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ICES ASC 2004 Theme Session R: New developments in fisheries acoustics. Paper R36

Recommendations for the collection of multi-frequency acoustic data

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Korneliussen, R.J., Diner, N., Ona, E. and Fernandes, P.G. (2004). Recommendations for the collection of multi-frequency acoustic data. *ICES CM2004/**R**:36*, 15 pp.

Traditionally, collection of acoustic data has been optimised for a single frequency, while requirements for the optimal combination of multifrequency data has been given less attention. Even though data manipulation can enable single-frequency data to be combined to some extent, optimal multifrequency comparisons cannot be made from a system if the input data are not collected properly. Multiple single-frequency [s(f)] data may be collected in various ways onboard research and fishing vessels. For detailed analysis, the physical and spatial characteristics of acoustic data should be as similar as possible. While direct comparability is impossible in all aspects, ideal data is defined as a reference point for the collection and analysis of multiple s(f) data. Acoustic data from several single frequencies are defined as ideal in this context if they can be used to generate combined frequency [c(f)] data at the same resolution as the original. This requires comparable physical measurements, carried out simultaneously from identical volumes, limited only by the effective range of the higher frequencies. Requirements necessary for recording ideal multi-frequency acoustic data are presented. Consequences of combining acoustic data originating from beams of different widths and separation distances are also analysed and illustrated.

Keywords: multi-frequency acoustics, species identification, data collection.

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Introduction

Multi-frequency data have been used since the late 1970's to identify and quantify the scattering from zooplankton (Holliday 1977), micronekton (Madureira *et al.* 1993) and, more recently, fish (Kang *et al.* 2002). Korneliussen and Ona (2002) drew attention to the data collection process, as, in many cases, acoustic survey data is collected in a manner that is optimised for a single frequency, whilst the requirements of acoustic data for a combination of frequencies has been given less attention. Even though data manipulation and processing can enable single-frequency data to be combined, optimal output data cannot be achieved from a system if the input data are not collected properly.

Multiple single-frequency [s(f)] data may be collected in various ways onboard research and fishing vessels. For detailed analysis, the physical and spatial characteristics of acoustic data should be as similar as possible. While direct comparability is impossible in all aspects, ideal data is defined as a reference point for the collection and analysis of multiple frequency s(f) data. Acoustic data from several single frequencies are defined as ideal in this context if they can be used to generate combined frequency [c(f)] data at the same resolution as the original. This requires comparable physical measurements, carried out simultaneously from identical volumes, limited only by the effective range of the higher frequencies. In this paper the requirements necessary for recording ideally multi-frequency acoustic data are presented.

A contradiction in the collection of multi-frequency acoustic data for combination at high spatial resolution is that acoustic scattering have a stochastic nature, and thus, there is a need to average many acoustic measurements. Smoothing data can achieve this, but the smoothing will in turn reduce the spatial resolution of the acoustic measurements. Some of the natural stochastic variation is reduced by the use of echo sounders capable of rapid sampling, but still there may be some stochastic variations due to e.g., radiation-patterns, tilting and distribution of the scatterers in the measurement volume. Since it is not clear how much smoothing is needed to remove the stochastic variation of the measurements, it is reasonable to collect the acoustic data to obtain as high a resolution as possible for the combined-frequency data in mind.

Multi-frequency data collection

Korneliussen (2002) proposed the following requirements as necessary for ideal multi-frequency data.

A) Requirements to make data physically comparable:

1. Echo sounder systems should be operated such that linear wave equations apply;
2. All echo sounder and transducer systems must be calibrated;
3. Insignificant noise:
   - 3.1. Measurements should not be biased by noise, and;
   - 3.2. Noise should not reduce the sampling volume (see point 7);
4. Insignificant interference between frequencies.

B) Requirements to make data spatially comparable:

5. Identical pulse lengths and pulse shapes at all frequencies;
6. Individual pings identifiable in the data files at all times;
7. Similar acoustic sampling volumes at all frequencies for comparable ranges to the scatterers, i.e., targets of interest should be acoustically visible in all parts of the sampled volume for the ranges used (Foote, 1991). Providing there is insignificant noise, this implies:
   - 7.1. Similar half-power beam widths, and;
   - 7.2. All transducers should have the same centre (including identical transducer depth) and same acoustic axis for the transducers.
8. Simultaneous transmission of pulses
9. Correct setting of measured sound speed and absorption coefficient

Several of the items in the ideal specifications are in practice not achievable using current systems. When working with hull-mounted transducers on research or fishing vessels, it is particularly difficult to obtain spatially comparable data. Different transducers are often mounted separately on the hull and may be several metres apart, so that the ideal case of co-locating all transducers at the same point is far from being fulfilled. Transducer size, beam width and selectable pulse length are generally optimised for target detection at each frequency, rather than for a combined analysis.

Each of these items is examined in detail below. Following this, an examination is made of the errors in echogram processing when Requirement 7 is compromised: i.e. data are collected from transducers that are spaced apart, or from transducers with different beamwidths.

A. Requirements to make data for physically comparable

1. Echo sounder systems should be operated such that linear wave equations apply

Most theory within fisheries is based on linear wave equations. Although backscatter due to sound generated from non-linear interactions in the water column can be useful, non-linear systems are difficult to calibrate, and are currently not sufficiently developed to be used within multi-frequency analyses. Non-linear interactions are always persistent, but are reduced compared to linear sound if the acoustic power output from the transducers is reduced. The compromise is, therefore, to use as much power as possible when the non-linearly generated sound is negligible compared to linearly generated sound. Measurements at 38 kHz indicate that 15 kWm^{-2}, or less output power is sufficient. For 60 % transducer efficiency, this gives 25 kWm^{-2} or less input power. In the examples given in Table 1, most transducers weight the power across the transducer-face to

Table 1. Recommended maximum input power for common sizes of Simrad transducers

Frequency [kHz]	**18**	**38**	**70**	**70**	**120**	**200**	**400**
Approx. transducer area [10^{-3} m^2]	200	100	30	12	10	4.4	1.1
Approximate 3 dB beamwidth	11	7	7	11	7	7	7
Recommended max input power for 60% electro-acoustic efficiency	5000	2500	750	300	250	110	28

reduce side-lobe levels, i.e. the power enforced on the outer elements is lower than at the central elements.

2. All echo sounder and transducer systems must be calibrated

Foote (1982, 1989) and Foote *et al.* (1987) described the accepted method for the calibration of echosounders. The total error in the calibration method should be no more than 4% (see Appendix A and e.g. Havforskningsinstituttet, 1994) provided there are no non-linear interactions in the water (and, of course, not in the transducer neither). The components of the calibration errors are the equivalent beam angle (Ψ, 1.6%), Time Varied Gain (TVG, 1.1%), target range (2.1%), target accuracy (2.2%) (i.e. accuracy of calibration sphere). Note that the total 4% is the uncertainty of the method itself so that absolute calibration accuracy better than this can never be achieved. During calibration exercises in the sheltered waters of Norway it is realistic to achieve a total uncertainty of the calibration close to 4%: this may not be the case in many other places. At a workshop on hydroacoustic instrumentation (ICES 1994) it was noted that a change in 0.5 dB (6%) in the calibration should prompt some form of action.

The echosounder and transducers should be used in other seawaters far from the location of calibration. Furthermore, the calibration of an echo sounder system is in principle valid only when the transducer is used at the same depth as during the calibration exercise: this condition is largely met for transducers on fixed platforms. An echosounder connected to a transducer used at varying depths (e.g., a transducer mounted on a drop-rig or on a towed vehicle) should take the transducer depth into consideration when the scatter is calculated. Note that the pulse-transmission delay discussed below should be accounted for, both to get the correct distance to the calibration sphere, and to get the correct TVG. Irrespective of this, the calibration sphere should be at a depth as large as practically possible.

Ideally, therefore, protruding instrument-keel-mounted transducers (Ona and Traynor, 1990) should be calibrated at the depth where they are most likely to be used prior to each survey, and preferably also after a survey. Transducers mounted at a drop-rig or a towed vehicle should be pressure stabilised, but still need to be calibrated at several depths. The calibration spheres should be as large as practically possible to increase their target strength (TS) and weight (to reduce motion and interference from fish).

In the case of the Simrad EK500 echosounder, all ranges are calculated relative to the trigger pulse, i.e. the depths are not corrected for the total system delays neither in the echogram (Mean Volume Backscattering Strength) or the TS data (personal communication with Haakon Solli, Simrad). The recorded MVBS ranges should, therefore, be corrected with a total system delay (see point 8 below). The TS depth is more difficult to correct since the first signal detected defines the depth.

The Time Varied Gain (TVG) was originally calculated from the depth of the front of the pulse, and did not consider the total system delay. The TVG used now is 3 x sample interval + half pulse-length. In practice, this means that the TVG will be correct if a standard version of EK500 is used with a “wide” bandwidth (due to the 3 x sample interval), but wrong otherwise. As an example, 38kHz/WIDE will estimate the total system delay to 3 x 10 = 30 cm, which is close to the measured 30 cm and calculated 29 cm. Special versions of programmable read only memory (PROM) available for the EK500 use 2 cm sample intervals and will therefore not compensate enough. This is, however, a minor problem at large distances.

In the case of the new Simrad EK60, the “centre of gravity” is calculated for each pulse, and the start of the pulse is a half pulse-length before this. The TVG is calculated for each sample before it is eventually used in any calculations. Since the pulse-transmission delay is unknown, this delay cannot be taken into account for neither the TVG or for the depth.

3. Insignificant noise

When the acoustic data are corrected for noise, and the noise is uncorrelated with the requested signal, the maximum range of the acoustic data is limited by the sampling volume. A proper definition of noise is needed before developing a model to remove it. In general, noise is all unwanted signals including transmitted sound backscattered from wind-generated bubbles. It is, however, difficult to separate free bubbles from swim bladders in small fish or bubbles generated for buoyancy by some types of plankton.

The definition of noise according to Korneliussen (2000) is: If the wanted signal is defined as all transmitted sound backscattered onto the transducer surface then noise is everything else.

Sound generated by ships, animals, collapsing bubbles, wind or sea are defined to be noise in this case, as is instrument noise not associated with the transmission of sound. With this definition, backscattered sound caused by unwanted electrical signals in the transmit part of the echosounder is not regarded as noise, and neither is sound backscattered from bubbles.

The acoustic sampling volume is the volume where all the targets of interest (at all orientations) are acoustically visible in all parts of the sampled volume for the ranges used: it is species and density dependent. Foote (1991) described the statistical properties of the sampling volume.

3.1 Measurements should not be biased by noise

To be able to quantify and remove noise, the noise and wanted signal should be uncorrelated. Noise can be quantified and removed from the measured signal using the methods described by Korneliussen (2000) or by Nunnallee (1987) provided that the echosounder does not truncate measurements below a threshold, and that noise is not removed automatically by an internal algorithm. In the case of the Simrad EK500 the “Noise margin” should be set to 0 dB.

In the absence of passive acoustic data, data needed to quantify noise may be picked according to a scheme suggested by Korneliussen (2004). Although backscatter from bubbles is not noise according to the definition above, it is undoubtedly unwanted backscatter within fisheries acoustics. It is, therefore, recommended that acoustic transducers should be mounted on the bottom of a protruding instrument keel (Ona and Traynor, 1990) such that they can be lowered below the bubble layer to reduce unwanted backscatter from bubbles.

3.2 Noise should not reduce the acoustic sampling volume

This requirement is to ensure that noise does not influence the spatial comparability of the acoustic data. In general, the valid distance from the transducer should be reduced rather than trying to correct data for being collected from a reduced sampling volume. (See also Point 6 below) The TVG function compensates the acoustic measurements for range, and the calculations are based on a detection-area A at range R. If noise exceeds the detection threshold, the area where the echo sounder can detect targets is less than A so that the sampling volume is being reduced. The data should therefore not be used beyond a range R where noise starts limiting the sampling volume.

4 Insignificant interference between frequencies

If the echosounder system at any frequency is interfered with by a system operating at one of the other frequencies, the signal and noise are correlated, such that the known algorithms to remove noise cannot be used. The interference can be checked, but ultimately, a solution must be provided by the echosounder manufacturers. A narrow bandwidth in the system will reduce this problem, but increase other problems connected to the pulse envelope and total system delay. Measurements to date indicate that interference between echo sounder systems is a minor problem, at least in the measurements of backscatter. However, strong targets may be visible at a frequency, e.g. 18 kHz, for a system running in passive mode if there is an active system running at a frequency close by, e.g., 38 kHz.

The choice of frequencies should, therefore, be sufficiently different so as to avoid mutual interference. Furthermore, care must be taken to avoid choices which are harmonics of one another (e.g., 200 and 400 kHz) due to non-linear generation of sound. Frequencies of odd multiples (3, 5, 7, …) should also be avoided due

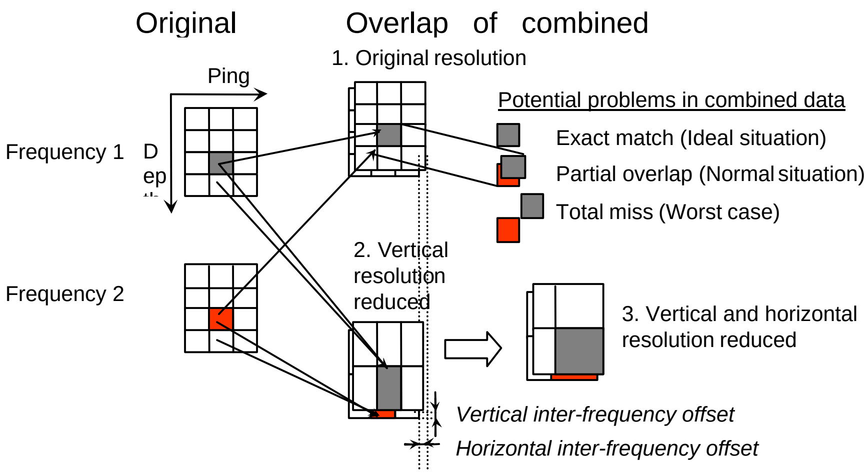

Figure 1. Illustration of some of the spatial problems for the generation of high-resolution combined frequency echograms from data at two arbitrary acoustic frequencies, frequency 1 and frequency 2. Partial overlap, or at best horizontal offset, is the normal situation. The effect of horizontal offset decreases with increasing depth, while the effect of vertical offset remains. Reduction of the vertical resolution may reduce the problem of vertical offset.

to linear generation of sound. The frequency sequence (in kHz) 18; 38; 70; 200; 333; 555; 926; 1543; 2572, … is one of many possible options.

B. Requirements to make data spatially comparable

Figure 1 illustrates the problem associated with horizontal, vertical, and the resulting spatial overlap. Considering a cone as a simplified beam, two such beams of equal beamwidth θ irradiate two partly overlapping discs of equal size. At a range R from the transducers, the percentage mutual horizontal overlap (PHO) of two beams with beamwidth θ is:

$$PHO = \left(\frac{2a}{p} - \frac{d \cdot \sin(a)}{Rp \cdot \tan(\frac{q}{2})} \right) \times 100 \qquad (1)$$

where:

$$a = \cos^{-1}\left(\frac{d}{2R \cdot \tan(\frac{q}{2})} \right)$$

d[m] is the separation distance between the transducer centres;

θ[rad] is the 3 dB beamwidth of the beams;

R[m] is the distance from the transducer face.

Figure 2 shows PHO as function of R for beams of 7° beamwidth. Note that PHO is not a measure of horizontal overlap between beams of different beamwidths since it is obviously meaningless to calculate mutual overlap for beams of different beamwidth. Only 56.6% of the backscatter that is measured within 11° is (on average) also within 7° of the same beam generated from a transducer radiating as a perfect circular piston, (at all ranges). This is calculated from the two-way Bessel directivity functions of intensity times ensonified area. For real beams, the level of the sidelobes is less than the Bessel directivity, so 60% within 7° may be a better estimate for real beams than 56.6%.

The percentage vertical overlap (PVO) for pulses of equal length and shape between data

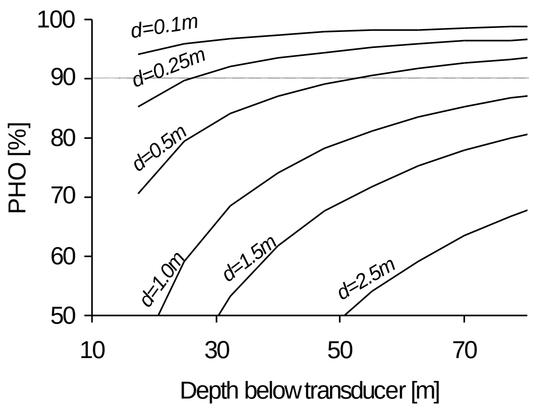

Figure 2. Percentage horizontal overlap, pho, of two beams with similar 3dB opening angles plotted as function depth R below the transducer for several distances, d, between two transducer centres.

collected at two acoustic frequencies (with similar beam-width) is defined as:

$$PVO = 100[1-\text{abs}(\Delta v1-\Delta v2)/\Delta z] \quad (2)$$

where:

$\Delta v1$ and $\Delta v2$ are the vertical offset distances due to the total system delays;

Δz is the vertical resolution.

PVO is increased if either ($\Delta v1-\Delta v2$) is decreased, or if the vertical resolution is decreased by increasing ?z. PVO can be improved if data are collected at a high enough resolution provided the 3 dB beamwidths are the same. Echosounder pulse envelopes differ from an ideal square pulse, especially for narrow bandwidth and wider beams at low frequencies (e.g., 18 kHz). This makes the result of vertical shifting of data at 18 kHz more uncertain. The correlation of vertically shifted data at 18 kHz relative to any of the other frequencies does not provide a significant improvement at tested sample data.

The percentage spatial overlap (PSO) between the beams at different frequencies is defined as:

$$PSO = 100(PVO/100)(PHO/100) \quad (3)$$

There is no strict requirement with respect to overlap needed to defend the generation of c(f) echograms, but a PSO ≥ 85 % seems reasonable. In the case of the 38 and 120 kHz transducers on the FRV “G.O. Sars” (2), where the transducers are the minimum distance of 39.5 cm apart, a PSO of 85% is achieved at 28 m. For methods involving division or multiplication of data at two frequencies, PSO = 85 % gives an uncertainty of about 15% in the result, in addition to the measurement uncertainty. PSO can never be better than PHO.

Further considerations of non-ideal situations, were data do not overlap due either to transducer spacing or different beam widths, are considered later.

5. Identical pulse lengths and pulse shapes at all frequencies

The nominal pulse lengths become equal when the pulse durations are equal at all frequencies. Equal nominal pulse durations at all frequencies are, therefore, a necessary requirement. The requirement of equal pulse shapes also requires equal bandwidth in the system, which is more difficult to achieve. Further, equal bandwidth in the systems, that contain both the echo sounder and the transducer, implies that there are no frequency differences in the total system delays.

A pulse duration of 1.0 ms is sufficient for the pulse envelope to raise to a stable level in 18 kHz echosounder systems with common bandwidths. This pulse duration should, therefore, be used across all frequencies; shorter pulse-durations would be sufficient if 18 kHz data is not used. Older equipment may require manufacturer modifications: in the case of the Simrad EK500, the same PROM that delivers 2 cm samples across all frequencies can be configured to deliver 1.0 ms pulse lengths. If the special EK500 PROM is not available, a short pulse length should be used for 12 – 27 kHz, medium for 38-70 kHz, and long for 120 kHz and above. In the case of the new Simrad EK60, it is possible to set the pulse length to 1.0 ms for all frequencies. In terms of bandwidth, for the Simrad EK500, it is recommended to use wide bandwidth, i.e. 10% of centre frequency, for 70 kHz and below, and narrow bandwidth, i.e. 1% of centre frequency, for 120 kHz and above. The bandwidths for EK60 are calculated by the system. When using 1 ms CW pulses, these are: 1.6kHz at 18kHz, 2.4kHz at 38kHz, 2.9kHz at 70kHz, 3.0kHz at 120kHz, 3.0 at 200kHz and 3.1kHz at 364kHz.

6. Individual pings identifiable in the data files at all times

This requirement ensures that simultaneous pings of different frequencies can be compared. It is insufficient to count pings in a data-file, since occasionally pings are lost, and the ping-rate may be different when several echo sounders are used simultaneously. Time should be registered when the echo sounder is triggered to transmit, and should be stored with a resolution high enough to avoid two pings at the same frequency being registered at the same time. A time resolution of 0.01 s is sufficient, but a resolution of 1.0 s is not.

7. Similar acoustic sampling volumes at all frequencies for comparable ranges to the scatterers

Targets of interest should be acoustically visible in all parts of the sampled volume for the ranges used (Foote, 1991). Providing there is insignificant noise, this implies similar half-power beam widths and that all transducers should have the same centre (including identical transducer depth) and same acoustic axis for the transducers.

This point is to achieve maximum horizontal overlap between the beams, which is generally not possible to achieve. At best, transducers with similar beam widths should be mounted at the same depth and with the same acoustic axis orientation. The smallest transducers should be placed in the middle in order to reduce the average distance between them. Standardisation the 3 dB beam widths to beamwidths of approximately 7° are a reasonable compromise between long range and wide beamwidth to cover a large volume. For commercial low-frequency transducers, for example, 18 kHz, generated beams of 11° may be smallest achievable (and hence closest to 7°). The transducer faces should be adjusted to give the same orientation of the acoustic axis of all transducers if this cannot be done electronically: the acoustic axis is expected to be very close to a vertical straight line.

Horizontal offsets are due to the distance between the transducers. The effect of the horizontal offsets is reduced with increasing range from the transducers because of the conical shape of the beams. Thus, the percentage horizontal overlap [PHO] increases with depth.

8 Simultaneous transmission of pulses

For equal bandwidth in the systems, there will be no differences in the total system delays (see point 5). However, in practice, the systems at different frequencies will have different bandwidths, and thus, also different total system delays, which have to be compensated for in some way. Total system filtering causes vertical offsets. Increasing the difference in total system delay increases the PVO while a reduction in vertical resolution reduces PVO. If the data-samples are collected with a sufficiently high vertical resolution and the vertical shift is known, the samples can simply be shifted vertically. If the data is not collected with a high enough resolution, the effect could be reduced somewhat by smoothing the data with weights shifted vertically.

Calculation of the delays referred to the echosounder internal trigger pulse is straightforward. It is not recommended to compensate for the total system delay until theoretical delay is verified by measurements. Simrad calculated theoretical expressions for the total system delays in the Simrad EK60, but these did not give the same results as preliminary measurements. It is therefore still not recommended to compensate for the total system delay of EK60.

Ona *et al.* (1996) measured the delays with a standard version of the Simrad EK500 software. Measurements and calculations were consistent, and indicated that:

- Total system delay in seconds for wide bandwidth (10% of the centre frequency): f[Hz] = 14.8/f
- Total system delay in seconds, narrow bandwidth (1% of the centre frequency): f[Hz] = 44.6/f

The vertical shift for wide bandwidth is then close to 1480(14.8/f)/2 [m] for EK500, which for 38 kHz is 29 cm. Depths associated with the measurements of MVBS in the Simrad EK500 are not corrected in the echosounder output data.

Synchronisation

Pulse transmission is properly synchronised within each Simrad EK500 echosounder, which can accommodate a maximum of three frequencies. When operating more than one EK500, the slowest of the utilised sounders, EK500a, should trigger the fastest, EK500b, or preferably, they should be connected to an external trigger unit. In the latter case, it may be difficult to use the common bottom depth dependent ping-rate.

Using an external time source as input to all EK500s will synchronise time, but if data is logged with time continuously synchronisation of time, some strange side effects may occur, e.g. wrong time or time-jump on one of the echo sounders. This effect is avoided by setting satellite-time once, and then switch back to the (now corrected) internal EK500 clock. This is done by setting the parameter “/UTILITY MENU/External Clock=Serial” to set time, and then “/UTILITY MENU/External Clock=Off”.

Pulse transmission is properly synchronised for all frequencies in the Simrad EK60.

9 Application of the correct sound speed and absorption coefficient

Sound speed and acoustic absorption can be calculated from formulae (e.g. Francois and Garrison, 1982). Both the sound speed and the absorption change with changing salinity, temperature and depth. The Conductivity Temperature Depth (CTD) probe should be employed in the survey area at the beginning of each survey to provide the necessary data. It is probably sufficient to use the same sound speed profile and the same frequency dependent absorption throughout all of the survey. It is probably also good enough to use the same sound speed throughout the water column. If a depth specific sound speed is used, the CTD profile used to calculate the sound speed profile should follow the acoustic data. The CTD profile used to calculate sound speed and absorption should, naturally, be taken in the survey area. It is, for example, poor practise to use the CTD profile taken at the calibration site to calculate sound speed and absorption in the survey area if the two areas are far apart or different hydrographically.

Compromised data

The ideal situation where two or more transducer axes overlap perfectly and/or have exactly same beamwidth is virtually impossible to fulfil. The remaining discussion centres on studies conducted to estimate the error in multifrequency analyses when the data has been compromised with regard to beam overlap: specifically, using data from two frequencies collected from transducers with axis spaced at some distance apart and with different beamwidths. All other requirements (identical pulse length and shape, simultaneous pulse transmission, etc.) are assumed to be fulfilled. Furthermore, what follows concerns only echo-traces obtained from large targets such as fish schools, not single echoes.

Two main analyses can be performed on shoals:

1. **Global MVBS.** In this case, the echogram from each frequency is processed separately and comparisons are made on descriptors of the echotraces at each frequency (e.g., average MVBS), extracted from each shoal. The instrumental error is estimated as the difference between MVBS values calculated for the echo-traces of the same shoal detected by two different beams of the same frequency.
2. **Ping to ping.** In this case, the data from two different channels are combined on a ping to ping basis to generate a new synthetic or virtual echogram. Echotrace descriptors are extracted from the virtual echograms. In this case, the instrumental error is equivalent to the mean difference in VBSs from the school between the two beams at the same frequency.

Potential instrumental errors are induced by athwartship or alongship distance between transducers and differences in beamwidth. The errors do not affect all types of multifrequency analyses:
- the "global MVBS" can be affected by the athwartship distance and the difference in beamwidth
- the precision of the "ping to ping" analysis depends furthermore on the alongship distance.

As the global process of school detection and generation of an echotrace is quite complex, instrument error was approximately estimated using simulations. Simulations were conducted on several schools of different dimensions and MVBS, at various depths, detected by three different nominal beamwidths: 7°, 11° and 16°. The images obtained were processed using different thresholds. This results in many permutations which are quite complex to analyse. This complexity can be reduced by normalising the results using the derived parameter Nbi: the dimension of the echo-trace relative to the beamwidth (Figure 3):

$$N_{bi} = \frac{L_i}{2D_i \tan(B_i / 2)} \qquad (4)$$

where:

$B_i = 0.44 \times q \times (dST)^{0.45}$

? = nominal transducer beamwidth (7° for example)

dST = difference between MVBS of the school echo-trace (S_{vi}) and threshold

L_i = length of shoal echo-trace

D_i = mean depth of shoal echo-trace

Note that the beamwidth is estimated using the detection angle, Bi, *not* the nominal angle of the transducer (Diner, 2001).

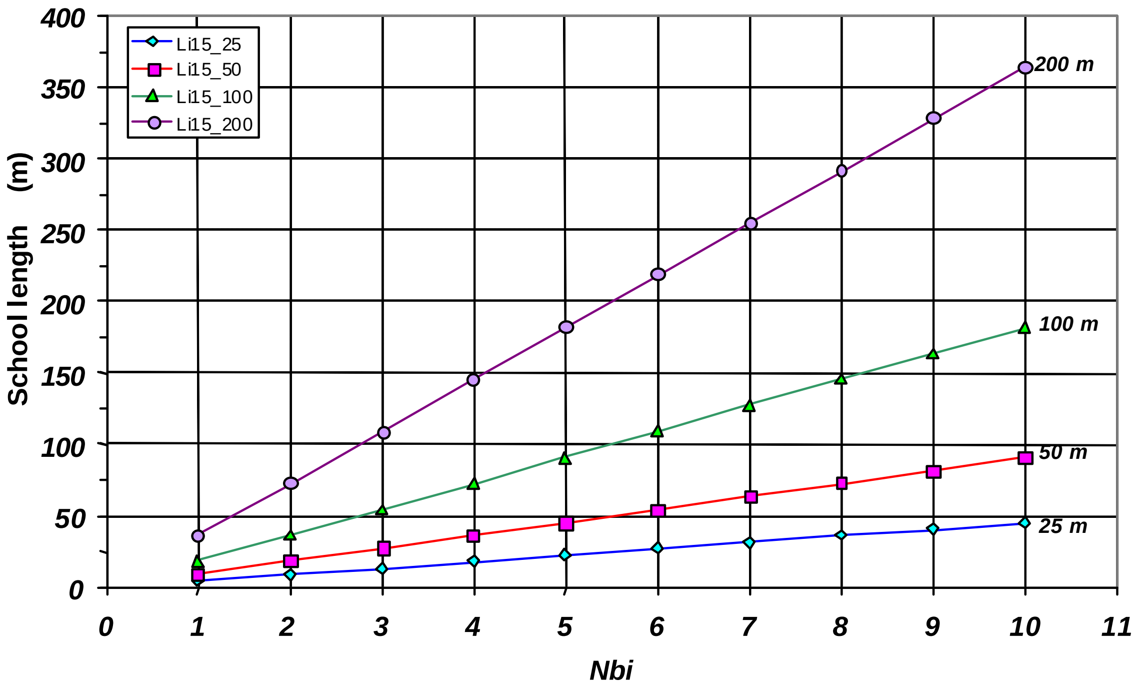

Figure 3. Shoal lengths as a function of N_{bi}, for different shoal depths and a fixed dST value of 15 dB.

Athwartship distance errors

An athwartship distance between transducers used in multifrequency analyses could have an effect on the results obtained as small schools could occupy the entire part of one beam and a smaller part of the other (Figure 4).

During the school detection process (with a single beam), the width of the detected schools is unknown. For convenience, therefore, it was assumed that school width and length were equivalent. The fact that only a part of the beam is occupied and that only the edge of the target is detected, causes cumulative attenuation effects resulting, for example, in a drastic reduction in the MVBS of the school detected through this beam.

The phenomenon is quite complex because the whole detection process of the school must be considered, i.e., all successive school echoes from the start of detection until the end, in addition to considering that the school is not on the beams central axis.

Simulations were carried out for 4 athwartship separation distances : 0.40, 0.70 m, 1.0 and 2.0 m. For an athwartship transducer distance of 0.40 m, instrumental errors remain low, mostly below 0.25 dB regardless of dST, school depth or relative size of the school. Therefore, this is an good figure to aim for when installing transducers.

Empirical relations were determined providing minimum Nbi values according to the instrument error (E, in dB, fixed by the operator), school depth Di, and dST factor. For an athwartship distance e_n (n in metres):

$$e_{0.70}:\ N_{bi} \geq \frac{20}{D_i} + \frac{8}{E^{0.05}} - 0.03dST - 6.8$$

$$e_{1.0}:\ N_{bi} \geq \frac{20}{D_i} + \frac{8}{E^{0.05}} - 0.03dST - 6.6$$

$$e_{2.0}:\ N_{bi} \geq \frac{20}{D_i^{0.8}} + \frac{8}{E^{0.05}} - 0.05dST - 6.3$$

These relations are approximations of the phenomenon and allow for a rapid selection of schools which can be processed with a potential instrumental error which may not disrupt further multifrequency analyses. Figure 5 gives a general representation of these limit Nbi values. At or shallow depths, such as 15 m, with a dST of 10 dB, the Nbi limit reaches high values, especially for large athwartship distances. Generally, the Nbi limit decreases when dST increases, i. e. when the processing threshold decreases.

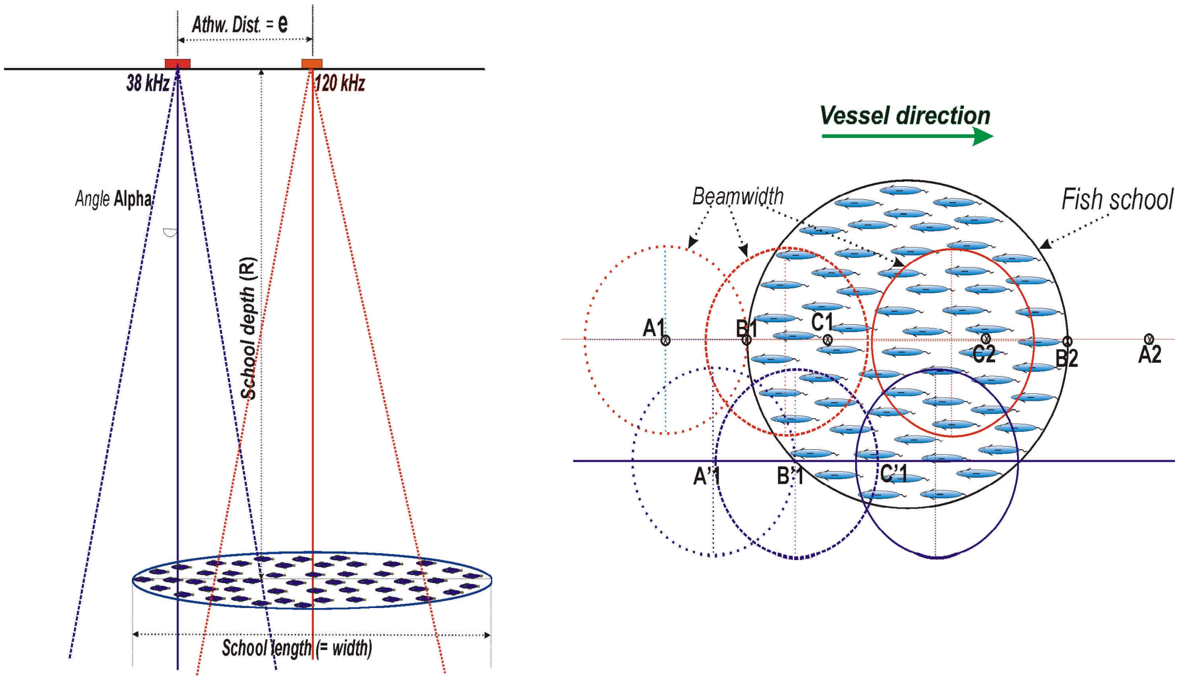

Figure 4. Schematic of the detection of a shoal by two different transducers spaced athwartship by a distance e, in the vertical (left) and horizontal planes (right). In the right hand panel, circles labelled “A” indicate when the beam is on the border of the school, and the school is not detected; “B” indicates cases where the centre of the beam is on the border of the school where the beam is partially occupied by the school; and “C” indicates cases where the school occupies the whole beam.

Alongship distance errors

When transducers are spaced apart longitudinally by several metres, instrumental errors are induced as one beam detects any school some pings before the other at the start of detection, and conversely, loses the school before the other, at the end of detection (Figure 6). If the transducers are not too far apart (< 6 m for example), the echo-traces of the same school, detected by the two beams are, in most cases, quite similar, and "global MVBS" is not subject to a large instrumental error. This is not the case for "ping to ping" analysis. During the phases of start or end of shoal detection, there is, from a ping till the other, a regular variation of the level of the received signal. This signal level, related to the proportion of the beamwidth occupied by the fish, increases until the beam is fully occupied. It then remains constant for some pings (the school kernel), and finally decreases as the proportion of the occupied beam lowers, until the end of shoal detection (Figure 7). If a comparison between frequencies is done, e.g., "$MVBS_{F1}$ - $MVBS_{F2}$", which is equivalent to the ratio of echo intensities "I_{F1}/I_{F2}", towards the end of detecting the school, the ratio would have high values as I_{F2} is lower than I_{F1} and conversely at the start of detection.

In order to determine the extent of this phenomenon, different school sizes, depths and MVBS were simulated. Errors due alongship separation distances of 0.5, 1.0, 1.5 and 2.0 m were calculated (with a ping interval of 0.5 m). For an alongship separation distance of 0.5 m and a dST value of 5 dB, the instrumental errors seem acceptable whatever school size and depth. For an alongship separation distance of 2.0 m with dST of 5 dB, the school depth must be over 25 m in order to reduce the instrumental error at an acceptable level (< 0.5 dB). With a dST of 10 dB, and worse 20 dB, the errors remain high whatever school size and depth.

One solution to this problem is to compensate for this alongship distance in term of ping numbers, i.e. to shift the frequency analysis by a number of pings equivalent to this distance.

Nevertheless, when vessel speed is high, 10 knots for example, and the ping rate low (1 ping per second), the distance between pings can be greater than the transducer alongship distance (about 5 m in the cited example). Therefore, the ping shift is unable to compensate for the separation distance. High ping rates and/or reduced vessel speed would give better results.

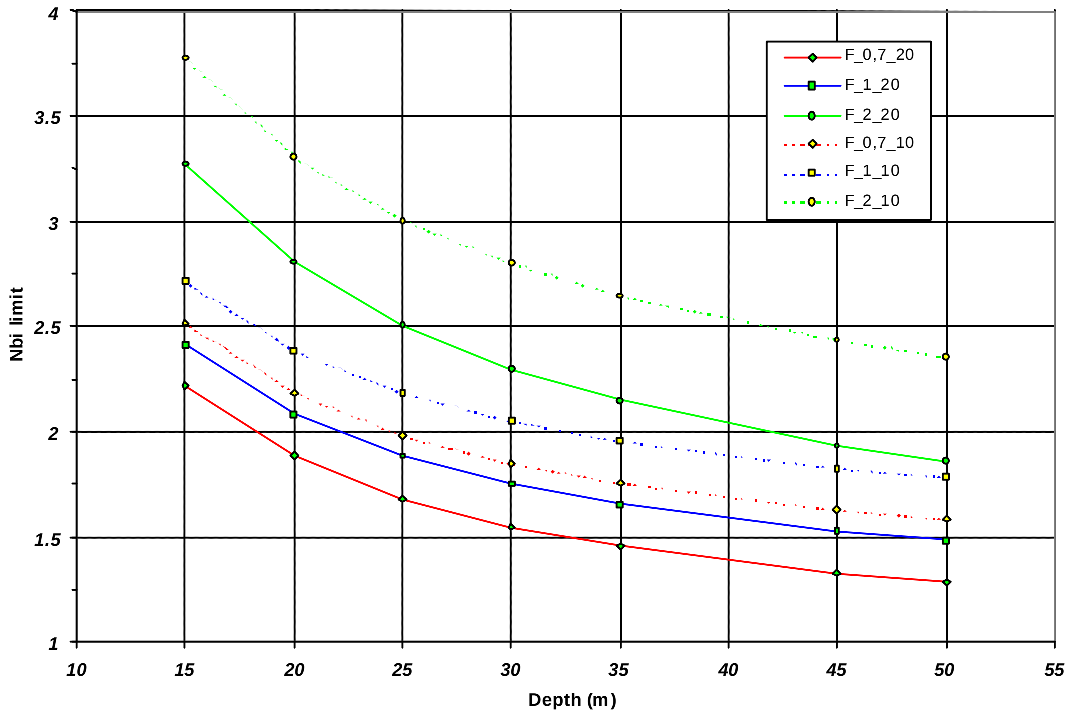

Figure 5. Nbi limit values, as a function of school depth, calculated by empirical relations, for an error of 0.5 dB, dST of 20 (continuous lines) or 10 dB (doted lines), and athwartship distances of 0.7 (red lines with diamonds), 1.0 (blue lines with squares) or 2.0 m (green lines with circles).

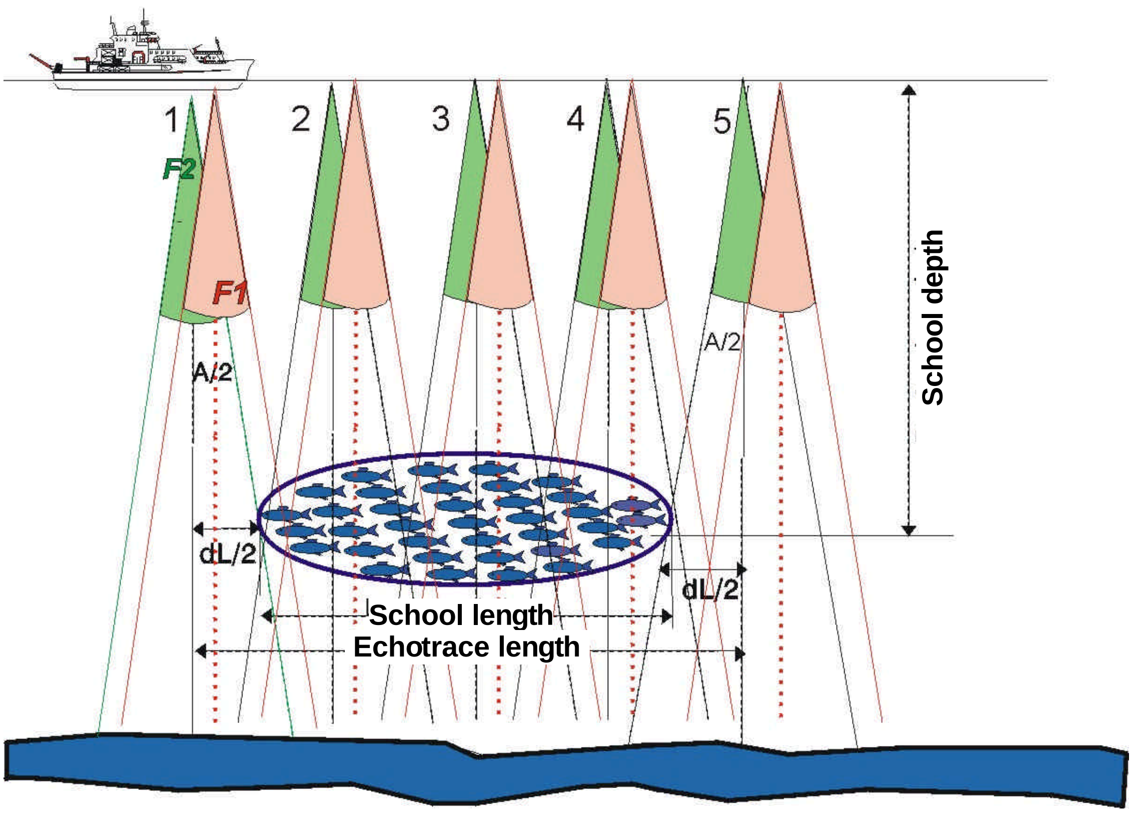

Figure 6. Detection of a school by 2 beams, F1 and F2, spaced a distance apart alongship, in 5 successive transmissions.

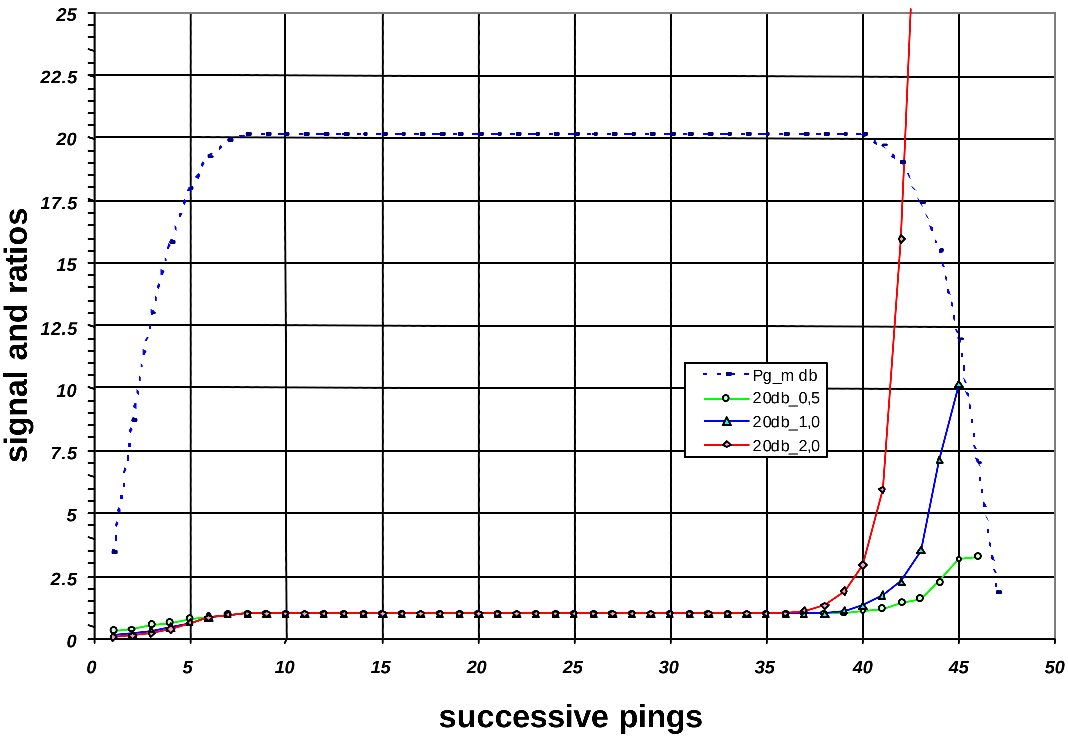

Figure 7. Successive ping amplitudes for the mean depth (dotted line) of a simulated shoal of 20 m long located at 25 m depth (simulated signal level in millivolts). Solid lines indicate the ratio of the latter to the school as detected by transducers separated by alongship distances of 0.5 m (green); 1.0 m (blue); and 2.0 m (red).

Beamwidth errors

The underestimation of the school MVBS is related to different parameters, but critically, to the relative shoal and beamwidth dimensions (Diner, 2001). Using different beamwidths causes underestimation in various parameters resulting in errors for multifrequency analysis in the "global MVBS" approach. Shifted detection due to different beamwidths generates problems analogous to alongship separation distance of transducers in the case of "ping to ping" analysis. In order to investigate this problem, simulations were carried out of school detection at different depths using 4 different beamwidths: 7°, 8°, 11° and 16°. In each case, the difference "X" was calculated as that between the echo-trace MVBS of the same school detected using two beam angles, ?1 and ?2: $X_{?1\_?2}$ = [$MVBS_{?1}$ - $MVBS_{?2}$].

When a school is detected by a vertical beam, its MVBS is systematically underestimated. This underestimate increases as the horizontal dimensions of the school become small relative to the beamwidth (i.e. low Nbi values). When a school is detected by two frequencies with same beamwidth, the two underestimates are similar and do not affect the result of the multifrequency analysis. In the case of two different beamwidths, the difference in the MVBS underestimate for the two directivities must be determined, this difference will be equivalent to the instrumental error in a multifrequency analysis ("global Sv").

An algorithm to determine correction in school descriptors (Diner, 2001) was used to investigate this. The underestimate in school MVBS in relation to Nbi is given by:

$$dSv = \frac{2.56}{N_{bi} - 1} \qquad (5)$$

The difference between errors in the index by the two frequencies is then:

$$\begin{aligned} X_{q1\_q2} &= dSv_{q1} - dSv_{q2} \\ &= 2.56\left[1/(N_{biq1} - 1) - 1/(N_{biq2} - 1)\right] \qquad (6) \end{aligned}$$

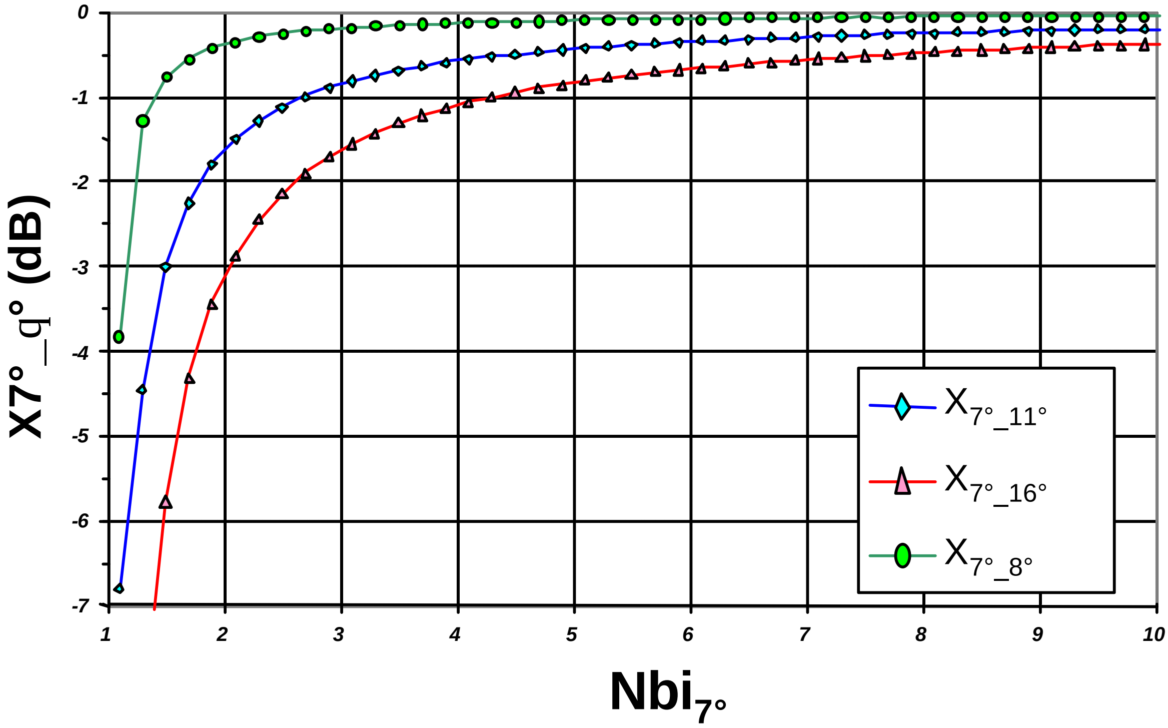

Figure 8. Potential errors, in relation to $Nbi_{7°}$, induced by using different nominal beamwidths: θ = 8° (green line, circles), 11° (blue line, diamonds) and 16 ° (red line, triangles); compared to 7°.

Practically, this coefficient "X", calculated from Nbi values obtained for the two beamwidths, allows to determine if the considered school conditions the maximum value fixed for the instrumental error induced by the beamwidth difference. By combining the results of simulation, the relationship between $Nbi_{7°}$ and other nominal beamwidths, i.e. $Nbi_{8°}$, $Nbi_{11°}$, and $Nbi_{16°}$. The X coefficient can then be expressed in relation to Nbi7° by adjusting the coefficients of Equation 6 as follows:

$$X_{7°\_8°} = 2.56\left[1/(N_{bi7°}-1) - 1/(0.87N_{bi7°}-0.87\right]$$

$$X_{7°\_11°} = 2.56\left[1/(N_{bi7°}-1) - 1/(0.59N_{bi7°}-0.57\right]$$

$$X_{7°\_16°} = 2.56\left[1/(N_{bi7°}-1) - 1/(0.46N_{bi7°}-0.41\right]$$

The potential errors for a range of Nbi values are given in Figure 8. General there are low errors for 7°/8°, in most cases lower than 0.5 dB. For 7°/11°, or worse 7°/16°, unless the schools are very large (Nbi7° > 7 or 10), large errors are obtained which hinders the comparison of data obtained with a 7° nominal beamwidth (e.g., 38, 120 or 200 kHz) and an 11° (18 kHz) or 16° (12 kHz) beamwidth.

A possible solution in such cases is to limit the analysis to data from shoal kernel, the portion of the detected school when the beams of the two frequencies are fully occupied by fish. Some pings at the start and end of school detection should, therefore, be removed from the analysis. This number (of pings) is calculated taking into account the larger beamwidth, but using the real detection angle, Bi:

$$B_i = 0.44 \times q \times (dST)^{0.45} \quad (7)$$

The relevant distance at the start and end of school detection, L_{pg} is:

$$L_{pg} = 2D_i \tan(B_i/2) \quad (8)$$

If the vessel speed is V_s (in m/s) and the ping rate P_g (in s), the total number of pings to be removed is then:

$$n_{pg} = \frac{2D_i \tan(B_i/2)}{V_s P_g} \quad (9)$$

E.g.:
? : 11°, dST : 20 dB => Bi : 18.6°,
D_i : 150 m, V_s : 10 knots, P_g : 0.5 s, n_{pg} : 19.1

? : 11°, dST : 20 dB => Bi : 18.6°,
D_i : 50 m, V_s : 5 knots, P_g : 0.5 s, n_{pg} : 12.8

? : 11°, dST : 10 dB => Bi : 11.6°,
D_i : 150 m, V_s : 8 knots, P_g : 0.75 s, n_{pg} : 11.6

Discussion

At this stage, more effort should be allocated to improving echo sounder systems and transducer platforms used for multi-frequency observations in terms of post-processing.

The minimum range for the described methods are limited by the requirement that PSO > 85 %, and the maximum range is limited by the effective range of the higher frequency (typically, 100 – 200 m for a 200 kHz system on weak targets from vessel mounted transducers). Most of the water column on the continental shelf may, therefore, be investigated at full survey speed. However, deeper fish and weaker targets (i.e. zooplankton) must either be investigated by a combination of lower frequencies, or from towed vehicles equipped with similar instrumentation. Calibration of multiple transducers over the pressure range then becomes a new challenge (Ona and Svellingen, 1999).

Acknowledgements

This document was made with support from the European Commission's Fifth Framework Programme (SIMFAMI project; Grant No. Q5RS-2001-02054). Thanks are due to Laurent Berger for comments on the manuscript.

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