Analysing Estimators in the Alternative Echo Integrator Method

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Abstract: New and existing estimators of the "Echo Value Constant" based on split-beam detected and integrated single target echoes in the "alternative echo integration method" have been compared by using acoustic data. Two new estimators were made to make consideration to the fact that the detected echo strengths of single targets outside the half power angle of the split beam transducer have positive average bias. Another new estimator that was proposed in a previous paper of the same author is, however, not of this type, and seems in general to be positively biased. The other new estimators seems to be better with respect to the bias than the old one, but one of them seems to be a bit unstable with significant negative bias in special cases. There may be developed even better, nearly beam independent, estimators of the Echo Value Constant.

"*In situ*" single echo Target Strengths, although not used, are computed, and these indicate that the increasing average positive bias with increasing beam angle is not dramatic within the angle of -10 dB transmit beam damping.

Keywords: Echo integration in terms of energy, Single target echoes, Position related echo strength bias, Fish density estimation.

INTRODUCTION

An alternative echo integration method was given in [1]. This is a method that bases the conversion of integrator values to fish abundance on the energies of single target echoes instead of echo intensity (Target Strength). In the alternative method, the conversion factor between "echo abundance", as defined in [1], and fish abundance is based on a collection of representative integrated single target echoes from fish "in situ". The conversion factor is termed the mean Echo Value Constant, and is the average contribution per fish to the echo abundance. A main difference between the alternative echo integration method and the classical echo integration method is that the former does not use single echo peak values, but bases the conversion factor "Echo Value Constant" on integrated single target echoes. This means that the Target Strength concept is not used. Instead, echo strength is expressed by a concept called "backscattering energy" that is defined in terms of the integrated single target echo, or the echo energy. In a symposium on fisheries acoustic in 1982, R. E. Craig proposed to replace power with energy in sonar theory, see [2]. This is exactly what the alternative echo integration method does. Note that the concept "backscattering energy" was defined in [1] and used in [6] under the name "backscattering power". However, backscattering power is not a good name in a model that is based on echo energy, and will hereafter be termed "backscattering energy".

The reason for using integrated single echoes instead of peak values is because the echo integration method integrates the acoustic signal. According to the random phase hypothesis this gives a value that, in average, is equal to the sum of the integrated single echoes in the acoustic signal even if echoes overlap. A requirement is of course that the shadow-effect [3] is negligible. It is demonstrated in Fig. (**5**) that single echo peak values and the integrator values are rather linearly related.

Two different types of estimators for the mean Echo Value Constant has been developed in [1], but one of these could not be used without modification because it requires representative single target fish echoes at detection angles between zero and an angle with the acoustic axis where the transmit-receive beam function has fallen – 20 dB. It is not possible to collect a representative sample of single fish echoes in this detection angle interval because many echoes far out in the beam are not detected. The purpose of this paper is to investigate an alternative modification of this estimator that compensates for the loss of many single target echoes in the outer part of the main lobe. The echo strengths of single echoes from this region are positively biased in average, mainly because the majority of the echoes that are lost are the weakest.

There is another cause that generates an average positive bias of the beam-corrected echo strength, or backscattering cross-section, of single echoes detected by the split beam system. This is called position related bias in estimates of the acoustic backscattering cross-section, and is caused by random errors in the detected phase angles and the curvature of the beam function. This is explained by Fleischman and Burwen in [4], and has biggest effect on the detected single echoes from far out in the beam. Although beam corrected echo strengths are not used in the alternative echo integration method, errors in the detected phase angles will also cause a bias in the average integrated single target echoes. Target Strengths are shown in some of the figures in this paper, but are not used.

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There are also studies of different factors that influence the "in situ" Target Strength of single fish, see [5]. Although such knowledge may sometimes be useful, the collection of single target echoes to be used in converting echo-integrator values to fish abundance require echoes that are representative for all echoes that are integrated. If this is fulfilled, the factors that might have affected the fish Target Strengths are not of importance.

In this paper, new modifications of both estimator types given in (1) and (8) in [6] are proposed, tried and compared. Special versions of both types of estimators were applied in the same paper. Here we will consider versions and modifications that reduce the effect of the positive bias in average detected backscattering strength of single target echo received at big detection angles in the main lobe.

Every single target echo detection algorithm tests each candidate echo for coming from a single target only. Echo duration, echo shape and stability of the phase angles are investigated and tested before an echo is accepted to be a single target echo. Echoes that do not pass one or more of these tests have other echoes of no-negligible strength to close so that at least the echo tails overlap. Phase angles and echo shapes of weak echoes may also be affected by noise. The echoes that are most likely to be disturbed by other echoes and noise are the weakest echoes. As most of the weakest echoes are those that are received from targets far out in the man lobe, it is natural that the fraction of echoes that do not pass the "single target tests" increases with the detection angle. Also, the fraction of echoes not passing the "single target tests" at a given detection angle are mainly the weakest echoes received at this angle. This is the main cause of the increasing positive bias of average echo strength with increasing detection angle. In [7] a multi-frequency method to decide if echoes come from single targets is described. This method discards a considerable bigger fraction of echoes than that of a single frequency routine.

The acceptance of perfectly overlapping echoes of similar strengths as one single target echo is also a source of positive bias in estimated average echo strength, but this is judged to happen rather seldom in this application both because of low fish density, but also because of the single target echo detection algorithm used here (described in [6]). This routine is, as far as the author knows, the only single target detection routine that integrates single echoes.

Analyses of several single target detection routines including the possibility of accepting multiple echoes as single target echoes have been considered in [8]. Otherwise, many papers on the use of "in situ" single target echoes exist. These are mainly concerned with estimating the mean backscattering cross section of individual fish to be used in the classical echo integration method, and are not fully relevant to the study in this paper that uses integrated single target echoes.

MATERIAL AND METHOD

Files of raw data recorded by SIMRAD EK 60 scientific echo sounders are used in this study. Recordings from a survey on cod in Lofoten, Northern Norway by the new "G. O. Sars" in 2004 and from a survey on Redfish in the deep Tromsø basin by a hired vessel in 2008 are selected. Most of the cod recordings are from moderate depths (a few hundred meters) where the fish stayed close over the bottom. The redfish recordings, however, were from deep waters (several thousand meters deep) and the recorded fish, although down to 600 m deep, were very far above the bottom.

The echo integration method in terms of energy described in [1] is used. An application of this method was given in [6], but there the effect of positive biased average echo strengths was not considered.

Estimator type (1) in [6] was modelled by assuming that the average beam dependent backscattering energy (not beam-compensated integrated single target echoes) of fish as a function of observation aspect (observation angle from the acoustic axis) is proportional to the transmit-receive beam function. This assumption is likely to be good for beams where the majority of the single targets are received at angles less than 10 degrees, ([1], Fig. **2**). The observation aspect angle is expressed by the symbol θ in subsequent mathematical formulas.

Only circular symmetric beam functions are considered in this paper. A theoretical model for the beam function was used. This is the Bessel function formula for the beam of a circular piston transducer, see [9]. The model can be expressed by (3) in [6]. i. e.

$$\mathrm{E}[\varsigma_{rb}(\theta)] = a[B_s(k\theta)]^4, \tag{1}$$

where the left side is the expected beam dependent backscattering energy of fish at observation aspect θ, while $[B_s(k\theta)]^4$ is the Bessel function model for the transmit-receive beam function. The value of the parameter k determines the opening angle of the beam while a is the factor of proportion between the average beam dependent backscattering energy of fish and the beam function.

The derivation in [6] leads to the following estimator for the mean Echo Value Constant $\overline{\Psi}$ ((5) in [6]):

$$\widehat{\overline{\Psi}} = \frac{\hat{a}}{k_b^{\,2}} 1.4406 \tag{2}$$

where $\hat{a}$ is an estimator of a. The parameter k_b is the particular value of k that gives the theoretical beam the same half power opening angle as that of the used transducer. The modelled beam function is then assumed to be a good enough approximation for the actual beam function in use. The half power opening angle of the used transducer is given in the files of raw data of acoustic recordings. To control this beam model against the measured beam function by SIMRAD of a 38 kHz transducer commonly used on Research Vessels, the measured and modelled beam are plotted in the same coordinate system in Fig. (**1**). The half power angle for the measured beam is not given, so the fit here is made by trial and error with modelled beams of different values of the parameter k. The figure shows that the model is rather good.

Since $B_s^{\,2}(0.8069) = 1/2$, $k_b = 0{,}8069/\theta_{1/2,r}$, where $\theta_{1/2,r}$ is the half power opening angle in radians from the acoustic axis of the transmit beam.

Inserting this in (2), gives:

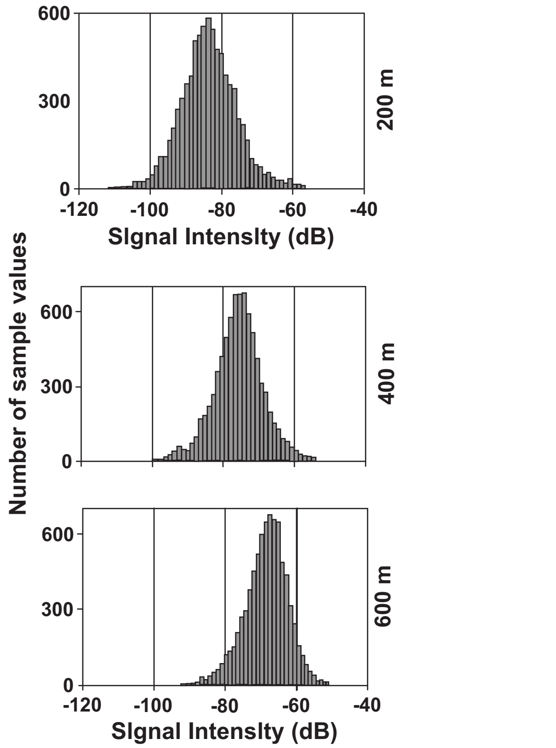

Fig. (12). Noise histograms of the 40 logR TVG signal in two, four and six hundred m depth.

this was not done, as it does not reduce the value of the results of this study.

Fig. (**14**) and Table **5** present the results from the deep interval (240-579 m).

The striking difference between the Figs. (**13** and **14**) are the observation aspect histograms. It shows that single echoes are lost from 2.5 degrees in the deep interval and from 6 degrees in the shallow interval.

The corresponding fish density per square meter estimates with using only one depth interval (single echo threshold corresponding to -45 dB) are: 0.01441 0.001516 and 0.01518. These estimates are higher, but less than 10% higher than the corresponding estimates summed over two depth intervals.

DISCUSSION

The two modified estimators (10) and (12) for the Echo Value Constant both seem to have moderate but significant biases, usually positive for (10) and negative for (12) as expected. As the correct value is not known, it is not possible to specify the exact biases in the different cases in this paper. However, there are reasons to believe that the fitted Echo Value of a sphere in most cases converge to a value that is closer to the true Echo Value Constant than the two modified estimates, in particular when all three Echo Value curves are close to each other for small angles. The bias in the Echo Value functions corresponding to (10) and (12) happens mainly when the observation aspect approaches θ_{-20}, which is slightly more than 6 degrees in the applications in this paper.

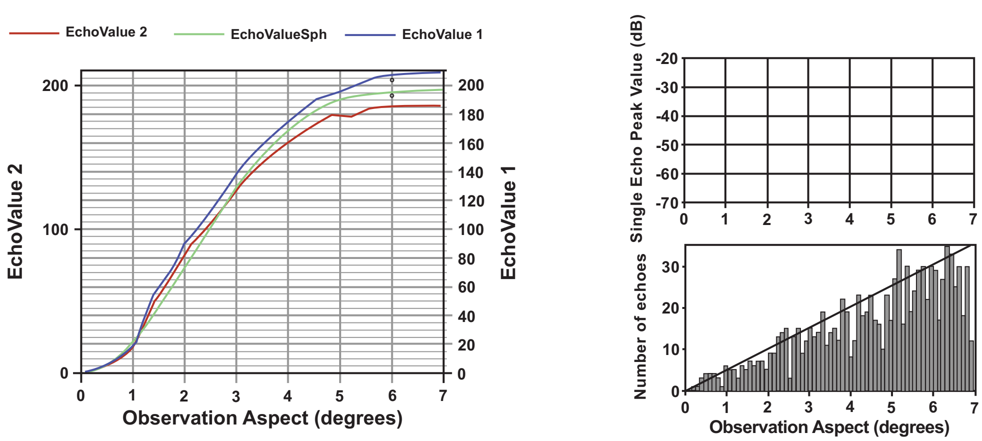

Fig. (13). Echo Values, Peak Values and number of echoes against observation aspect.

Table 4.

Number of echoes is 4886 before, and 1013 after applying the single target threshold

Sailed distance: 9292 m. Integrator value: 0.864

Echo Value Constant	Aksland 2006	Weight function 1	Weight function 2	(10)	(12)
	192.96	198.89	198.72	207	185
Fish density (individuals pr. square meters):	0.00448	0.00435	0.00435		
Mean TS (see explanation above **Table 1**)	-36.223	-37.071	-35.073		

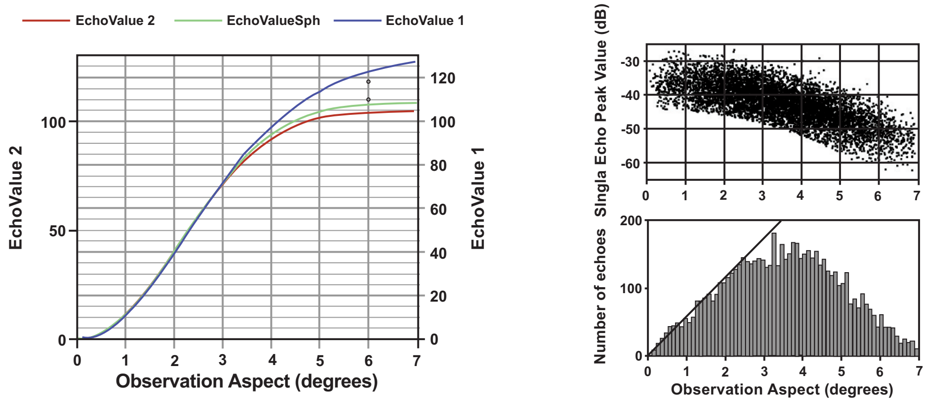

Fig. (14). Echo Values, Peak Values and Number of echoes against observation aspect.

Table 5.

Number of echoes is 7695 before, and 6133 after applying the single target threshold

Sailed distance: 9292 m. Integrator value: 1.060

Echo Value	Aksland 2006	Weight function 1	Weight function 2	(10)	(12)
	117.32	110.39	110.29	123	104
Fish density (individuals					
pr. square meters):	0.00904		0.009600.00961		
Sum, both intervals	0.01352		0.01395 0.01396		

Mean TS (see explanation above **Table 1**) -38.272 -39.319 -35.784

A lot more files of raw data than those presented in this paper have been analyzed, and corresponding figures have been made. This discussion is therefore based on more experience than that represented by the figures shown here.

The estimates based on (3) seem usually to be closer together than those based on (10) and (12). Without exception the estimates based on Weight function 1 and 2 in (5) are so close that they are difficult to distinguish on the graphs. The corresponding estimates of fish density are also always so close that it may be concluded that the most complicated Weight function 2 is not necessary.

Also, the estimates based on the beam model usually have values between the Echo Value Constants following from (10) and (12) except for difficult cases. It is also striking that the estimate based on Weight function 1 usually are close to the curve of the fitted Echo Value of a sphere. When the three Echo Value curves are close to each other near the acoustic axis, but differ when they pass θ_{-20}, it is likely that the fitted Echo Value of the sphere makes out the best approximation to the true Echo Value function. This indicates that the estimator based on Weight function 1 is rather good, and better than the Weight function used in [6]. Due to the tendency of too high average single echo strength of echoes received far out in the main lobe, the beam model estimator used in [6] is likely to give a slightly overestimated estimate of the Echo Value Constant, and hence a slightly underestimated fish density estimate.

The estimators based on (3) depend on the beam model. Although this seems good (Fig. **1**), the best had been to base the estimators on the actual beam function of the used transducer. This is possible if the beam function is precisely known out to the angle θ_{-20}. If the calibrated beam is a fitted model, this could replaced the beam model in (1) if the beam is circular symmetric. If not, the beam depends on two angles, and this is a straightforward generalisation of (1) since the split beam system detects two angles corresponding to each single target echo. This requires that the beam function can be calculated everywhere where the transmit beam damping is less than – 10 dB. If a table represents the calibrated beam function, the problem is to find the value of the beam damping in the table at the angles closest to those detected. If necessary, interpolations can be computed if the table has not enough resolution.

Most of the different plots of single echo Target Strength against observation aspect indicate that the detected Target Strength increases with aspect angle, in particular around and beyond θ_{-20}. The increasing value of the weakest detected echoes with aspect angle is simply caused by the fact that many echoes far out in the beam are too week to be detected due to the beam damping. The increasing value of the strongest echoes with aspect angle has several causes. One is that the number of candidate echoes increases with aspect angle (see (7) and (8)), and it is likely that the strongest echo strength of many echoes is bigger than the strongest among fewer echoes closer to the acoustic axis.

Also, positive errors in the detected phase angles of echoes lead to overcompensations of the beam damping, and this effect is stronger the steeper the beam function is, that is far out in the main lobe. Here, errors in detected phase angles are common. This is the same effect that is described in [4].

Lastly, in this paper, where beam compensation is computed from a beam model, the beam compensation will be wrong if the beam damping based on the model is different to that required for the actual beam. If the relation between the model and the actual beam function is as in Fig. (**1**), beam compensation far out in the main lobe is too strong. The author does not think that this effect is serious out to θ_{-20}, but beyond θ_{-20} it is serious, according to data in this study.

The author of this paper hoped to develop a beam independent estimator of the Echo Value Constant by (10). However, (10) seems to have on average too high positive bias, and (12) that often behave better, is in some cases too low. An unfortunate property with (12) is that it depends on the number of echoes received within about 60 % of the half power angle of the transducer. If this number happens to be too high or low, the corrections made further out in the main lobe will be wrong. The problem that estimator (12) depends on the parameter s_i associated with undetected echoes is judged to be a minor problem. It may produce some non-negligible bias in some situations with big variations in the sailing speed and/or systematic change in the ping-rate, but this happens seldom.

It may be possible to develop a more advanced estimator that depends on a better analysis of the number of echoes at different observation aspect angles. It is tempting to use the apparent true hypothesis that the correct single echo Target Strength and beam compensated integrated echo strength are independent of the observation aspect for small angles, that is within θ_{-20} for most transducers used in acoustic surveys. However, this is not easy to use when the purpose is to derive a "beam independent" estimator of the Echo Value Constant. A modified beam independent estimator should also preferably be based on the echo parameter values used to compute the estimator, and not use any general compensation. This is because there are many different situations that affect the number of echoes at different angles, such as depth or/and noise, mixture of different species including plankton, different fish densities, fish close to the bottom and so on. An improved estimator should be based on better knowledge about the different factors that affect the empirical distribution of observation aspect angles of single target echoes, and this will not be done here.

It may also be possible to develop a beam independent estimator of the Echo Value Constant based on model (1). Then (4) must be used to estimate both a and k by the method of least square. This has been looked into enough to conclude that it is mathematically and computationally possible, although it requires computed values of the derivative of the Bessel function, which is straightforward by using the power series of the derivative. This method has not been tried, because k is expected to be estimated with negative bias, i. e. giving a wider beam than the actual. The reason for this is the positively biased fish back scattering strengths out in the main lobe. The author believes that it is difficult to compensate for this, because weighting down echoes out in the beam will at the same time reduce the information about k.

When using "in situ" - detected single fish echoes to convert "integrator values" to fish densities, there is always a problem with choosing a good single echo threshold. Most often the echo signal does contain echoes from other organisms than the target fish population, and these have to be filtered away. This problem is easy when the echo strengths from fish and the alien organisms do not overlap much. However, this happens seldom, and deciding a value for the single echo threshold is usually a compromise between accepting some alien echoes while rejecting some fish echoes. The threshold values used in this paper do not necessarily give the best estimates of the Echo Value Constants, but choosing the best threshold is not the topic of this paper.

The way of setting Integrator threshold in this paper is only applicable when the echo signal consists of mainly single target echoes. In particular, if the plankton echoes are heavily overlapping, it is not possible to filter them away by means of an Integrator threshold.

The average Target Strength values given in the tables show the effect of positive biased echo strengths of single echoes received at big observation angles in the main lobe. It shows that the weighted average are the smallest in almost all cases, and this is likely to be closest to the true value. However, the average Target Strength values indicate that the Target Strength bias is not dramatic within the beam angle at -10 dB transmit beam damping. There are two effects on the Target Strength values given here that should be mentioned. The first is that Target Strength is not accurately calibrated in this work, and the values may therefore have a small, constant bias. This will, however, not affect the relative variation with observation aspect. The other effect is caused by the difference between the beam model and the actual beam. Beam compensations are computed from the beam model, but the bias caused by this is believed to be small for observation aspects within -10 dB transmit beam damping.

CONCLUSION

Two types of estimators of the mean Echo Value Constant are adjusted to reduce the influence of echoes from the outer main lobe. They are tried and compared with real acoustic data. Detected single target echoes are subject to an increasing average positive bias of echo strengths with increasing observation angle.

One new estimator type, see (2), seems to be better than the old that seemed to have a moderate positive bias. This are estimator types that require a model of the beam dependent average integrated echo strength of fish as a function of observation angle.

The other type of estimators, see (6), is independent of a model of the beam dependent integrated echo strength, but requires a representative sample of single target fish echoes within the observation angle where the transmit beam has dropped -10 dB in beam intensity. In general, it is not possible to collect a representative sample of single target echoes within this angle interval, since many echoes from far out in the main lobe fails to be detected. Two different adjusted estimators, see (10) and (12), of this type to compensate for the loss of many echoes in the outer part of the main lobe are compared with real acoustic data. One of them seems to have a positive bias, although moderate in many cases. But this estimator don't compensate for the positive bias of detected echo strength. The other estimator was often better, but seemed to be unstable with negative bias in special cases. The acoustic data used represented many recordings with different depth distributions and fish densities.

Although the used single target echo detection routine integrates the detected echoes, it also detects the peak values of these echoes. Different average beam compensated peak values from within -10 dB transmit beam damping are computed and converted to "*in situ*" Target Strength. It is demonstrated that weighted averages with low weigh of echoes received from the outer main lobe give lower mean Target Strength than that of an ordinary average of echoes. This holds in all except one case with high fish density. The difference was not dramatic, and was in most cases less than 1 dB.

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