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ABSORPTION TERM IN TIME-VARIED-GAIN FUNCTIONS

By

KENNETH G. FOOTE

Department of Applied Mathematics, University of Bergen.

ABSTRACT

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A potential source of error in acoustic measurements of fish density is the absorption part of time-varied-gain functions. This should be determined from the 1977 Fisher and Simmons equation. Use of its predecessor, the 1962 Schulkin and Marsh equation, is shown by comparison to introduce large errors in fish density estimates. Adjustment of the absorption term with changing hydrography is also necessary. This is supported by an analysis of errors due to deviations from an assumed reference temperature. The various computations are performed for six echo sounder frequencies used in fisheries surveying; namely, 30, 38, 49.5, 70, 105, and 120 kHz. A broad hydrographical range is considered.

INTRODUCTION

Absorption of sound in the sea remains an incompletely understood phenomenon despite more than thirty years of research (FISHER and SIMMONS 1977). At ultrasonic frequencies typical of fisheries echo sounders, however, the causative mechanisms of absorption are well known. These are, in order of increasing influence with frequency, boric acid relaxation, magnesium sulfate relaxation, and intrinsic absorption due to viscosity of the water molecule. The *a priori* or theoretical functional forms of the corresponding absorption terms agree with observation, which is used to determine the several multiplicative scaling factors.

An early exercise in parameter-fitting was conducted by SCHULKIN and MARSH (1962). They considered only the absorptions due to magnesium sulfate relaxation and pure water; that of boric acid relaxation not yet having been discovered. Schulkin and Marsh based their parameter determination, moreover, on data gathered from 2 to 25 kHz. The equation thus derived applied strictly to this frequency regime. Extrapolations to lower and higher frequencies were to have been regarded with suspicion. This was the case, at least, at the lower frequencies where an anomalous absorption was measured by THORP (1965). At the higher frequencies, however, there was a general lack of data. This apparently encouraged the use of the Schulkin and Marsh equation at such frequencies – for want of something better.

This situation has now been remedied by two developments: discovery of the low-frequency sound absorption mechanism (YEAGER *et al.* 1973) and measurement of absorption at frequencies above 25 kHz. These new data have consistently disagreed with extrapolations from the Schulkin and Marsh equation. FISHER and SIMMONS (1977) have collected the extended low and high frequency data and determined an equation based on three absorption mechanisms. Adoption of this new equation in fisheries acoustics, as for assigning the absorption part of time-varied-gain functions (FORBES and NAKKEN 1971), has been slow.

It is argued in this paper that differences in the equations of SCHULKIN and MARSH (1962) and FISHER and SIMMONS (1977) are sufficiently large at the typical echo sounder frequencies used in fisheries research that the newer equation should be adopted. The consequences of retaining the older equation, which are often an overweighting of fish density estimates, are shown through an error analysis at six discrete echo sounder frequencies from 30 to 120 kHz.

A further problem in the assignment of the absorption part of time-varied-gain functions is treated here. This is that of choosing the absorption for a fixed hydrography, i.e., for a constant temperature and salinity, and ignoring changes in absorption due to changing hydrography, which are common in virtually every fisheries research cruise. This inflexibility is evidently due in part to the application of time-varied gain by hardware. The current and growing use of computers in the real-time analysis of echo sounder signals obviates such application. If the time-varied gain, or at least the absorption part of it is computer-applied, then this can just as easily as not be adjusted to reflect the actual survey conditions. Correction of the coefficient could even be effected automatically at each hydrographic station where temperature and salinity measured by electronic salinity-temperature-depth or conductivity-temperature-depth sensors are generally logged directly in the computer (FOFONOFF *et al.* 1974, RODEN and IRISH 1975, SCARLET 1975). In any case, the consequence of ignoring changing hydrography is shown by an analysis of range-dependent errors in fish density estimates. These are computed for the same six echo sounder frequencies as in comparing the two absorption equations.

The various computations of paper are referred to a rather broad temperature range. This is meant to span the hydrographic conditions encountered by fisheries research vessels. These are as varied as those of deep Arctic waters and shallow tropical waters.

METHOD

The subjects of the present inquiry are two expressions for the absorption coefficient of sound in sea water. Each describes the coefficient as a function of frequency, temperature, salinity, and pressure. Both are stated here for completeness.

The older of the two expressions was determined by SCHULKIN and MARSH (1962) on the basis of data from 2 to 25 kHz and a model of absorption with two mechanisms: magnesium sulfate relaxation and pure water viscosity. It is the following:

$$\alpha'_{sm} = [ASf_T f^2/(f_T^2+f^2)+Bf^2/f_T]\ (1-6.54\cdot 10^{-4}P)\ \text{nepers/m} \quad , \qquad (1)$$

where

$$A = 2.34\cdot 10^{-9} \quad ,$$

$$f_T = 21.9\cdot 10^{[9-1520/(T+273)]}\ \text{Hz} \qquad ,$$

and

$$B = 3.38\cdot 10^{-9} \qquad ,$$

where f is the frequency in Hertz, T is the temperature in degrees centigrade, S is the salinity in parts per thousand, and P is the pressure in atmospheres.

The newer expression for the absorption coefficient contains an additional term due to boric acid relaxation. The expression, which was derived by FISHER and SIMMONS (1977), is essentially the following:

$$\alpha'_{FS} = A_1 f_1 f^2/(f_1^2+f^2) + A_2 P_2 f_2 f^2/(f_2^2+f^2) + A_3 P_3 f^2\ \text{nepers/m} \quad , \qquad (2)$$

where

$$A_1 = (1.03\cdot 10^{-8}+2.36\cdot 10^{-10}T-5.22\cdot 10^{-12}T^2)\ \text{sec/m}$$

$$f_1 = 1.32\cdot 10^3\ (T+273.1)\ \exp\,[-1700/(T+273.1)]\ \text{Hz} \qquad ,$$

$$A_2 = (5.62 \cdot 10^{-8} + 7.52 \cdot 10^{-10}T)S/35 \text{ sec/m} \quad ,$$

$$f_2 = 1.55 \cdot 10^7(T+273.1) \exp[-3052/(T+273.1)] \text{ Hz} \quad ,$$

$$P_2 = 1 - 1.03 \cdot 10^{-3}P + 3.7 \cdot 10^{-7}P^2 \quad ,$$

$$A_3 = (55.9 - 2.37T + 4.77 \cdot 10^{-2}T^2 - 3.48 \cdot 10^{-4}T^3) \cdot 10^{-15} \text{ sec}^2\text{/m} \quad ,$$

and

$$P_3 = 1 - 3.84 \cdot 10^{-4}P + 7.57 \cdot 10^{-8}P^2 \quad ,$$

where f, T, S, and P retain their meanings as in α'_{SM}. The single difference with the equation given in the reference is the inclusion here of a linear salinity dependence in A_2. This was recommended, however, although specified expressly for the case S=35 ppt.

For convenience below, both absorption coefficients are expressed in units of decibels per meter. The conversion is effected by multiplying the above coefficients by $20\log_{10}e = 8.686$, i.e.,

$$\alpha_{SM} = 8.686\ \alpha'_{SM} \text{ dB/m}$$

and

$$\alpha_{FS} = 8.686\ \alpha'_{FS} \text{ dB/m} \quad ,$$

where α_{SM} and α_{FS} are the common logarithmic measures of absorption.

Differences in α_{FS} and α_{SM} may be observed directly by comparing Eqs. 1 and 2 for the same hydrographic conditions. The significance of the differences to fish density estimation may be seen through an analysis of errors due to the use of the Schulkin and Marsh equation for the Fisher and Simmons equation. Since the α-term in the time-varied-gain function, when applied to the signal amplitude and expressed with respect to the range r, is

$$10^{\alpha r/10} \quad ,$$

where r is in metres, the effect on the estimate of fish density at the same range is

$$10^{2\alpha r/10} \quad .$$

This expresses the usual assumption that the estimated density is proportional to the echo energy or time-integral of signal intensity or squared signal amplitude (Forbes and Nakken 1972). Thus if α_{SM} is used where α_{FS} provides the correct number, the relative error in derived fish density estimate is

$$10^{2\Delta\alpha r/10} - 1 \quad ,$$

where $\Delta\alpha = \alpha_{SM} - \alpha_{FS}$. Positive errors denote over-estimation of density, while negative errors denote under-estimation.

No matter how the absorption coefficient is determined, if it is not referred to the actual hydrography of fish observation, the density estimate will in general be biased. The implication of this may be judged by an analysis of the above sort, but where the correct absorption coefficient α_{FS} is that which obtains for the actual conditions, while the applied coefficient assumes another, or reference, hydrographic state. If the two values of α_{FS} are denoted by α and α_0, respectively, then the effect on the fish density estimate is a range dependent error of the kind show above, but where $\Delta\alpha = \alpha_0 - \alpha$.

RESULTS

The two expressions for the absorption coefficient are developed pairwise in Figs. 1 and 2. The first shows the frequency dependence of each coefficient from 10 to 200 kHz for a range of temperatures for the salinity 35 ppt. Fig. 2 shows a similar frequency dependence for a range of salinities for the temperature 10°C.

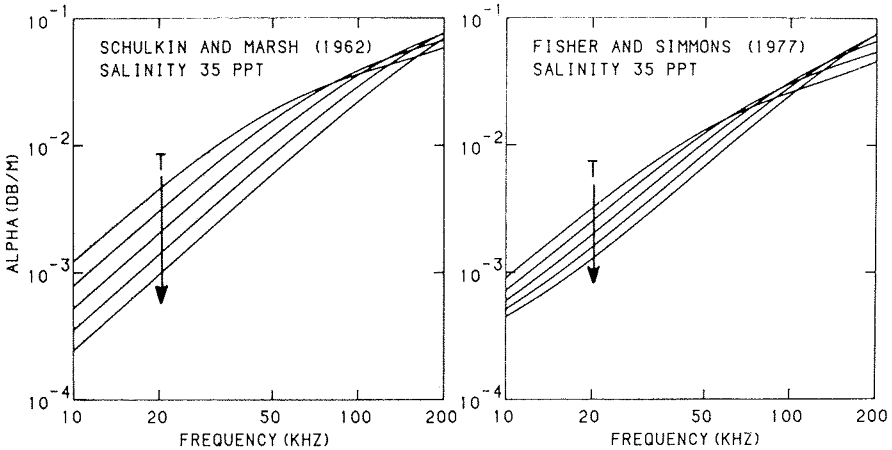

Fig. 1. Frequency dependence of two absorption coefficients for temperatures T = 0, 10, 20, 30, 40°C. Salinity = 35 ppt, pressure = 10 atm.

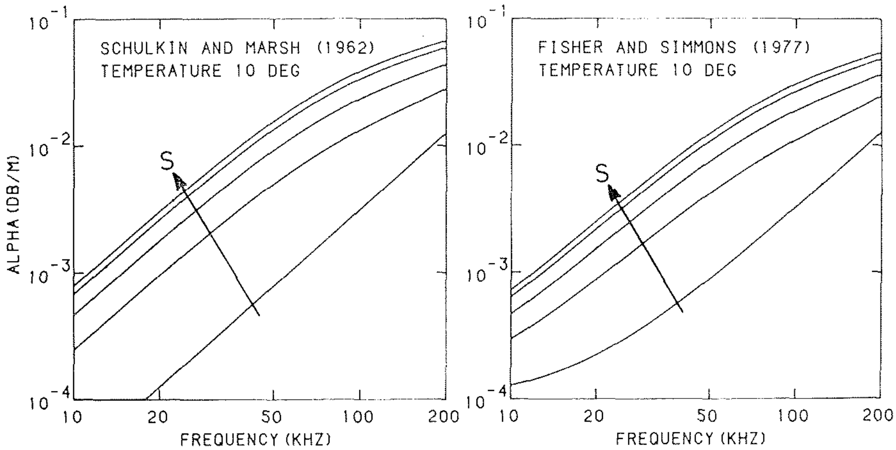

Fig. 2. Frequency dependence of two absorption coefficients for salinities S = 0, 10, 20, 30, 35 ppt. Temperature = 10°C, pressure = 10 atm.

Figs. 3 to 8 show the temperature dependence of the same coefficients for a range of salinities for each of six echo sounder frequencies. These correspond to the nominal operating frequencies of echo sounders of some prominence in the surveying of fish stocks.

Differences in the Schulkin and Marsh and Fisher and Simmons expressions are illustrated through an analysis of errors in fish density estimates in Fig. 9.

The consequence of not adjusting the absorption term in time-varied-gain functions to changing hydrographic conditions is examined in Figs. 10–16. In all of these figures the Fisher and Simmons expression is used to describe both the correct value and the erroneously applied values of the absorption coefficient. Each of Figs. 10–15 shows the effect of temperature deviations on the fish density error for four different reference temperatures for the same echo sounder frequency. Comparable results for the case of a 5°C reference temperature are plotted in Fig. 16 for each of the six frequencies.

DISCUSSION

Figs. 1 and 2 show the characteristic frequency dependences of the two absorption coefficients for a variety of temperatures and salinities. Differences in the coefficients for the same frequency and hydrographic state are discernible, although hardly striking because of the use of logarithmic scales. The relative temperature and salinity dependences for a fixed frequency are very similar. This is not surprising as boric acid relaxation is principally a low-frequency phenomenon, with only slight influence at

10 kHz and negligible influence for frequencies above 20 kHz in ordinary sea water (Fisher and Simmons 1977). For the special, essentially theoretical case of vanishing salinity, the boric acid relaxtion is seen to contribute significantly to the absorption term below about 40 kHz. Differences in the two expressions for absorption in sea water above 10 kHz are therefore due mainly to relative differences in the hydrographic dependences of the magnesium sulfate relaxation and pure water terms.

The temperature and salinity dependences of the two expressions are displayed in some detail for each of six echo sounder frequencies in Figs. 3–8. That there are large differences in the two coefficients is obvious. The differences are observed to be especially large for sea water of temperature less than about 15°C. This happens to describe the conditions common to many important commercial fish stocks (Harden Jones 1968) where acoustics are or might be used to assess abundance.

As noted above, the computations of Figs. 3–8 were performed for the operating frequencies of standard echo sounders used in fisheries surveying. Because the Schulkin and Marsh expression is still widely used, the pairs of figures may be used in conjunction to determine corrections for the exact hydrography of interest. For those instances in which the Fisher and Simmons expression is applied under assumption of a constant temperature and salinity, which are found to be different during observation, the same graph will specify the correction factor.

In these and all other computations of the paper the hydrostatic pressure is assumed to be a constant 10 atm. This incurs an entirely negligible error for all practical situations of fish stock surveying. At 1000 m depth, for instance, the absorption coefficient will be reduced from the values calculated here by a mere one per cent.

Differences in the two absorption coefficients for the same hydrographic conditions are quantified in more vivid fashion in Fig. 9. This illustrates the penalty to be paid for using the Schulkin and Marsh absorption in time-varied-gain functions. The errors are observed to bear an inverse relationship to water temperature: the largest errors are associated with the lowest temperatures, which agrees with expectations from Figs. 3–8. At the lowest frequencies the errors become threateningly large at 200 m depth; at frequencies above 50 kHz they are servere already at 100 m. In every considered case for temperatures less than or equal to 20°C, use of the Schulkin and Marsh equation results in an over-weighting of fish density, leading to corresponding over-estimation in abundance. The magnitude of expected errors at ordinary depths of fish detection ought to serve as a warning in the assignment of the absorption term. For the practical case of acoustically surveyed deep-lying fishes, such as blue whiting and a number of mesopelagic fishes, the magnitude of

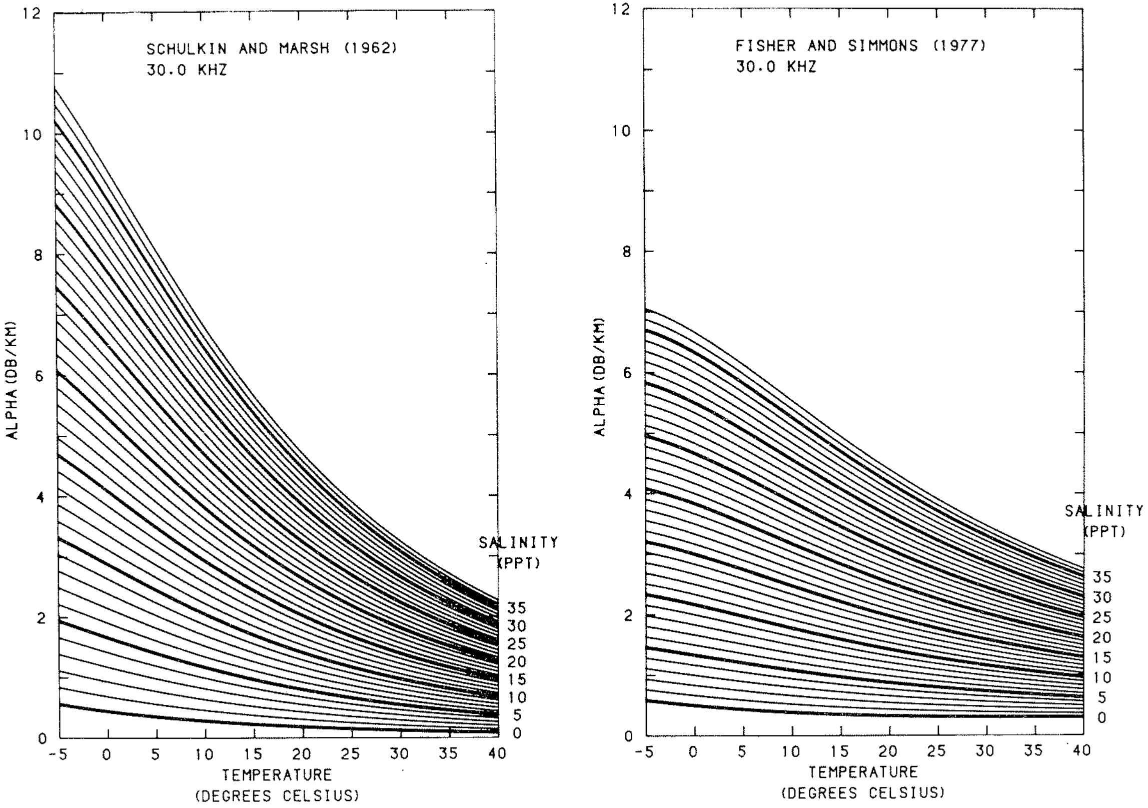

Fig. 3. Dependence of two absorption coefficients on temperature and salinity at 30 kHz. Pressure = 10 atm.

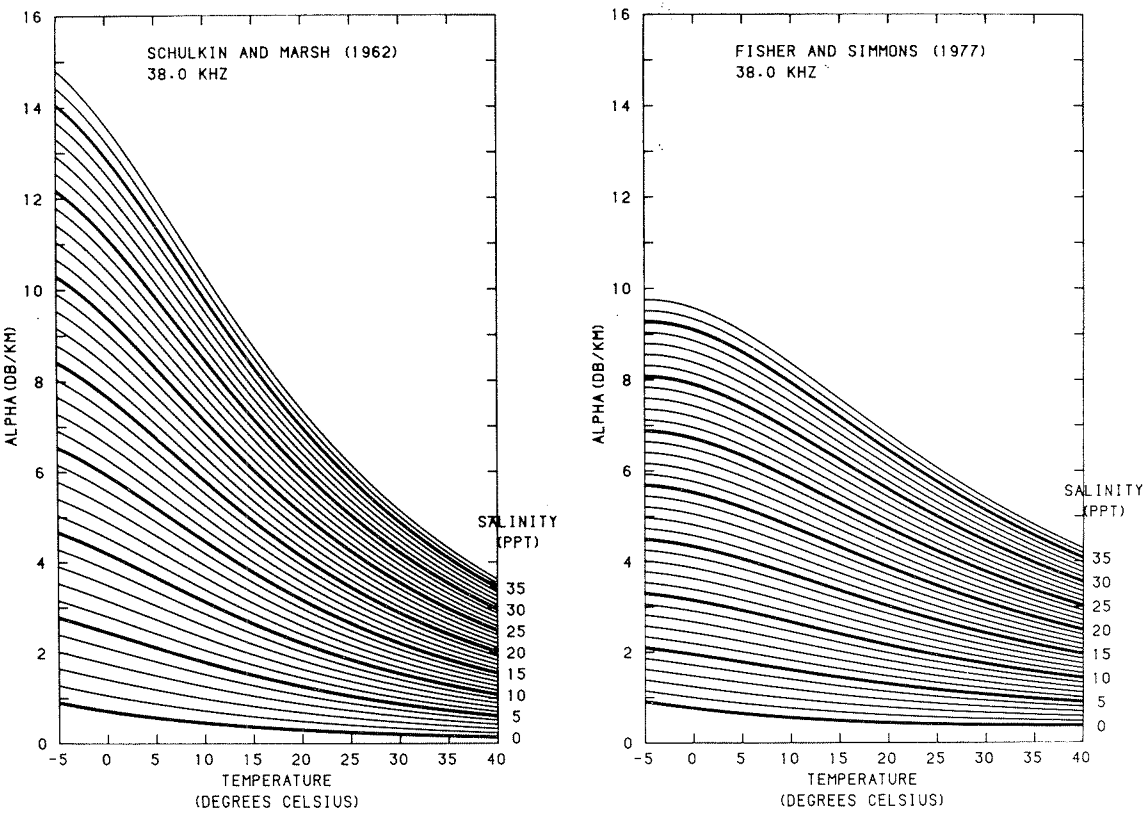

Fig. 4. Dependence of two absorption coefficients on temperature and salinity at 38 kHz. Pressure = 10 atm.

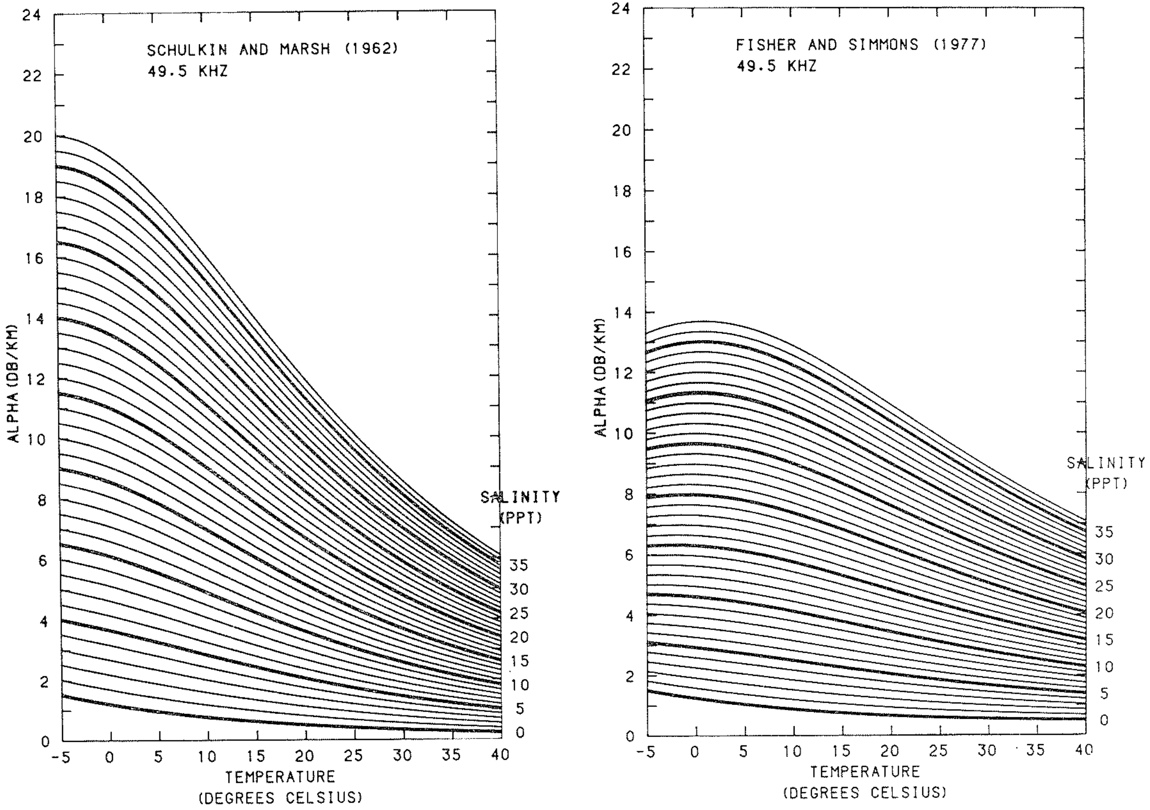

Fig. 5. Dependence of two absorption coefficients on temperature and salinity at 49.5 kHz. Pressure = 10 atm.

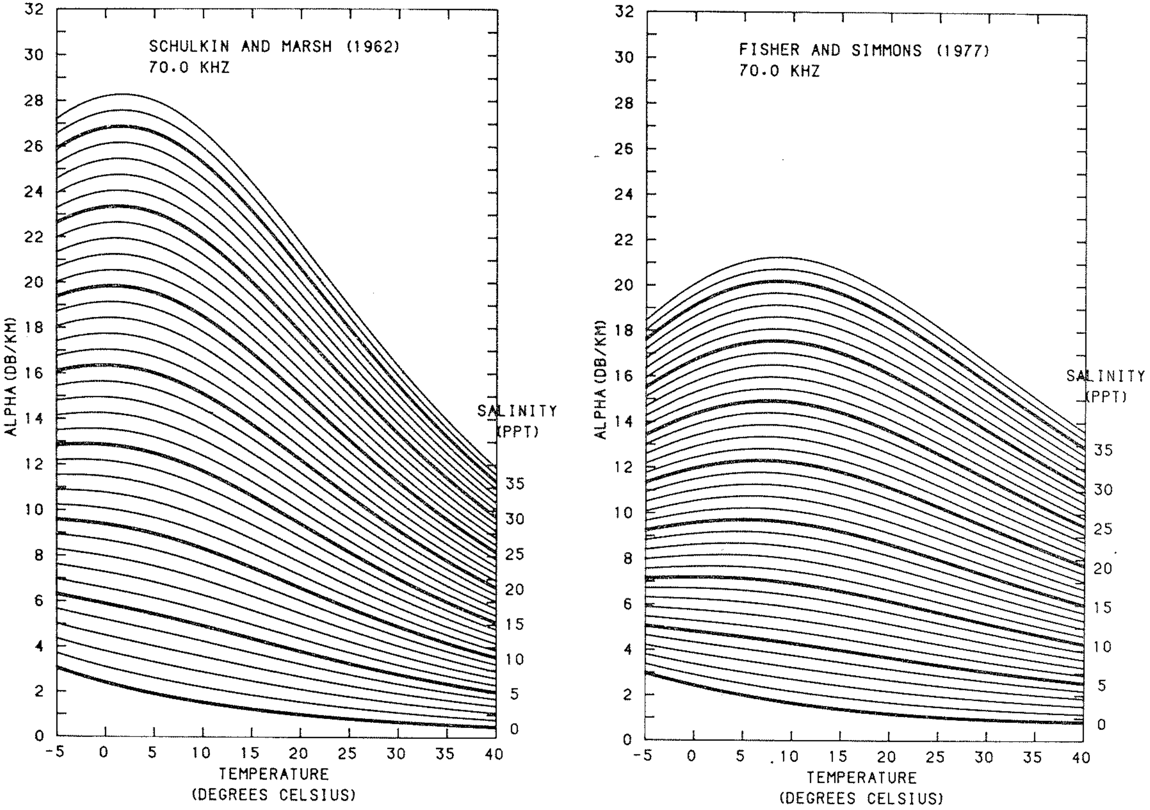

Fig. 6. Dependence of two absorption coefficients on temperature and salinity at 70 kHz. Pressure = 10 atm.

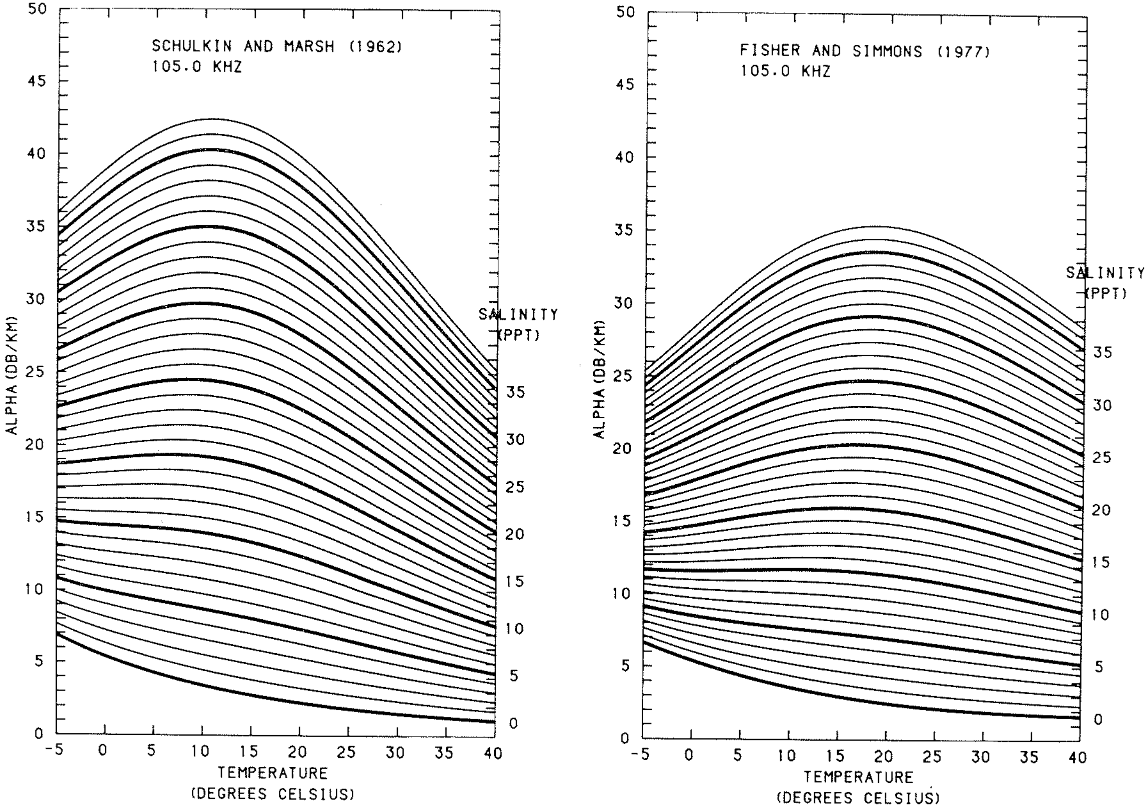

Fig. 7. Dependence of two absorption coefficients on temperature and salinity at 105 kHz. Pressure = 10 atm.

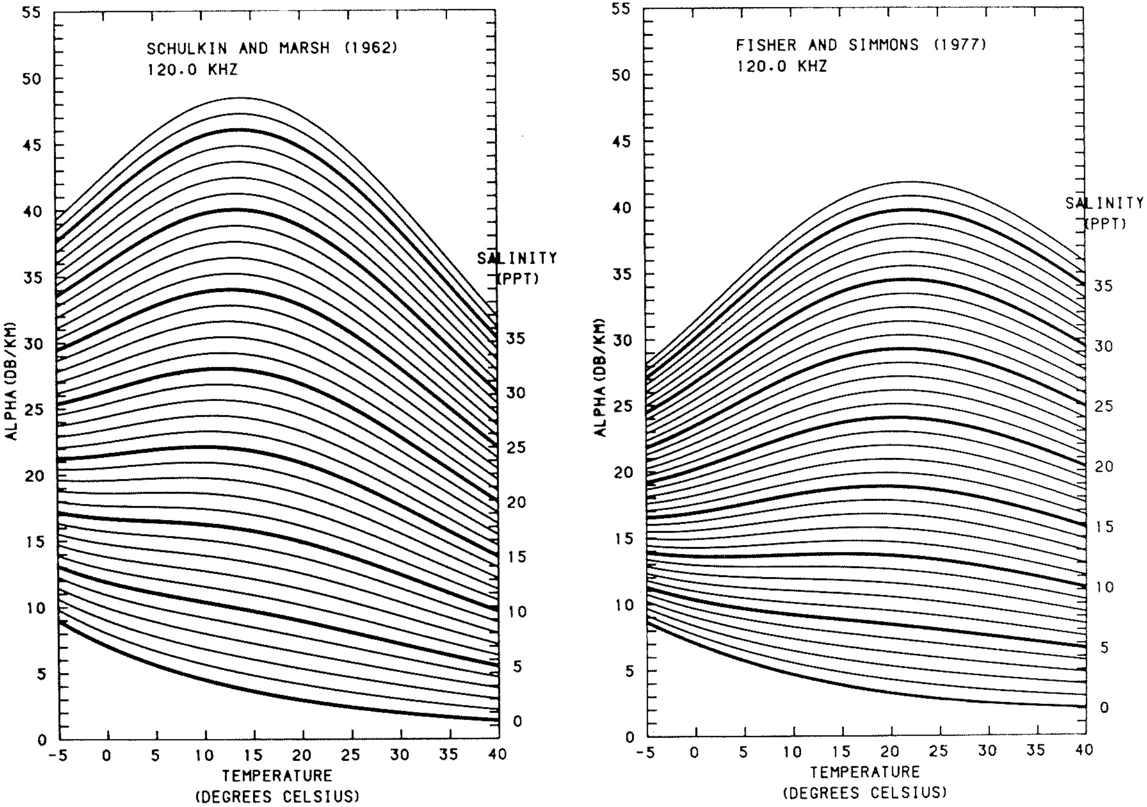

Fig. 8. Dependence of two absorption coefficients on temperature and salinity at 120 kHz. Pressure = 10 atm.

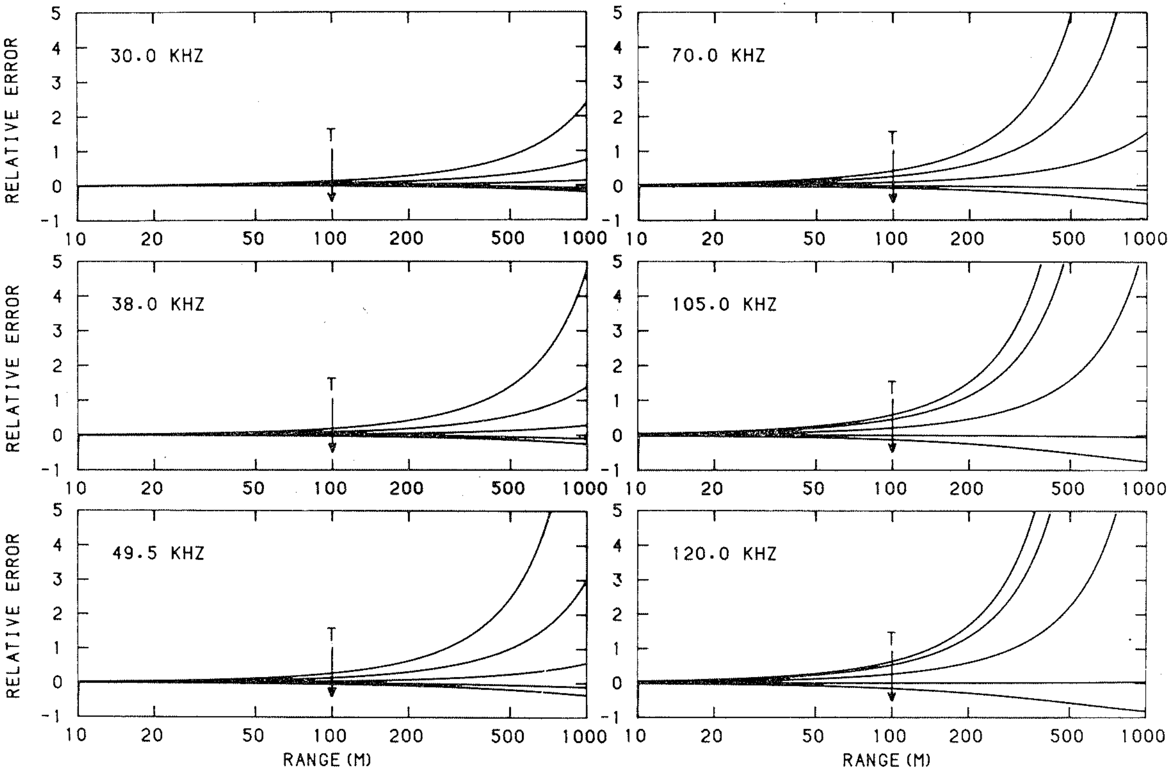

Fig. 9. Range dependence of relative errors in fish density estimates due to use of a_{SM} for a_{FS} in time-varied-gain functions. Temperature T = 0, 10, 20, 30, 40°C. Salinity = 35 ppt, pressure = 10 atm.

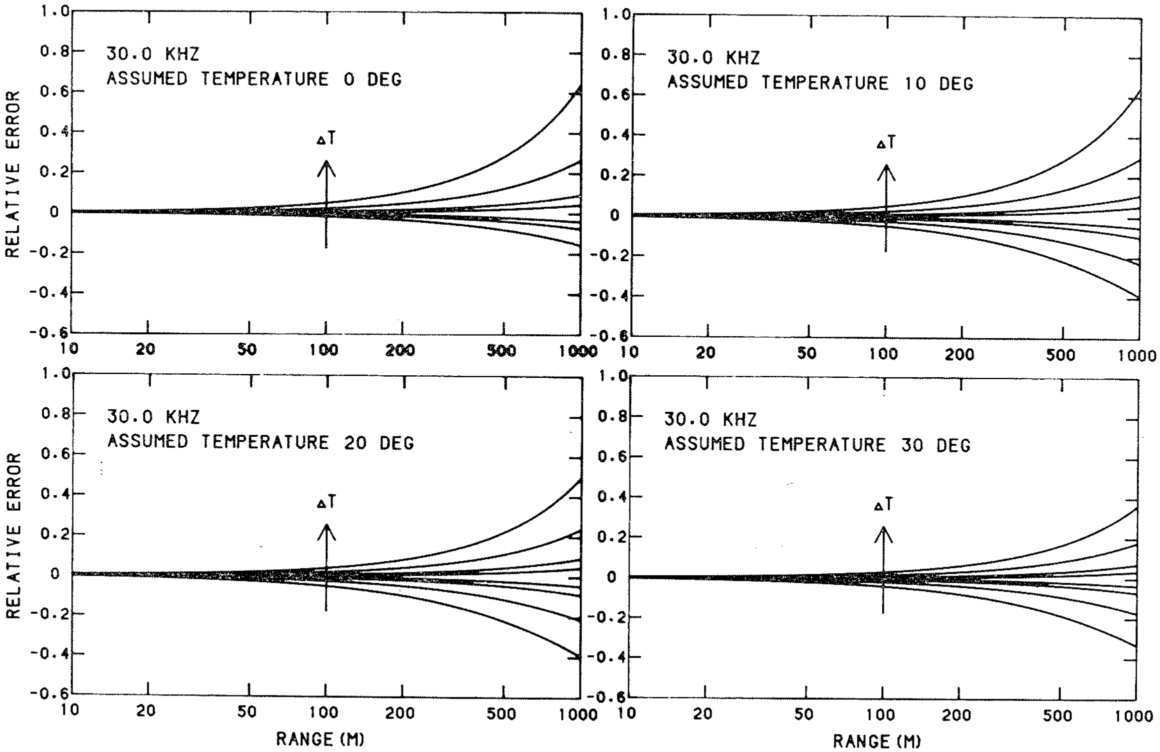

Fig. 10. Range dependence of relative errors in fish density estimates at 30 kHz due to uncompensated deviations ΔT from the assumed reference temperature T. ΔT varies monotonically thus: –10, –5, –2, –1, 1, 2, 5, 10°C except in the cases that T = 0°C, for which ΔT begins at –5°C, or that ΔT is shown explicitly. Salinity = 35 ppt, pressure = 10 atm.

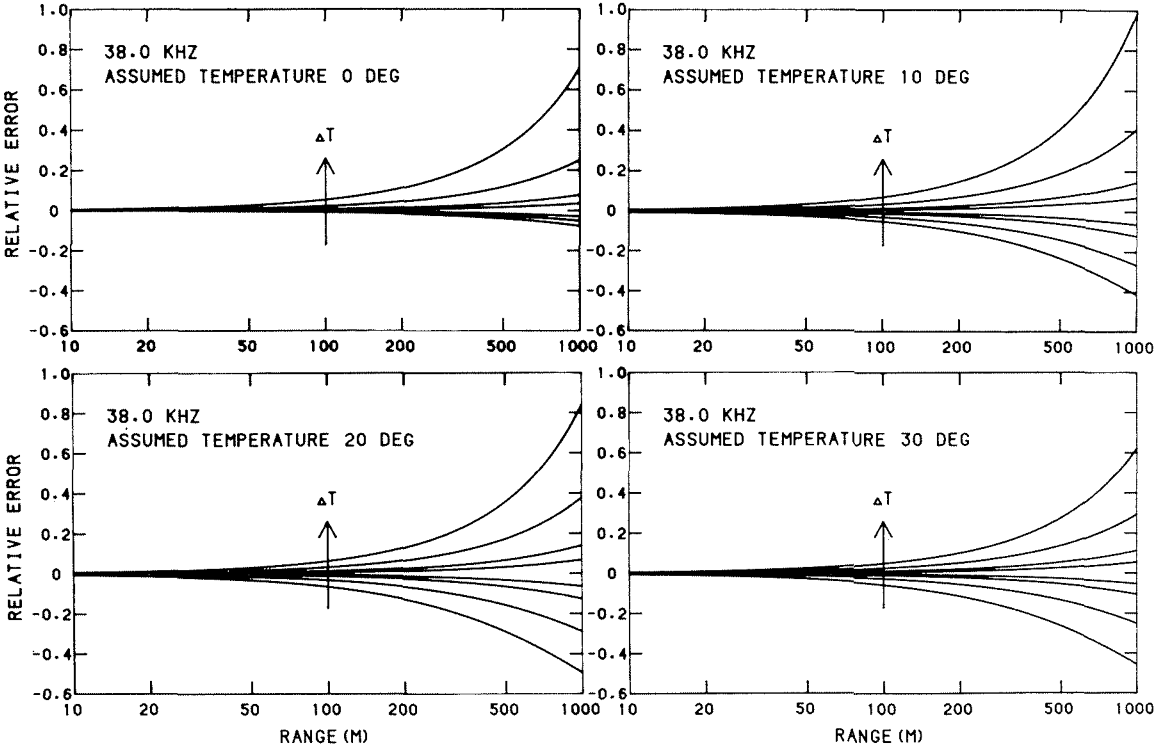

Fig. 11. Range dependence of relative errors in fish density estimates at 38 kHz due to uncompensated devations ΔT from the assumed reference temperature. ΔT varies as described in the caption to Fig. 10.

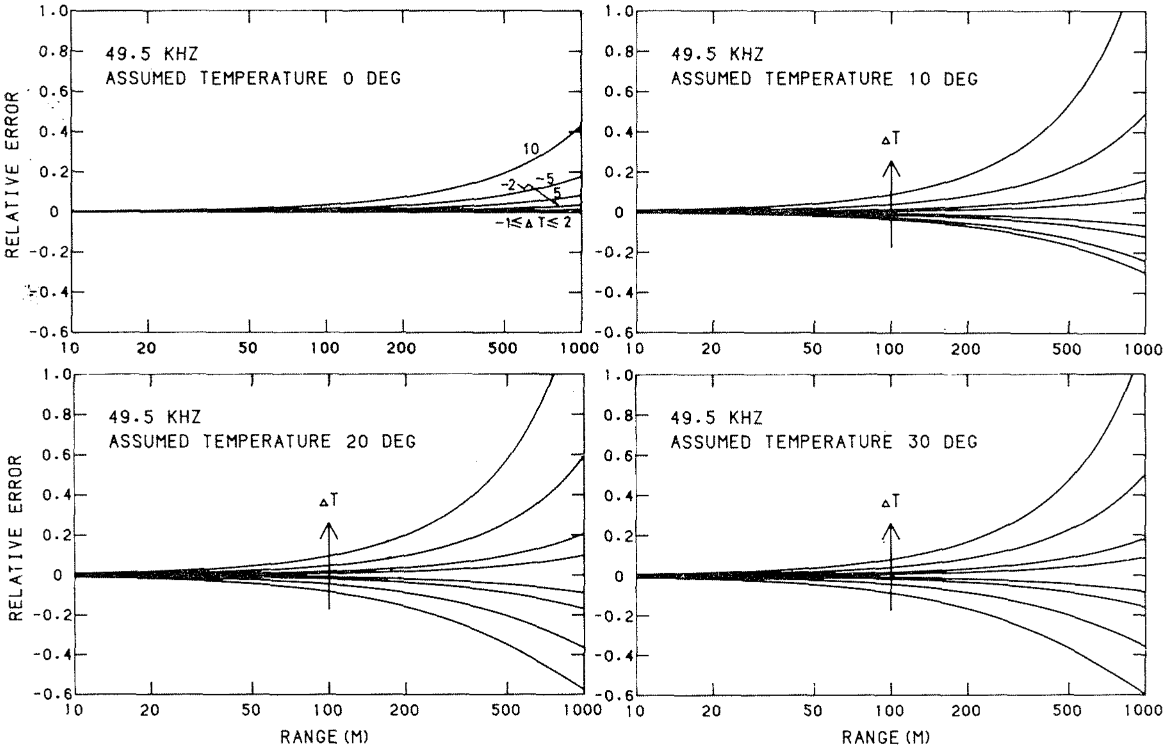

Fig. 12. Range dependence of relative errors in fish density estimates at 49.5 kHz due to uncompensated devations ΔT from the assumed reference temperature. ΔT varies as described in the caption to Fig. 10.

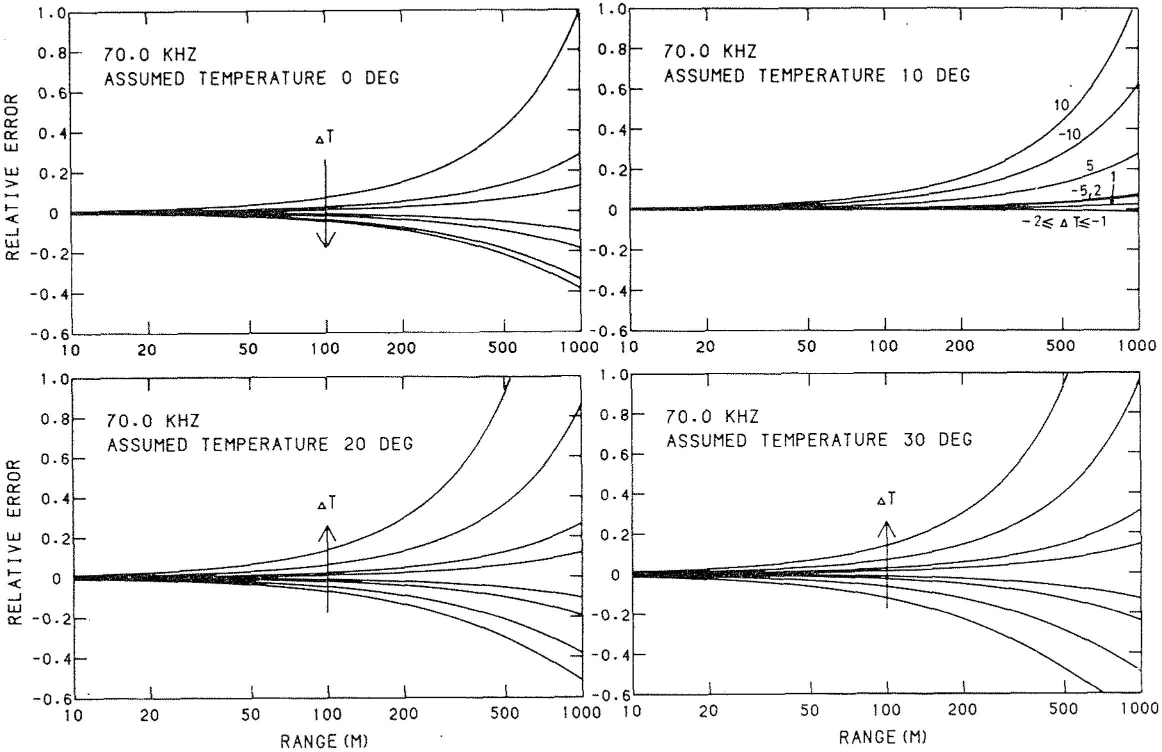

Fig. 13. Range dependence of relative errors in fish density estimates at 70 kHz due to uncompensated deviations ΔT from the assumed reference temperature. ΔT varies as described in the caption to Fig. 10.

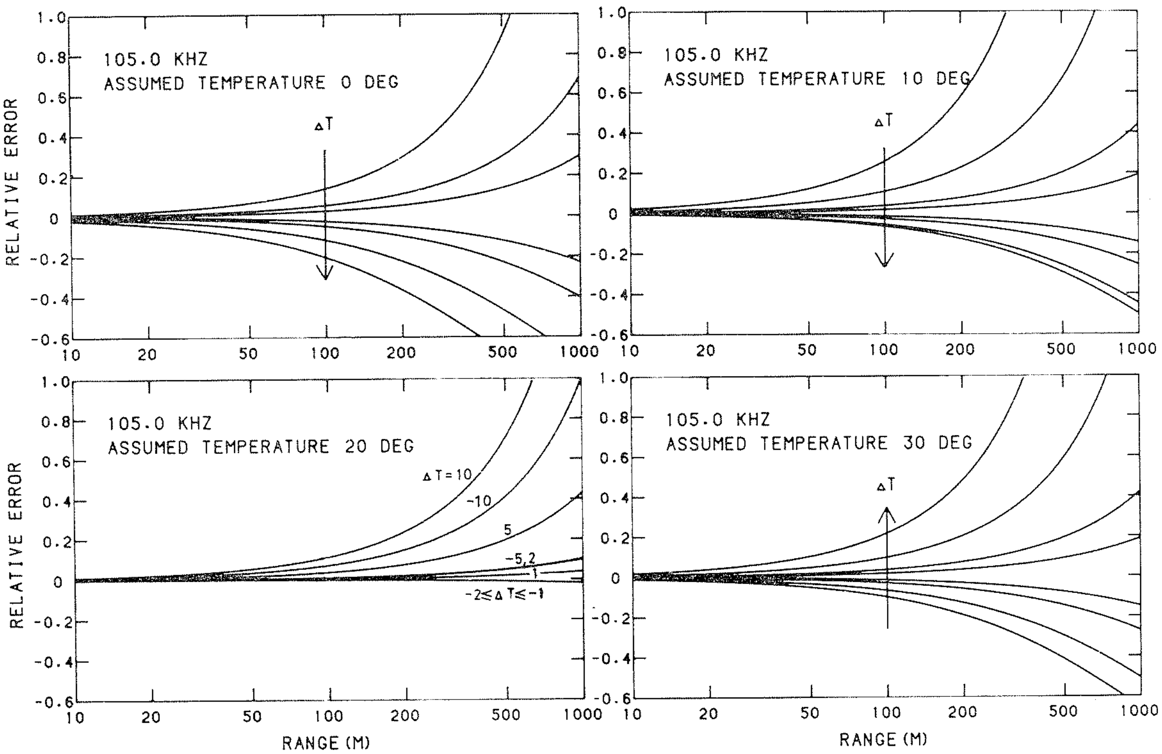

Fig. 14. Range dependence of relative errors in fish density estimates at 105 kHz due to uncompensated deviations ΔT from the assumed reference temperature. ΔT varies as described in the caption to Fig. 10.

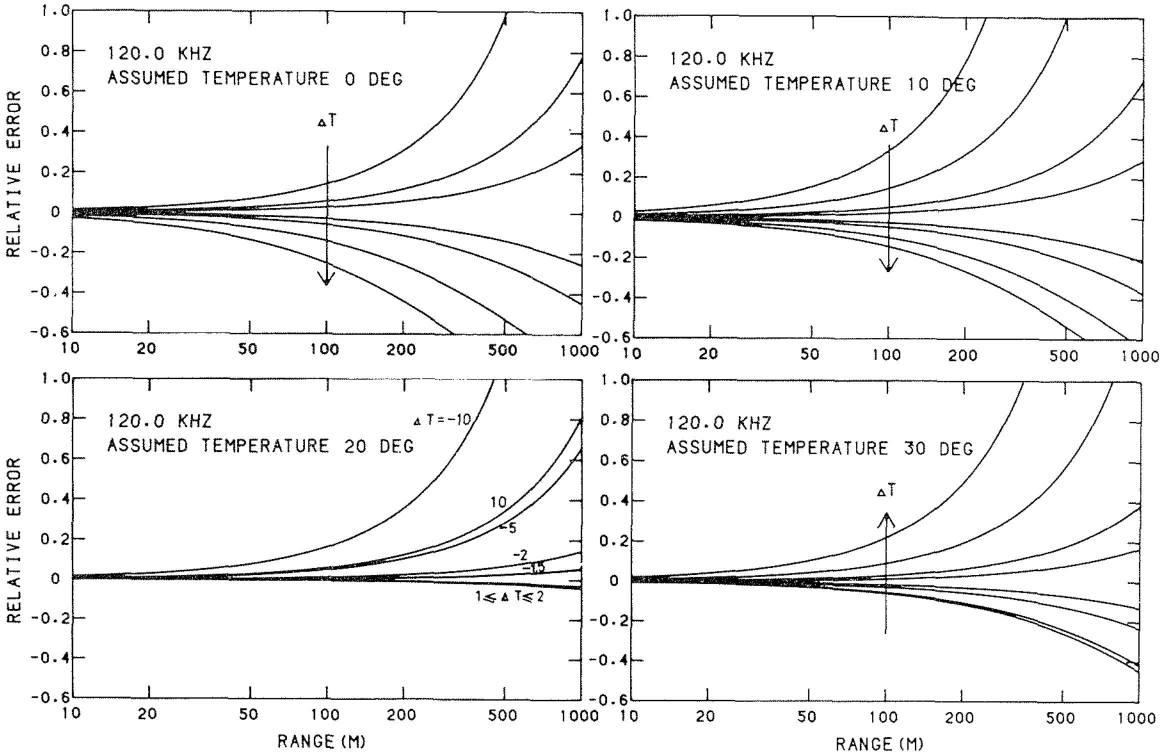

Fig. 15. Range dependence of relative errors in fish density estimates at 120 kHz due to uncompensated deviations ΔT from the assumed reference temperature. ΔT varies as described in the caption to Fig. 10.

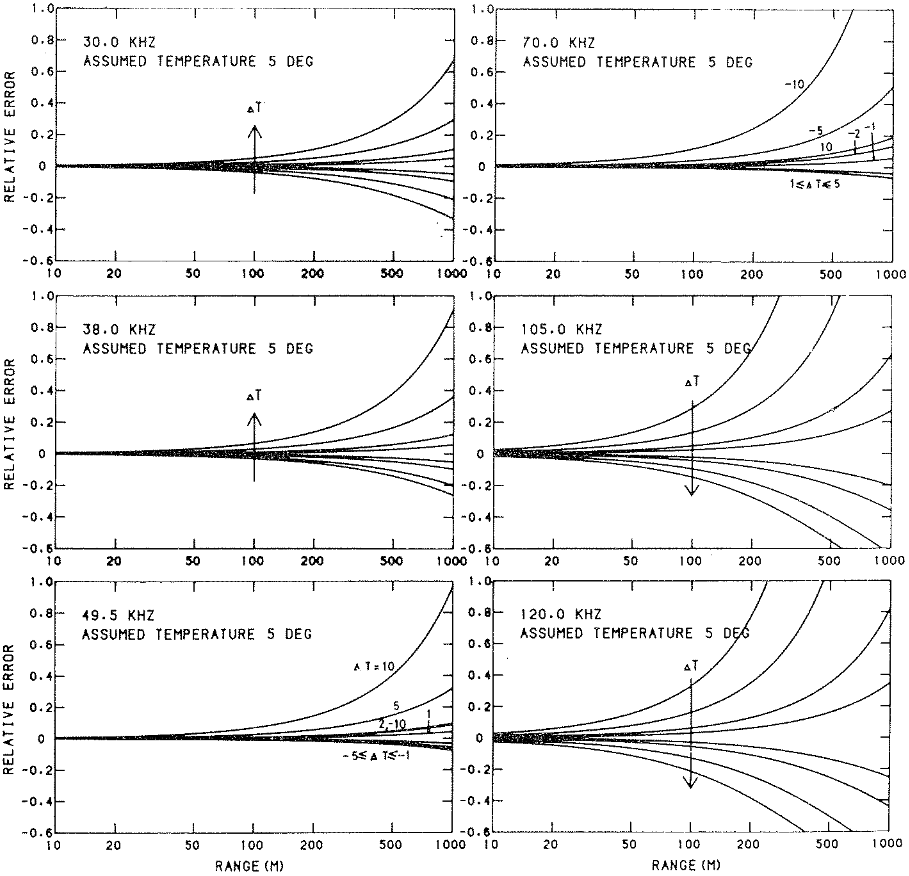

Fig. 16. Range dependence of relative errors in fish density estimates at six ultrasonic frequencies due to uncompensated temperature deviations △T from the assumed reference temperature 5°C. ΔT increases monotonically thus: –10, –5, –2, –1, 1, 2, 5, 10°C unless stated otherwise. Salinity = 35 ppt, pressure = 10 atm.

errors could be consequential to present or planned stock exploitation.

Even if the Fisher and Simmons expression is used to determine the absorption term, it is still possible to commit sizable errors by ignoring the influence of changing hydrography. Figs. 10 to 16 present an analysis of errors in fish density estimates associated with departures in temperature from a reference temperature assumed in assigning the absorption term. A conclusion of Simmonds and Forbes (1980), that the error in time-varied-gain function applied to a 38 kHz signal will in practice be insignificant at depths less than 100 m, is generally supported here, but with more qualification. The present finding is that the likely error in estimates of fish density at 100 m will not exceed about 10 per cent if the temperature assumed in determining the absorption is within five degrees of the actual temperature. This conclusion applies, moreover, at all frequencies from 30 to 120 kHz. At depths greater than 100 m, however, the error increases rapidly. At 200 m the error varies from about 10 to 30 per cent for temperature excursions of 5°C.

It was suggested in the introduction that adjustment of the absorption term in time-varied-gain functions for a changing hydrography often does not have to be a problem. If the real-time signal processing is conducted by a digital computer, then a small programming addition can permit direct application or correction of the absorption term. The feasibility of this is apparent from a number of computer applications in fisheries surveying, for example, those of SIMMONS (1975), SHOTTON and and DOWD (1976), EDWARDS (1978), AZZALI (1979), COOMBS and FRANCIS (1979), and TRAYNOR and NELSON (1979). The absorption coefficient could thus be adjusted continually to reflect the known or anticipated hydrography. If the signal processing is performed entirely by hardware, then the derived estimates of fish density should be distinguished by depth and corrected after the manner of analysis in Figs. 10–16.

In all of the foregoing the Fisher and Simmons expression has been assumed to describe correctly the absorption coefficient. Certain shortcomings are recognized, particularly in that understanding of the influence of hydrography which is needed to explain oceanic differences in absorption. At the usual ultrasonic frequencies of fisheries echo sounders, however, the Fisher and Simmons expression agrees well with observation, unlike the older Schulkin and Marsh expression. Further research will undoubtedly refine the present description, but should not disclose any surprises or large discrepancies at conventional frequencies.

As a consequence of the several error analyses presented here the following recommendations are urged:

1. That the Fisher and Simmons equation be used in assigning the absorption term of time-varied-gain functions,

and

2. That the estimation of fish density effected with time-varied gain reflect the hydrographic conditions of observation.

Adoption of these, in addition to rendering the present study obsolete, will advance the process of controlling errors in the acoustic assessment of fish abundance.

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