 97 |
| 2016 Winter | 10 | 39.1192 | 125.2397 | 43 | 2.55 | 5.9 | 256 | 141 | 85 |
| 2016 Winter | 11 | 39.1202 | 125.2287 | 43 | 2.59 | 6.0 | 256 | 118 | 99 |
| 2016 Winter | 13 | 37.9578 | 123.5278 | 28 | 1.67 | 6.0 | 210 | 125 | 96 |
| 2016 Winter | 18 | 37.2152 | 124.0930 | 42 | 3.01 | 7.2 | 211 | 237 | 100 |
| 2016 Winter | 21 | 35.9870 | 123.8852 | 43 | 2.43 | 5.7 | 235 | 139 | 92 |
| 2016 Winter | 29 | 37.1723 | 124.0630 | 42 | 2.99 | 7.1 | 231 | 332 | 98 |
| 2016 Winter | 30 | 39.0515 | 125.1992 | 42 | 3.00 | 7.1 | 200 | 225 | 99 |
| 2016 Winter | 32 | 42.5568 | 125.8293 | 44 | 2.75 | 6.3 | 287 | 143 | 97 |
| 2017 Summer | 1 | 34.9915 | 121.0798 | 26 | 2.14 | 8.2 | 331 | 37 | 98 |
| 2017 Summer | 4 | 36.4908 | 122.1897 | 28 | 2.15 | 7.7 | 415 | 1163 | 98 |
| 2017 Summer | 10 | 38.3297 | 123.6627 | 37 | 2.39 | 6.5 | 395 | 531 | 98 |
| 2017 Summer | 14 | 39.1445 | 124.0088 | 38 | 2.30 | 6.1 | 403 | 351 | 95 |
| 2017 Summer | 16 | 40.8132 | 124.5613 | 40 | 2.90 | 7.3 | 419 | 316 | 91 |
| 2017 Summer | 19 | 41.6540 | 124.4612 | 27 | 1.91 | 7.1 | 250 | 90 | 99 |
| 2017 Summer | 20 | 41.8235 | 124.4860 | 28 | 1.87 | 6.7 | 242 | 586 | 100 |
| 2017 Summer | 25 | 42.9898 | 125.1188 | 41 | 2.92 | 7.1 | 226 | 119 | 95 |
| 2017 Summer | 31 | 44.1580 | 124.9715 | 39 | 2.76 | 7.1 | 396 | 202 | 98 |
| 2017 Winter | 3 | 42.1720 | 124.5940 | 19 | 1.28 | 6.7 | 156 | 51 | 96 |
| 2017 Winter | 4 | 37.2585 | 123.3062 | 35 | 2.22 | 6.3 | 201 | 123 | 93 |
| 2017 Winter | 6 | 35.4527 | 123.5482 | 43 | 3.21 | 7.5 | 191 | 99 | 100 |
| 2017 Winter | 7 | 34.4397 | 120.7680 | 21 | 1.07 | 5.1 | 401 | 100 | 100 |
| 2017 Winter | 12 | 38.9510 | 124.0153 | 34 | 1.67 | 4.9 | 301 | 1080 | 100 |
| 2018 | 18 | 44.5778 | 124.6725 | 41 | 2.81 | 6.9 | 245 | 378 | 100 |
| 2018 | 19 | 44.5685 | 124.6752 | 43 | 2.67 | 6.2 | 236 | 156 | 97 |
| 2019 | 7 | 35.3937 | 121.1582 | 22 | 1.26 | 5.7 | 212 | 52 | 100 |
| 2019 | 8 | 35.5583 | 121.4342 | 23 | 1.69 | 7.3 | 212 | 104 | 99 |
| 2019 | 12 | 36.0648 | 121.7403 | 24 | 2.44 | 10.2 | 220 | 87 | 97 |
| 2019 | 19 | 37.5640 | 123.0483 | 32 | 2.32 | 7.3 | 356 | 178 | 100 |
| 2019 | 22 | 38.0565 | 123.5303 | 42 | 3.70 | 8.8 | 349 | 525 | 99 |
| 2019 | 24 | 38.5600 | 123.7883 | 38 | 3.01 | 7.9 | 322 | 121 | 94 |

**Table A1.** *Cont.*

| Year | Haul Number | Latitude (Deg North) | Longitude (Deg West) | Mean Fork Length (cm) | Standard Deviation of Fork Length (cm) | CV (%) | # of Length Samples | Total Catch (kg) | % of Hake by Weight |
|---|---|---|---|---|---|---|---|---|---|
| 2019 | 25 | 38.7320 | 123.8278 | 39 | 3.17 | 8.1 | 334 | 141 | 100 |
| 2019 | 29 | 39.4012 | 123.9842 | 40 | 2.25 | 5.6 | 326 | 182 | 92 |
| 2019 | 30 | 39.7312 | 124.2135 | 41 | 2.22 | 5.4 | 441 | 210 | 98 |
| 2019 | 33 | 40.3948 | 124.7948 | 41 | 2.07 | 5.0 | 403 | 413 | 100 |
| 2019 | 35 | 40.5643 | 124.7252 | 41 | 2.68 | 6.5 | 438 | 612 | 99 |
| 2019 | 36 | 40.7295 | 124.8352 | 41 | 2.57 | 6.3 | 468 | 648 | 100 |
| 2019 | 38 | 41.0465 | 124.4185 | 42 | 2.83 | 6.7 | 373 | 393 | 100 |
| 2019 | 45 | 42.7263 | 124.7283 | 42 | 3.23 | 7.7 | 381 | 1567 | 100 |
| 2019 | 46 | 42.8943 | 124.9795 | 42 | 2.99 | 7.1 | 366 | 576 | 100 |
| 2019 | 47 | 43.0708 | 125.0855 | 42 | 2.54 | 6.0 | 235 | 115 | 97 |
| 2019 | 48 | 43.2257 | 124.7650 | 42 | 2.47 | 5.9 | 343 | 313 | 100 |
| 2019 | 50 | 43.7210 | 125.0668 | 43 | 2.44 | 5.7 | 215 | 111 | 100 |
| 2019 | 54 | 44.0552 | 124.9563 | 41 | 2.73 | 6.7 | 381 | 701 | 99 |
| 2019 | 56 | 45.0540 | 124.7597 | 44 | 1.97 | 4.5 | 83 | 46 | 97 |
| 2019 | 57 | 45.2223 | 124.6620 | 43 | 2.02 | 4.7 | 276 | 148 | 97 |
| 2019 | 59 | 45.5570 | 124.5612 | 45 | 2.12 | 4.7 | 184 | 107 | 97 |
| DAISY | | | | | | | | | |
| 9/7/2014 | 36 | 41.6582 | 124.5003 | 29 | 1.25 | 4.3 | 101 | 259 | 80 |
| 9/12/2014 | 41 | 48.9242 | 126.5505 | 48 | 3.41 | 7.1 | 174 | 161 | 82 |
| 3/23/2016 | 30 | 50.0170 | 123.9078 | 33 | 4.70 | 14.2 | 150 | 29 | 99 |
| Mean | | 41.0717 | 124.1269 | 36.2 | 2.34 | 6.5 | 299 | 379 | 98 |

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