Development of an Acoustic-Optical System to estimate Target-Strengths and Tilt Angles from Fish Aggregations

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***Abstract* - The J-QUEST instrument package, a quantitative 70kHz split-beam echo sounder and a stereo TV camera, is being developed to observe mesopelagic fish. *In situ* acoustic and optical measurements of single fish within aggregations include swimming speed, target strength, length, and tilt angle. Acoustic data and two video signals are monitored in real-time via an optical-power composite cable and receivers on deck. The J-QUEST was deployed from the R/V Kaiyo-maru in the transient waters of the Kuroshio current from Kashima-nada to off the coast of Sanriku in the east of Japan. J-QUEST was tethered from the surface to a depth of 200m and worked well. In Kashima-nada at a depth of 10m, Pacific saury (*Cololabis saira*) were attracted to the underwater lights and formed a large aggregation around J-QUEST. We could monitor fish on both the TV monitors and on the echogram. Average target strength of Pacific saury was –37.9dB and normalized TS (by squared fork length) was –66.8dB.**

I. INTRODUCTION

Target strength is an important parameter used to convert acoustic backscatter measurements to fish abundance and as a parameter to estimate fish length. The swimbladder of a fish contributes over 90% of the acoustic scattering from the fish [1]. Target strength (TS) of fish is influenced by several factors including orientation of fish relative to the transducer, the ratio of acoustic wavelength to fish length, and physiological condition [2]. *In situ* TS measurements collected simultaneously with echo-integration data are preferable, as this approach can be used to quantify variability in TS [3]. Empirical backscatter measurements and simulation studies have observed that TS values from individual fish become larger than actual TS when fish targets are deep or fish density is high [4][5]. Algorithms for single echo detection do not work well in these conditions.

Identification of species and length frequency distributions are obtained from the analysis of biological samples such as trawl catches, given the constraint that every fishing gear differs in catch selectivity. Length frequency distributions from catch data may differ from that of the actual fish aggregation. One alternative approach is to lower a transducer closer to the fish school [6] and collect optical species composition, length, and orientation data simultaneously with acoustic TS measurements. Ermolchev *et al.* developed a laser underwater television (LTV) with a range-gate system and showed that the video-acoustic technology is a promising way to improve the quality of acoustic stock assessments [7]. They could see free-swimming young cod (15-21cm) within 10m of the camera. Unfortunately, their system cannot measure spatial orientation. The current system, J-QUEST (Japan QUantitative Echosounder and Stereo Tv camera system), has been developed to measure TS, length, orientation, swimming speed, and the inter-fish distances within aggregations [8,9]. Both the acoustic and optical devices are installed in a pressure tight case and the system can be deployed on medium size research vessels that are equipped with a crane and a winch. This paper describes the system and acoustical experiments that were carried out in a tank and at sea. Additional details of the optical devices and associated experimental results are described in a companion paper [10].

II. MATERIAL AND METHODS

A. Requirements

(1) Target species

Mesopelagic fish are important to commercial fisheries and to the pelagic ecosystem. Fish length and the ability to resolve individuals were used to determine the specifications needed for an optical system. The minimum target strength of fish was used to determine the specifications of an acoustical system. Lanternfishes, which have a vast biomass, are found in all of the world's oceans. We chose California headlightfish (*Diaphus theta*) as the smallest fish (50 to 100 mm [9]) that will be resolved by the J-QUEST system. *Diaphus theta* is the dominant species in the transitional area of Kuroshio current off Japan and is known to undergo a diel migration.

(2) Sampling volume

Sampling volumes covered by both echosounder and stereo-TV cameras should be as large as possible to identify behavioral and target strength differences by fish during day and night.

(3) Real-time monitoring

Real-time acoustic and optical monitoring is required when the system is approaching a fish aggregation.

(4) Motion monitoring

Monitoring the motion of the pressure tight case is required to compensate behavior measurements of fish.

(5) Practical maximum depth

Maximum depth of the system should be 300 m. The maximum depth of the existing pressure tight case is 300m but the practical depth is about 250m due to the limitation of the composite cable length (300m).

(6) Underwater illumination

Underwater lighting and its control system should be remote and variable to adjust for changing light conditions during night and with depth.

B. Configuration and specifications of J-QUEST

Figure 1 and 2 depict the main housing and electrical block diagram of J-QUEST.

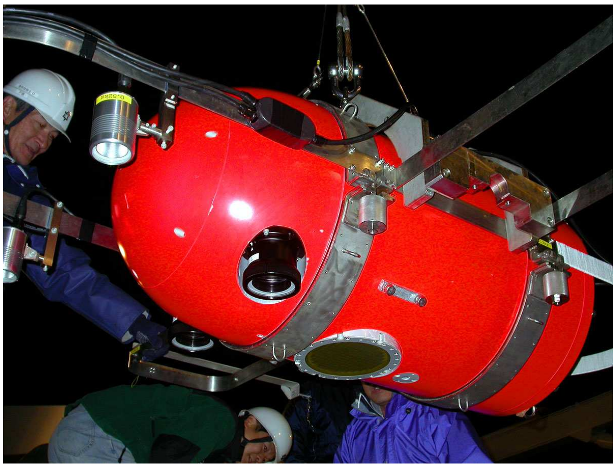


Fig.1 Tethered J-QUEST on deck.

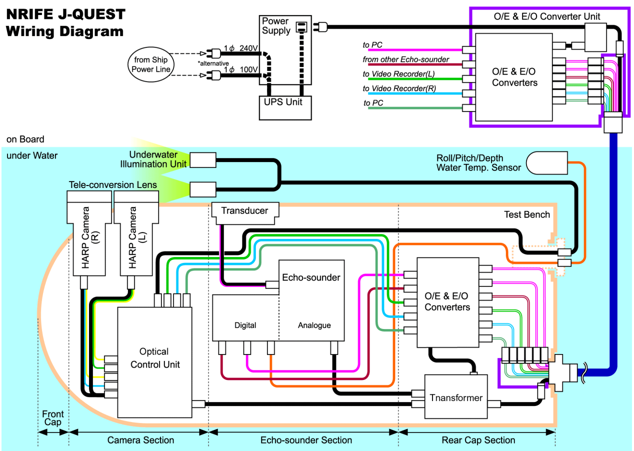


Fig.2 J-QUEST system block diagram

The upper part of the block diagram in Fig.2 shows the on-deck unit that consists of a power supply and optical/electrical converters. Two PC's are used to control the acoustic system and camera lights. The lower part of Fig.2 (shaded) shows the underwater unit. The on-deck unit and the underwater unit are connected via an optical-power composite cable composed of six optical fibers and power lines.

The echosounder and video cameras are installed in a pressure case. Motion (roll and pitch), depth, and temperature sensors are installed in another small pressure case. These pressure cases are connected by an underwater cable. Sensor information and acoustic data are indexed by acoustic pulse and recorded on deck to a

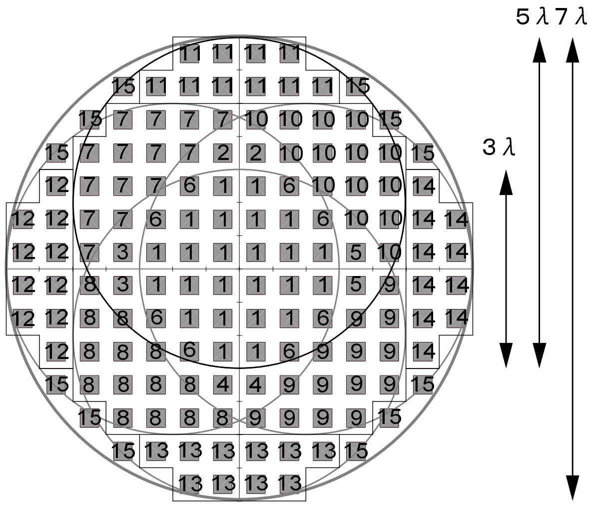


Fig.3 Transducer array elements of the J-QUEST transducer. Transducer channel diameters are indicated using wavelength (λ).

hard disk as a raw echosounder file. Underwater illumination is provided by two halmeic lights (color temperature of 3075K) are attached to the frame around the pressure case.

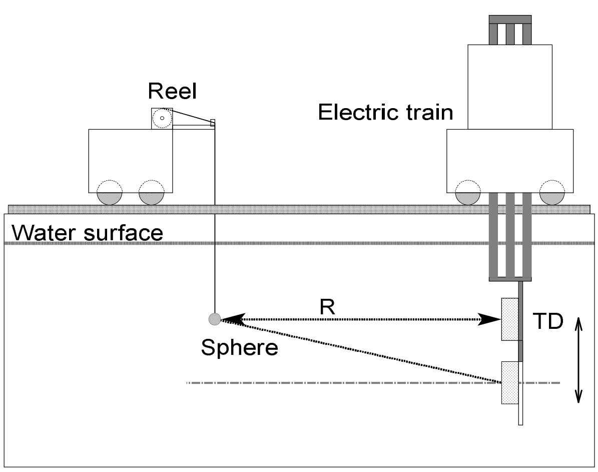
A modified, KFC5000 echosounder with a 70 kHz split-beam transducer (Kaijo Sonic Corp.) is installed in the J-QUEST system and controlled from the deck PC via a TCP/IP cable. Pulse duration can be selected among 0.6, 1.2, and 2.4ms.

Transducer array elements are grouped in separate channels to facilitate split-beam data collection (Fig. 3). Signals from channels 1, 2, 3, 5, 6, 7, 10, and 11 are inversely weighted to the number of elements and added to form the phase signal of the 'Fore' beam . The elements composed of channel 1, 2, 3, 5, 6, 7, 10, and 11 are also used to transmit a narrow beam (11.8 degrees at half power points) that approximates the 15 degree field of view of the stereo TV cameras (see the companion paper [6] for details).

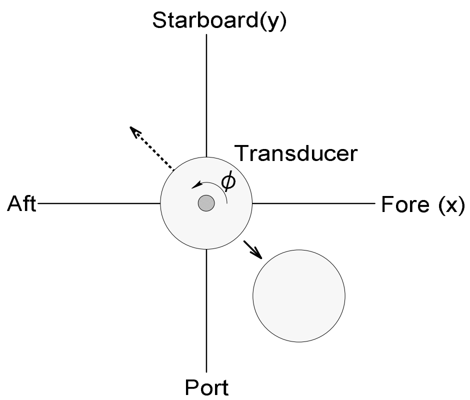
C. Calibration and measurements of Directivity and position

Sphere calibration was conducted using a 38.1 mm diameter, tungsten-carbide sphere. After calibration, directivity patterns of the transmit and receive beams, and the accuracy and precision of acoustically estimated positions were measured in an indoor tank (Fig. 4a). The same calibration sphere was tethered from an train (left side Fig. 4a) facing the transducer that was mounted on a mechanical stage capable of precise movements in two horizontal, one vertical, and one rotative dimensions. Directivity of transmit and receive beams can be measured by changing the position of the transducer (Fig.4 b). The distance between the transducer and the sphere was set at 3.2m to confirm precision and accuracy of short range measurements.

The directivity of the Narrow beam, D_N, is calculated by measuring the echo level of the narrow beam, EL_N, the transmit and receive coefficient, TR_N, the range from the center of the narrow beam to the target, R, the absorption coefficient, α, and the target strength of the standard sphere, TS. The directivity of composite beam, D_C, is calculated in a similar way (Eq. 2).



(a) Side view of an indoor tank.



(b)Side view from sphere side.

Fig.4 Experimental set-up for calibration and directivity measurement of the J-QUEST transducer.

$$D_C = EL_C - TR_C + 40\log r + 2\alpha r - TS - D_N \quad (1)$$

$$D_N = 1/2\,(EL_N - TR_N + 40\log r + 2\alpha r - TS) \quad (2)$$

Strictly speaking, the distance between the center of the transducer and the target, r_C, is different from the distance between the center of the narrow beam and the target, r. The range r_C is almost the same as r, since the offset between the center of narrow beam and the center of the transducer is only 2.14 cm. The ratio between the offset and the range, r_C, is 0.0214 at r_C=1m. At typical ranges during TS measurements, we can consider r_C equal to r.

TR_N is calculated when the sphere is on the narrow beam axis. The angle from the normal to the transducer was calculated using the mechanical position within 1 cm accuracy. Measured angle, θ, was calculated as

$$\theta = \sin^{-1}\left(\frac{\sqrt{\delta x^2 + \delta y^2}}{kd}\right) \quad (3)$$

where δx and δy are the electrical phase angles in the fore-aft and port-starboard directions, k is the wave number, and d is the distance between the center of each phase beam pair.

One hundred echoes at each position were used to estimate directivity patterns and positions.

D. Directivity compensation

The offset between the center of the narrow beam and the center of the transducer affects the directivity compensation of a target, especially when a target is close to the transducer. Target position should be included in directivity compensation. Assuming a Cartesian system with the origin at the center of the transducer, a target position (x,y,z) is expressed as

$$x = r_C \sin\theta_C \cos\phi_C \quad (4)$$

$$y = r_C \sin\theta_C \sin\phi_C \quad (5)$$

$$z = r_C \cos\theta_C \quad (6)$$

where r, θ, and ϕ are parameters in the spherical coordinate system and the subscript c denotes that the origin is the center of the transducer. The position of the center of the narrow beam is (x_0, 0, 0), where x_0 is the offset. The range, r_C, is calculated as

$$r_C = \sqrt{r^2(1-\sin^2\theta_C\cos^2\phi_C)\,x_0^2} + \sin\theta_C\cos\phi_C\,x_0 \quad (7)$$

where r is the distance from the center of the narrow beam to the target.

The angle from the center of the narrow beam is expressed as

$$\theta = \cos^{-1}(z/r) \quad (8)$$

Directivity compensation is calculated using a Bessel function of the 1st order, J_1, as

$$D_N = 20 * \log\left|2J_1(ka\sin\theta)/ka\sin\theta\right| \quad (9)$$

where a is the radius of the narrow beam.

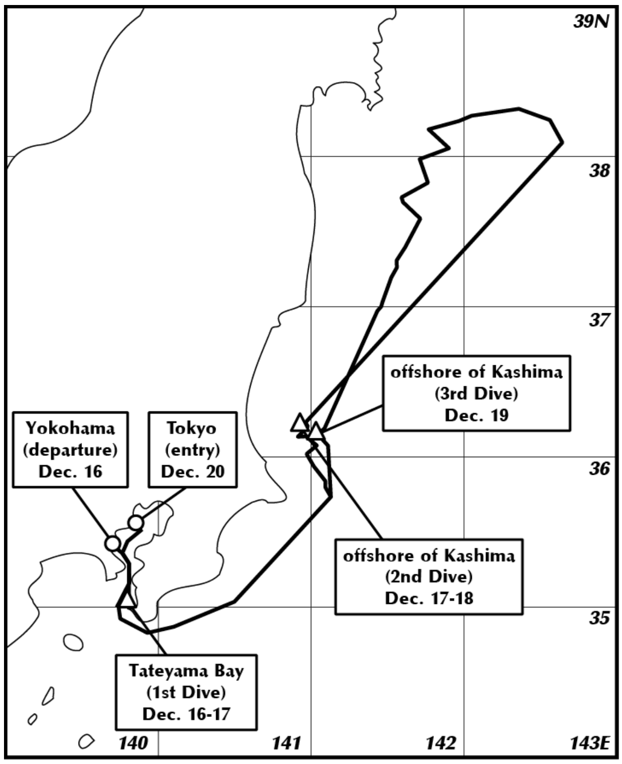


Fig. 5 First trial site of J-QUEST.

E. Sea Trials

The RV "Kaiyo maru" conducted at-sea gear trials with J-QUEST in the transient waters of the Kuroshio current from Kashima-nada to off the coast of Sanriku from 16 to 19 December, 2003. This area was selected as it has been reported to be within the range of lanternfishes [**11**].

Calibration of the hull-mounted echosounder and test of J-QUEST was conducted in Tateyama Bay from 16 – 17 December.

Hull-mounted echosounders (Simrad EK500120kHz, 200kHz; Kaijo KFC3000 38kHz) were operated during the gear trials. A pulse duration of 0.6ms and a 50 m range were set on the J-QUEST acoustic system. A calibration sphere (tungsten carbide, 38.1 mm diameter) was tethered during J-QUEST operations to provide a standard target and to check the depth dependence of the transmitting and receiving factors.

When targets on the echograms were thought to be lanternfishes, fish sampling was conducted using a Rectangular Midwater Trawl (RMT). After trawling, the water was profiled using a conductivity-temperature-depth (CTD) instrument, and J-QUEST was lowered into the aggregation. Acoustic and optical data were recorded for several hours.

TS and SV analysis software (TSAN, Kaijo Sonic corp.) was used to measure echo levels of the narrow and composite beams, uncompensated TS, and electrical fore-aft and port-starboard phase angles. Calibrated parameters were used to calculate TS and directivity was compensated using Eq. 9.

III. Results

A. Calibration and measurements of Directivity pattern and position

Figure 6 shows the measured directivity patterns in the fore and aft plane. Bold lines show calculated directivity patterns assuming circular piston transducers with diameter of 5 λ (Narrow beam) and 3 λ (Composite beam). Measurements matched calculations well.

Figure 7 shows the accuracy and precision of position estimates in the 0° -180° and the 45° - 225° plane. Specified angles were calculated using the distance moved by the electric train.

The regresion equation for 0° -180° plane with an angular range extending from -6.7° to 6.6° was

$y = 0.98018x + 0.00182,\ R^2 = 0.9997$.

And the regression equation for the 45° - 225° with an angular range of –8.6° to 9.3° was

$y = 1.0065x - 0.03129,\ R^2 = 0.9992$.

The results indicate that target positions are accurately measured by the acoustic system.

B. Trial at sea

Three dives were conducted using the J-QUEST system with a total diving time of 26 hours 32 min. Several kinds of fishes were observed during the dives.

Pacific saury (*Cololabis saira*) aggregations were attracted to the lights of J-QUEST at 10m depth when offshore of Kashimanada (Fig. 8). An example echogram of Pacific saury and analysed results are shown in Fig. 9. Optic stereo images were recorded simultaneously with acoustic data.

Unfortunately, we could not directly sample Pacific saury. Fortuitously, eight fishes were dropped on the deck by sea birds. Average fork length of the 'bird' samples was 27.46 cm ± 4.10 cm standard deviation (Table 1). The ratio between total length and fork length was 0.944 with a standard deviation of 0.007 cm.

Average body length of 24 Pacific saury was estimated

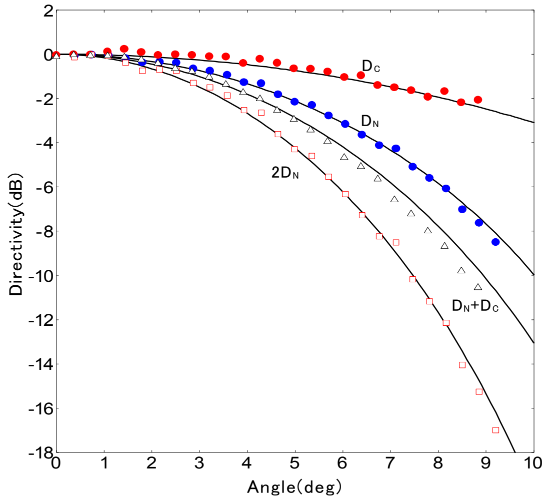


Fig.6 Measured and calculated directivity patterns.

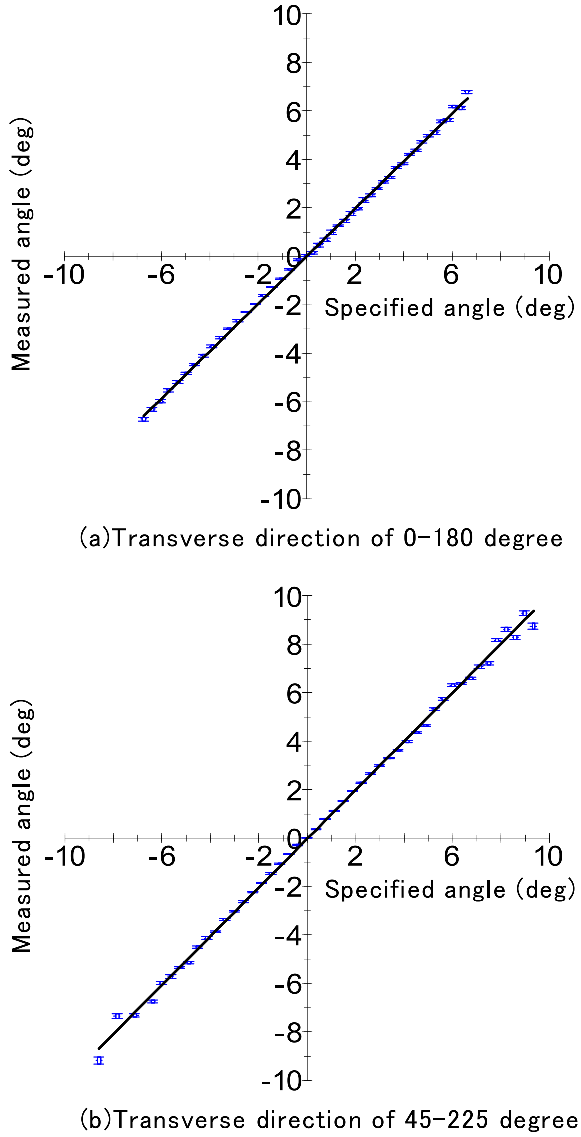


Fig. 7 Measured precision and accuracy at transverse angle of 0-180° and 45-225°.

using optic data and resulted in an estimated total length of 25.7 cm with a 3.0 cm standard deviation. These values correspond to an average fork length of 24.2 cm ± 2.8 cm standard deviation .

Table 1 Length and weight information derived from “Bird samples”

No.	FL(cm)	TL(cm)	FL/TL	BW(g)
1	22.2	23.5	0.94468	38.2
2	27.0	28.5	0.94737	81.5
3	22.0	23.4	0.94017	33.4
4	33.0	35.1	0.94017	142.1
5	30.4	32.6	0.93252	129.1
6	30.4	32.3	0.94118	104.8
7	29.8	31.2	0.95513	108.7
8	24.9	26.2	0.95038	51.0
Average	27.46	29.10	0.94395	
Standard Dev.	4.10	4.40	0.0070	

Fig.8 A frame image of Pacific saury (*Cololabis saira*) aggregations recorded by J-QUEST stereo camera system. The characters in the figure shows a elapsed time and the frame number, as 04hours, 01minute, 09 seconds, and 6th frames.

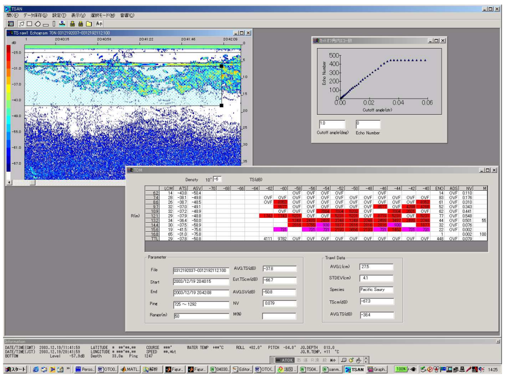


Fig.9 Echogram and analysed results using TSAN. The upper left panel shows echogram of Pacific saury in 40 log r TVG. The upper right panel shows single-echo numbers in the narrow beam. The lower panel shows the density of single-echoes by TS at 2 dB step and by depth at about 1m step. Number of fish in a reveberation volume is also calculated as an index for the precise TS estimation.

Figure 10 shows number of echoes and average TS within the sampling volume at specified cut-off angles. A

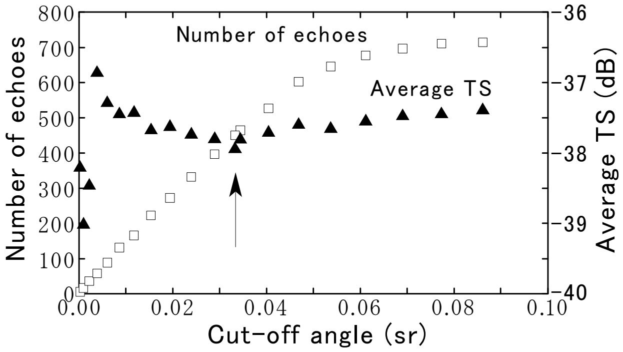


Fig.10 Echo numbers in cut-off angles and averaged TS. White squares denote the number of echoes and black triangles denote average TS at each cut-off angle. The arrow shows the number of echoes and average TS at selected cut-off angle (5.9 °).

cut-off angle arbitrarily defines the sample volume for TS collection. Within the half power points of the transducer (5.9 degrees), a collection of 450 echoes resulted in an average TS of –37.9 dB .

IV. Discussion

Only the fore beam is used as the transmit beam (i.e. level beam). This may be unusual but there are advantages to this approach when estimating TS using the split beam method. Four phase beams and the level beam have the same directivity. Generally, single echo detection algorithms are applied only to the level beam signal. The directivity of the phase beam becomes broader than that of the level beam in typical split-beam transducers [12] that transmit pulses using all elements. There are possibilities that single echoes from the level beam are not always single echoes due to potential differences in phase beam widths. Moreover, the signal to the noise ratio (SNR) of the phase beam is lower than that of the level beam, as the area of the phase beam is smaller than the level beam in typical split-beam transducers. Measured phases derived from multiple echoes or those derived from single echoes in low signal to noise (i.e. SNR) conditions are incorrect. Phase measurement errors will result in TS estimation errors [3] as phase measurements are used to compensateTS when the target is off the acoustic axis. It may be preferable to apply the single-echo detection algorithm to the level beam and the phase beam, or match the beamwidths of the phase and level beams which will minimize TS estimation error.

One concern is that the forbeam is offset from the center of the transducer phase beams by 1λ. This offset complicates directivity compensation, especially in at short ranges as shown in Eqs.7 through 9.

Predicted directivity patterns of the narrow and composite beams agreed with those measured in the tank. Strictly, TS measurements using the composite beam is a bistatic measurement. Since the angle between the transmit and receive beams is only 0.6 degrees at a 1m range, the difference is expected to be inconsequential.

We believe that the estimated average TS is precise as the number of echoes is large and single-echoes are uniformly distributed (see Fig. 10). Normalised TS ($TScm$) can be calculated using average TS (TS_A), average fork length, L_A, and its standard deviation (L_S) :

$TS_{cm} = TS_A - 10\log(L_A^2 + L_S^2)$

We would obtain a TScm of –66.8 dB at an average fork length of 27.5 cm with standard deviation of 4.1 cm and a TScm of –65.69 dB at an average fork length of 24.2 cm ±3.0 cm standard deviation [6]. The optic-based estimated lengths are lower than the 'bird' samples but sample sizes are too small to statistically compare. Further analysis from stereo camera data is expected.

The number of fish in a reveberation volume (NV) can be used as an index for the precision of TS estimation. Using the 'bird' length samples, Ona's TS to length equation for herring [13] predicts an average TS value of –38.4 dB. The resulting NV value of 0.079 suggests a low fish density that we believe is suitable for precise TS measurements.

Pacific saury were not present in the recordings of the hull-mounted echosounders. J-QUEST can be used to overcome potential limitations of vessel avoidance by fish or low probability of encounters in small sampling volumes at short ranges directly below the hull.

Acknowledgments

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