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Some Range Dependent Variations Affecting Acoustic Fish Stock Estimations

by

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Abstract

This paper describes a theoretical study of some of the range dependent factors which influence the accuracy of acoustic fish stock assessment. Two principal sources of error are considered, the effect of hydrographic conditions on the required time varied gain function, and the apparent change in transducer beam pattern due to movement of the transducer through the water. Both of these factors produce errors which increase markedly with depth, and the errors caused by typical conditions are described in detail.

Résumé

Ce document décrit une étude théorique des quelques facteurs dependant de gamme qui agissent sur la précision d'évaluation acoustique du stock de poisson. On considere deux sources principales d'erreur, l'effet des conditions hydrographiques sur le fonction d'accroissement exigé avec variation du temps, et le changement evident du dessin du faisceau du transducteur causé par le mouvement du transducteur au travers l'eau. Tous les deux facteurs provoquent erreurs qui augmentent d'une façon marquée en relation de profondeur, et on décrit de point en point les erreurs causés par conditions typiques.

Introduction

The use of acoustic methods for fish stock assessment has been increasing steadily over the past years. One of the problems has been the compensation that is required to correct for spreading and attenuation losses at different ranges.

With increasingly sophisticated digital electronics becoming available at steadily decreasing prices, it is now possible to develop relatively accurate dedicated range compensation equipment. In order to examine the requirements of such equipment two different sources of range dependent variations were investigated. The first is the effect of hydrographic conditions on both the speed of sound and the attenuation coefficient due to absorption. The second is the effect of the motion of the transducer. Although this is a time dependent factor rather than range dependent, it is useful to think of pitch and roll effects in this way.

1. Variation of temperature and salinity

Both the speed of sound and attenuation due to absorption vary with salinity, temperature and depth of sea water. In order to determine the effect of these variations data were selected from several typical hydrographic stations, carried out between the Butt of Lewis and Faroe Bank for the four months March, May, August and November. The locations of stations are shown in Table 1. For each station salinity and temperature had been recorded at 0, 10, 20, 30, 50, 100, 150, 200, 300, 400, 500, 600 metres as the depth permitted. For each depth at each station the attenuation coefficient and the speed of sound were calculated using the following formulae:-

For the speed of sound (C):- (Ref 2)

$$C = 1449.2 + 4.623\ T - 0.0546\ T^2 + 1.391\ (S-35) + 0.017\ R$$

and for the attenuation coefficient (α):- (Ref 3)

$$\alpha = \left[\frac{0.0186\ S\ f_\tau f^2}{f_\tau^2 + f^2} + \frac{0.0268\ f^2}{f_\tau}\right](1-6.33 \times 10^{-5} R)$$

where $f_\tau = 2.19 \times 10^{(6-1.520/(T + 273))}$

and C = speed of sound (m/s)
T = temperature (degrees celsius)
S = salinity (‰)
R = depth (m)
f = frequency (38 kHz)
α = attenuation coefficient (dB/m)

The attenuation coefficient and speed of sound were compared for same months in different years. The differences between these were found to be negligible and so all data from different years were combined. The results of this are shown in Figures 1 and 2. The vertical scales of these graphs are from 0 to 600 metres depth while the horizontal scales are offset to show speed between 1450 and 1510 m/sec and attenuation coefficient between 7 and 14 dB/km. The continuous line shows the mean values and the bars show the range of values at each depth. The different months are shown together for comparison.

The variations of speed of sound are quite small. The mean value varies by less than 1%, and the range of values is less than ±2.5% down to a depth of 600m or ±1.5% down to 500 m depth.

The variation in attenuation is much more substantial. The mean varies by 15%, the range of values is greater than ±30%.

To consider the effects of these variations some assumptions have to be made. In fisheries acoustics two main compensation characteristics are used in practice.

(1) $20 \log R + 2\ \alpha R$

to give an output proportional to fish density for integration, and

(2) $40 \log R + 2\ \alpha R$

to give an output proportional to fish target strength for individually insonified targets.

In both cases the effect of variations in α, the attenuation coefficient, will be the same. Figure 3 shows the attenuation factor for the mean and for both upper and lower limits of the data for each month.

The attenuation factor is

$$\text{antilog}\left[2 \sum_{o}^{R} \alpha_i \; R_i \big/ 10\right]$$

where α_i is the attenuation coefficient at depth i (dB/m)
and R_i is the range over which that coefficient is applied (m)

From the diagrams it is possible to see that the differences are insignificant before 100 metres depth. However by 600 metres depth a substantial range of values (between 15 and 22) are possible, although the range of monthly mean values is substantially less than this only being about 6%.

The variation of speed of sound effects both the attenuation term and the spread loss term. To examine the overall effect it is necessary to look at the effects of both these together. In Figures 1 and 2 the speed and attenuation coefficient are shown. As the speed of sound increases the attenuation decreases. This can be seen most clearly for the month of August.

In fisheries, compensation for these losses is applied in time with a Time Varied Gain function. So if the speed of sound increases above the 'expected' value then the returned echoes come from further away than is expected and although the losses increase with the increased range, the attenuation coefficient will have decreased and this will compensate to some extent.

For the purposes of this analysis only the loss function used for fish density estimates will be summarised. This Time Varied Gain function is expressed as 20 log R + 2 αR. It is however applied in time and assumes a fixed known speed of sound (usually 1 500 m/s). To consider the effects of varying speed of sound, and attenuation coefficient the losses to each depth (R) were determined, from each set of data, for each hydrographic station. The time (t) at which the loss occurred was then calculated and the difference between the loss calculated and the loss predicted by a 20 log (ct/2) + 2 α (ct/2) function was determined.

At depth R

$$\text{Calculated Loss} = 20 \log R + 2 \sum_{o}^{R} \alpha_i \, R_i$$

$$\text{Time } t = \sum_{o}^{R} R_j \big/ C_j$$

$$\text{Predicted Loss} = 20 \log \; C \sum_{o}^{R} R_j \big/ C_j \; + 2 \, \alpha C \sum_{o}^{R} R_j \big/ C_j$$

Error =

$$20 \log R + 2 \sum_{o}^{R} \alpha_i \, R_i \; - \; 20 \log \left[C \sum_{o}^{R} R_j \big/ C_j \right] - 2 \, \alpha \, C \sum_{o}^{R} R_j \big/ C_j$$

where R is depth (m)

α_i is attenuation coefficient at depth i (dB/m)

R_i is depth over which this is applied (m)

C_j is speed of sound at depth j (m/s)

R_j is depth over which this is applied (m)

and C and α are assumed constant values of speed of sound and attenuation respectively.

Figure 4 shows the mean, standard deviation and range of this error for three different values of C and α combining all data from all seasons. The horizontal scale is in dB from -1.2 to +1.2 dB. The mean error is shown as a continuous line. The mean plus and minus one standard deviation, and both the upper and lower limits of the data are shown as small vertical ticks. The data limits are connected by a horizontal line. It can be seen from these graphs that by choosing fixed values of C and α it is possible to get very low mean error. The first of the graphs, in Figure 4 shows the error for the standard values C = 1 500 m/s and α = 0.01 dB/m. The second graph shows minimum mean error from 0 to 600 m by using values of C = 1 490 and α = 0.0102 dB/m. In this case the mean error is less than 0.02 dB at any depth. The third graph shows a mean error of zero between depths of 100 and 500 m using values of C = 1 485 and α = 0.01027. However in this case the mean error is 0.05 dB at 20 and 600 m. This indicates that it is unnecessary to vary α or C with depth in order to get acceptable mean error. However this assumes that it is the mean of all values that is required. If the fish populations are distributed independently of hydrographic conditions then this would be the case. But it is quite likely that this is not so. If some relationship does exist between, say water temperature and the fish distribution, it would be possible for an error of 0.5 dB (12%) to occur.

In order to check if seasonal variations are important the error has been plotted again for each of the four months separately. Values of 1 490 m/s and .0102 dB/m were chosen for C and α respectively. From Figure 5 it can be seen that some bias is introduced, this is always less than .15 dB (3.5%). The error has been redrawn again in Figure 6 to show the different values of speed of sound and attenuation coefficient required to obtain minimum mean error.

2. Effects of movement of the transducer

To examine the effects of pitch and roll of a transducer it was necessary to develop an expression for the beam pattern. The transducer used by the Marine Laboratory in Aberdeen is a Simrad 38 kHz transducer which is made from a total of 34 individual elements arranged in 5 rows, 2 of 6 elements, 2 of 7 elements and a central row of 8 elements.

A single row of elements can be considered as an array of point sources. This can then be used to produce a description of the point source array for all five rows of elements. The final beam pattern is obtained by multiplying the directivity function of the point source array by that of an individual element (Ref 4).

Using spherical polar coordinates r, θ and ϕ as defined in Figure 7a, the directivity function for a single line array is

$$D_L(\theta, \phi) = \sin(n K (d/2) \cos\phi) \,/\, n \sin(K (d/2) \cos\phi)$$

where

n = number of elements
d = diameter of elements (spacing of centres)
$K = (2\pi/\lambda)\sin\theta$
λ is wavelength

For the 34 element array with 2-6 element, 2-7 element, and 1-8 element rows spaced $\sqrt{3}\,d/2$.

$$D_A(\theta,\phi) = \frac{1}{34}\left[\frac{\sin(8K(d/2)\cos\phi)}{\sin(K(d/2)\cos\phi)} + 2\frac{\sin(7K(d/2)\cos\phi)}{\sin(K(d/2)\cos\phi)}\cos(K\sqrt{3}\,d/2)\sin\phi) + 2\frac{\sin(6K(d/2)\cos\phi)}{\sin(K(d/2)\cos\phi)}\cos(K\sqrt{3}\,d\sin\phi)\right]$$

The function for one element

$$D_E(\theta) = \frac{2J_1(K\,d/2)}{K\,d/2}$$

where $K = (2\pi/\lambda)\sin\theta$

J_1 is first order Bessel function

Therefore the function for the whole transducer is

$$D_T = D_E(\theta) \times D_A(\theta,\phi)$$

$$D_T = \frac{2J_1(\pi(d/\lambda)\sin\theta)}{(d/\lambda)\sin\theta}\;\frac{A}{34\sin(\pi(d/\lambda)\sin\theta\cos\phi)}$$

where A =

$$\sin(8\pi(d/\lambda)\sin\theta\cos\phi) + 2\sin(7\pi(d/\lambda)\sin\theta\cos\phi)\cos(\pi\sqrt{3}\,d/\lambda)\sin\theta\sin\phi)$$
$$+ 2\sin(6\pi(d/\lambda)\sin\theta\cos\phi)\cos(\pi(2\sqrt{3}\,d/\lambda)\sin\theta\sin\phi)$$

The effect of the beam pattern for echo integration is (Ref 5)

$$\int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi} D_{TT}^2(\theta,\phi)\,D_{TR}^2(\theta,\phi)\sin\theta\,d\theta\,d\phi$$

where

$D_{TT}(\theta,\phi)$ Beam pattern function on transmission

$D_{TR}(\theta,\phi)$ Beam pattern function on reception

Under normal circumstances $D_{TT}(\theta,\phi) = D_{TR}(\theta,\phi)$ for the same transducer. But when the transducer moves then this will not be the case. In order to evaluate the effects of movement the above integral was evaluated with both $D_{TT}(\theta,\phi)$ and $D_{TR}(\theta,\phi)$ coinciding. Then $D_{TT}(\theta,\phi)$ and $D_{TR}(\theta,\phi)$ were shifted and the integral revaluated. To do this in the direction of pitch a new set of angular definitions were chosen (Figure 7b) so that

$\sin\alpha \sin\beta = \sin\Theta \cos\phi$
$\cos\alpha = \sin\Theta \sin\phi$
$\sin\alpha \cos = \cos\Theta$

where β is the angle of pitch

The integral becomes

$$\int_{\alpha=0}^{\pi} \int_{\beta=-\pi/2}^{\pi/2} D_T^2(\beta + \varepsilon/2, \alpha)\, D_T^2(\beta - \varepsilon/2, \alpha) \sin\alpha \, d\alpha \, d\beta$$

where ε is the change in angle between transmission and reception in the pitch direction. A plot of this as a function of ε is given in Figure 8.

Similarly for the roll direction angular definitions became:- (Figure 7c)

$\cos\alpha = \sin\Theta \cos\phi$
$\sin\alpha \cos\beta = \cos\Theta$
$\sin\alpha \sin\beta = \sin\Theta \sin\phi$

where β is now the angle of roll

The integral became

$$\int_{\alpha=0}^{\pi} \int_{\beta=-\pi/2}^{\pi/2} D_T^2(\beta + \varepsilon/2, \alpha)\, D_T^2(\beta - \varepsilon/2, \alpha) \sin\alpha \, d\alpha \, d\beta$$

A plot of this against ε is shown in Figure 8.

If the transducer is pitching or rolling then the angle between transmission and reception will vary with time. In order to represent these changes a family of curves have been drawn in Figures 9 and 10 for pitch and roll respectively. Although the change is in time the curves have been drawn against depth assuming a speed of sound of 1 500 m/s. Normal rates of pitch and roll of a vessel are less than 2° per second. However in bad weather it is quite possible for pitch rates to be significantly greater than this.

The effect of forward motion of the transducer can also be examined from this data. This motion is equivalent to a constant small pitch change between transmission and reception of $\frac{2v}{C}$ **radians** where v is the ship's speed and C the speed of sound. For a vessel travelling at 10 knots this angle is only about 0.4°, and it can be seen from Figure 8 that its effect is negligible.

The curves shown in Figure 8 are drawn specifically for a Simrad 38 kHz ceramic transducer. If the angular scale is altered in proportion to beam width however they may be applied as a good approximation for most uniformly excited transducers.

Conclusions

The variations of sound speed with hydrographic conditions is not important. However in order to compensate correctly for both spread loss and absorption loss it is useful to consider both of these factors together.

It is possible to introduce small seasonal bias at ranges exceeding 100m by selecting single values for the attenuation coefficient and the sound speed. This bias in the mean is not a significant source of error. However if the distribution of fish stock is correlated with the hydrographic conditions then this must be considered or significant bias may be introduced.

The effect of ship speed on beam pattern is negligible, so too is the effect of roll under normal conditions. However the effect of pitch may be significant, except in calm weather, particularly with unstabilised hull mounted transducers. In order to compensate for this sensing equipment would be required. Without compensation equipment, measurements of deep water stocks should be considered with care if transducer pitch rates exceed 4^{o}/sec.

References

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3	Urick, R.J.	1967	Ibid., pp 88-89
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TABLE 1 POSITION, MONTH AND YEAR FOR EACH STATION

Position		Month							
		March		May		August		November	
60 54' N	8 16' W	1952	1950	1952	1950		1927		1950
60 45' N	8 08' W	1952	1950	1952	1950				1950
60 35' N	8 00' W	1952	1950	1952	1950	1951	1927	1952	1950
60 23½'N	7 49½'W	1952	1950	1952	1950	1951		1952	1950
60 12' N	7 40' W	1952	1950	1952	1950	1951	1927	1952	1950
59 56' N	7 27' W	1952	1950	1952	1950	1951		1952	1950
59 44' N	7 15' W	1952	1950	1952	1950	1951	1927	1952	1950
59 31' N	7 05' W	1952	1950	1952	1950	1951		1952	1950
[illegible] 17' N	6 53' W	1952	1950	1952	1950	1951	1927	1952	1950
59 00' N	6 40' W	1952	1950	1952	1950	1951		1952	1950
58 50' N	6 26' W	1952	1950	1952	1950	1951	1927	1952	1950
58 40' N	6 10' W	1952	1950	1952	1950	1951		1952	1950

Figure 1 Speed of sound against depth for four months showing mean and upper and lower limits of the data

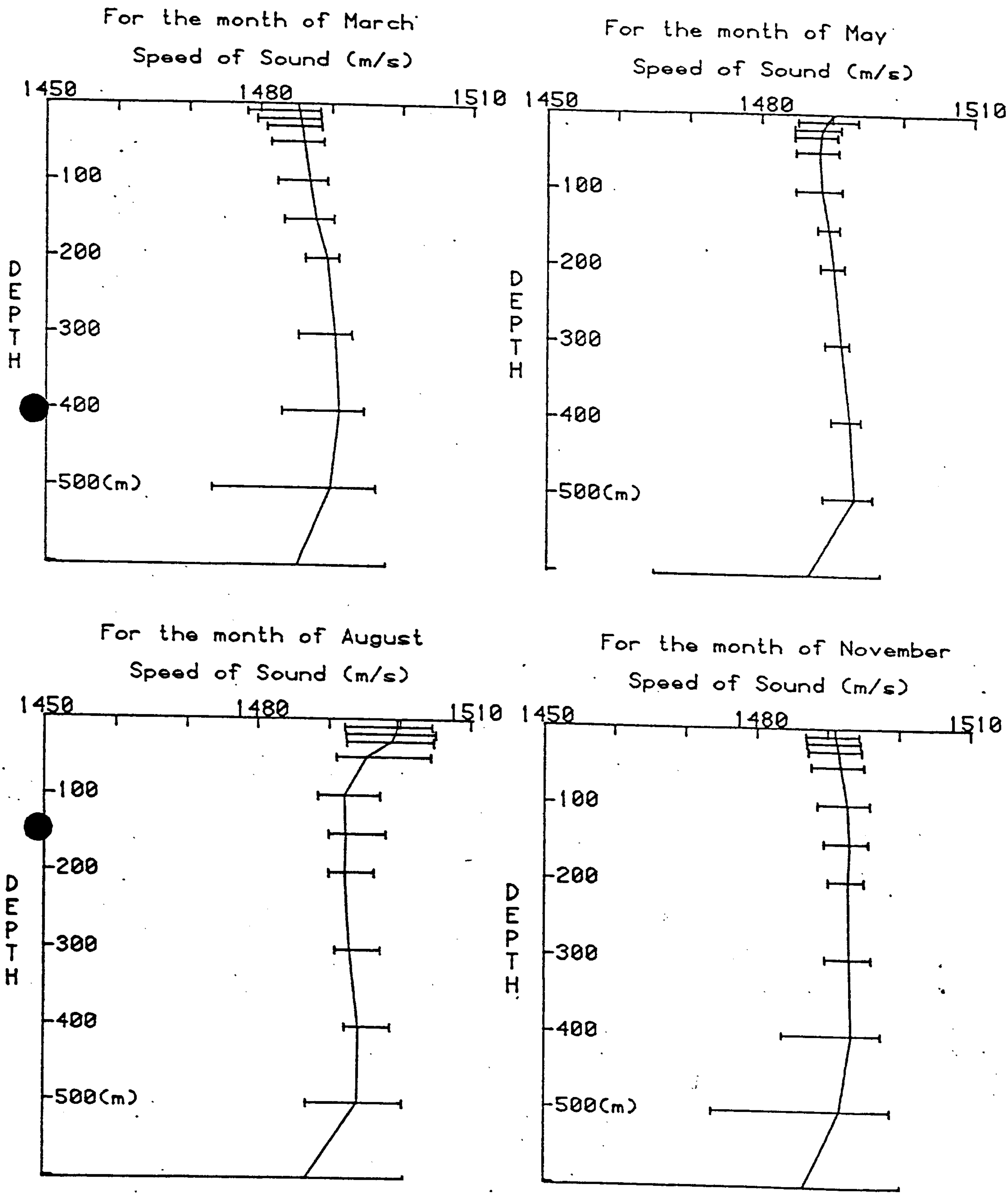


Figure 2 Attenuation coefficient against depth for four months showing mean and upper and lower limits for the data

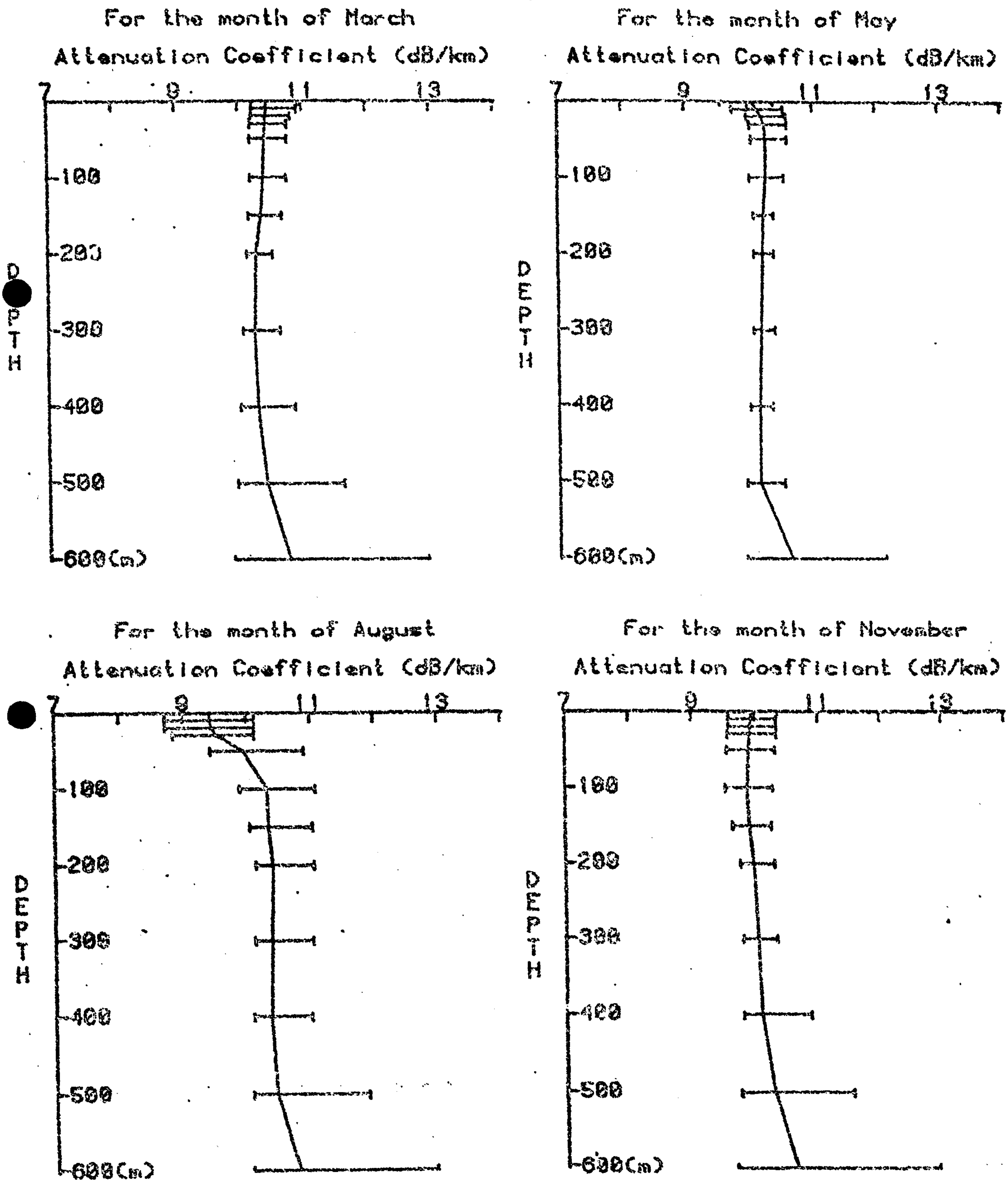


Figure 3 Attenuation factor against depth for four months showing the mean and the upper and lower limits

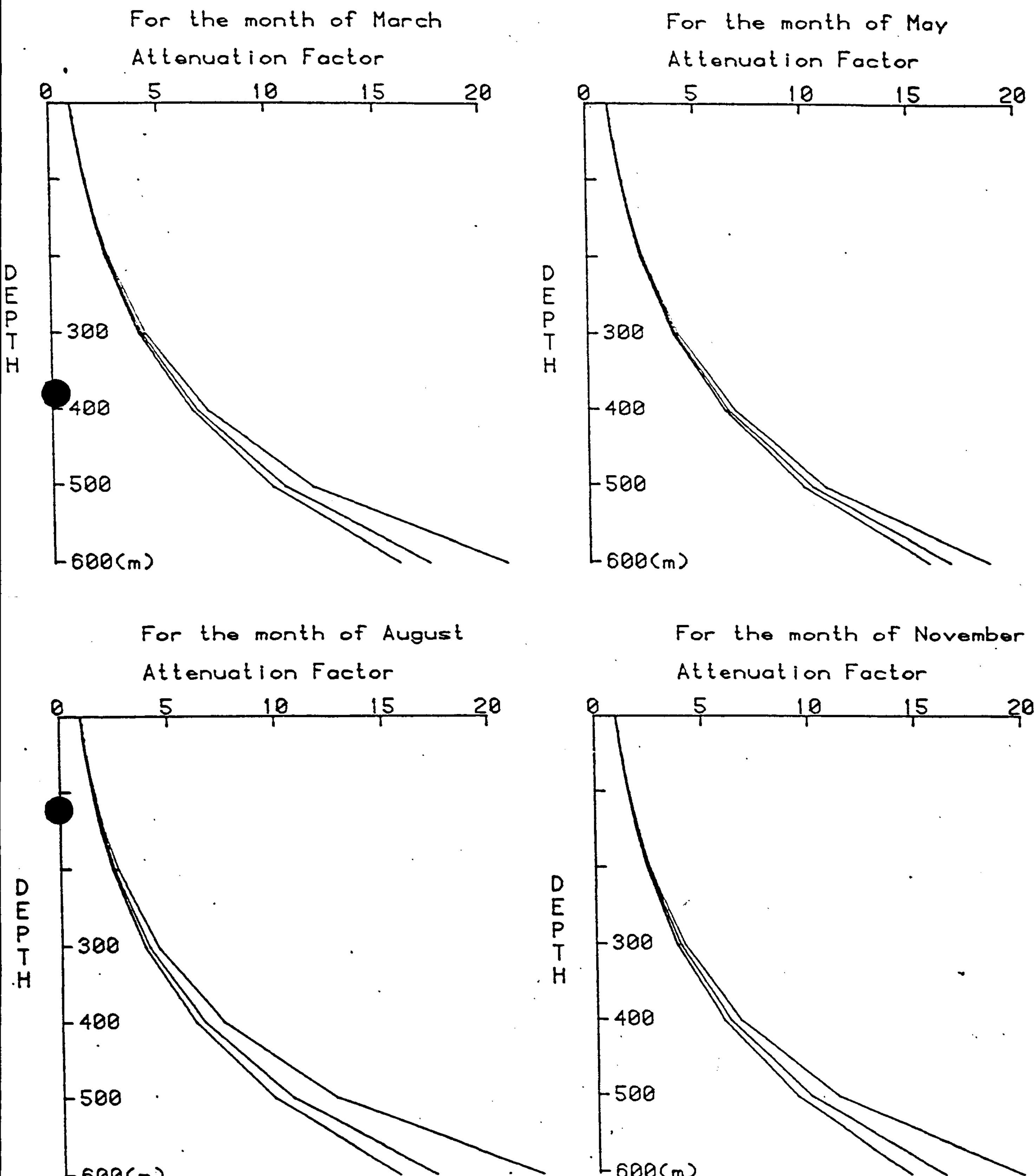


Figure 4 Error between calculated and predicted 20 log R + $2\alpha R$ loss functions. showing three different values of attenuation coefficient and sound speed

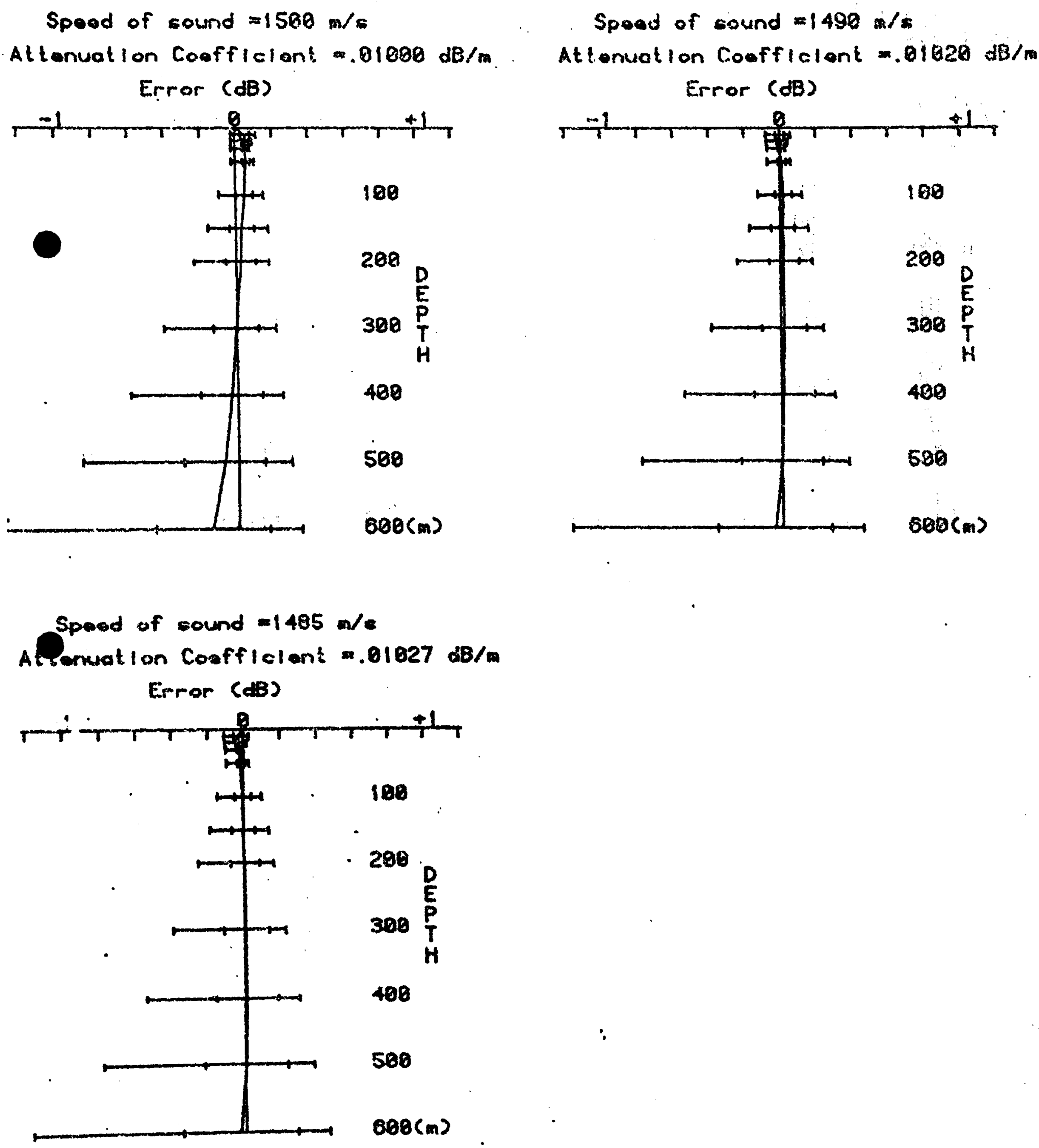


Figure 5 Error between calculated and predicted 20 log R + 2αR loss function for four months. Using values of:-

Attenuation coefficient (α) = .0102 dB/M
Speed of sound (c) = 1490 m/s

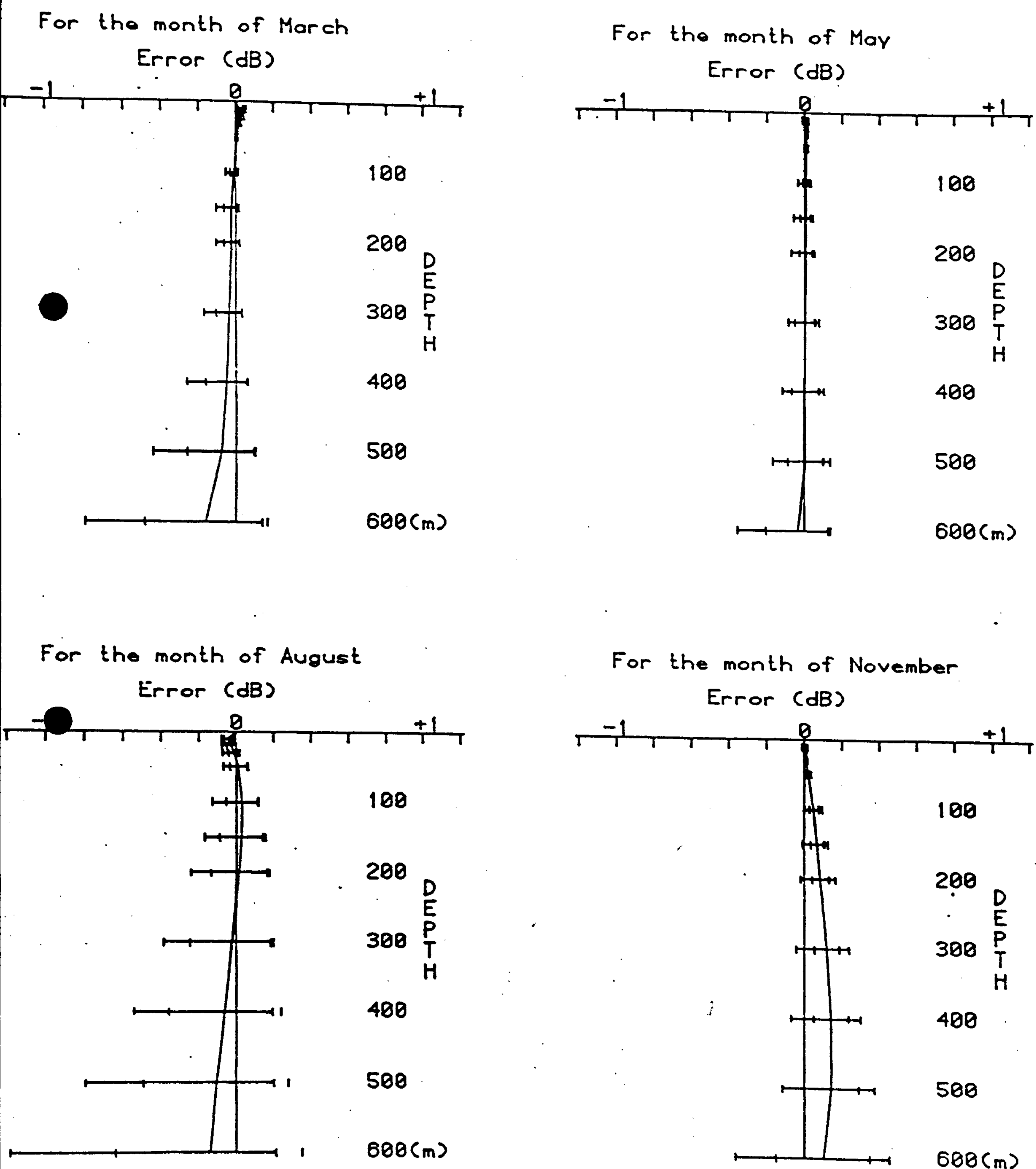


Figure 6 Error between calculated and predicted 20 log R + 2α R loss functions for four months

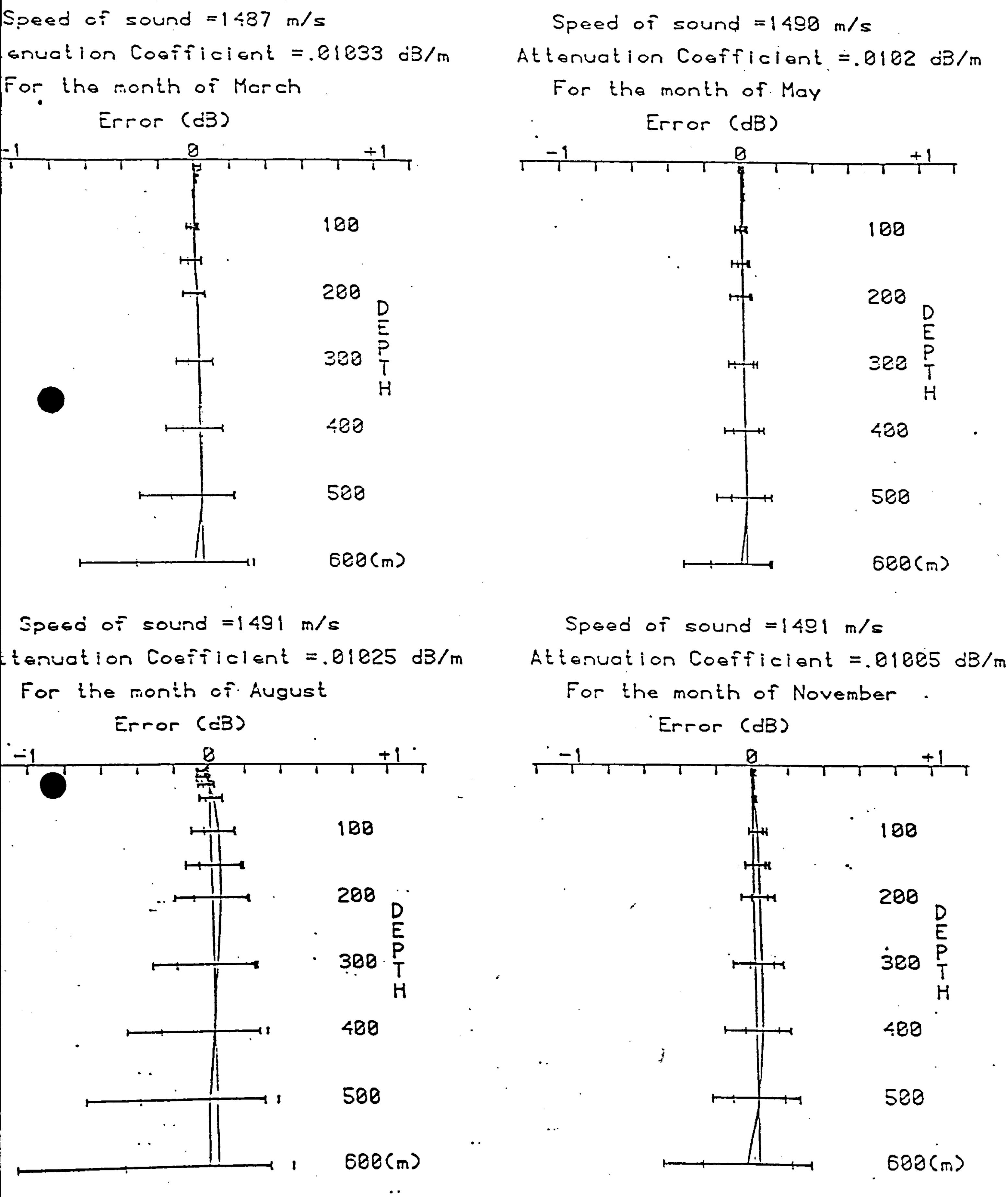
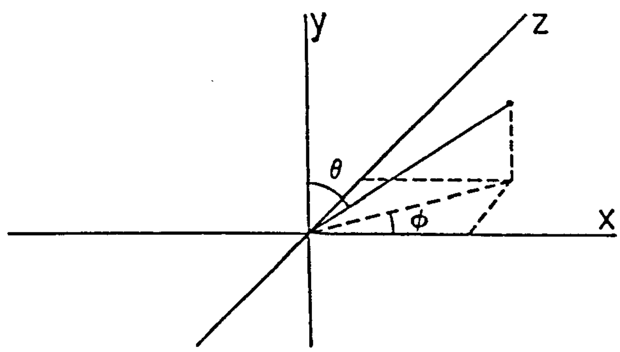


Figure 7

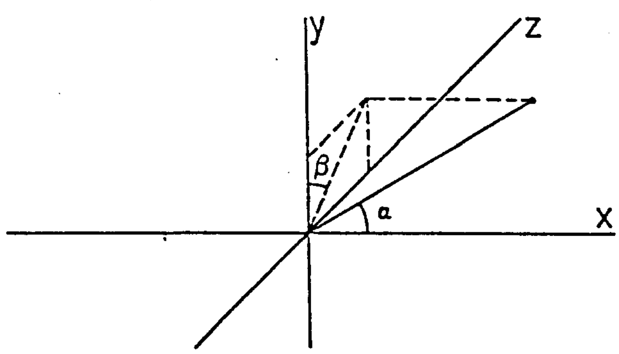
(a) NORMAL ANGULAR DEFINITIONS



$$x = \sin\theta \cos\phi$$
$$y = \cos\theta$$
$$z = \sin\theta \sin\phi$$

$$\int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} B(\theta,\phi) \sin\theta \, d\theta \, d\phi$$

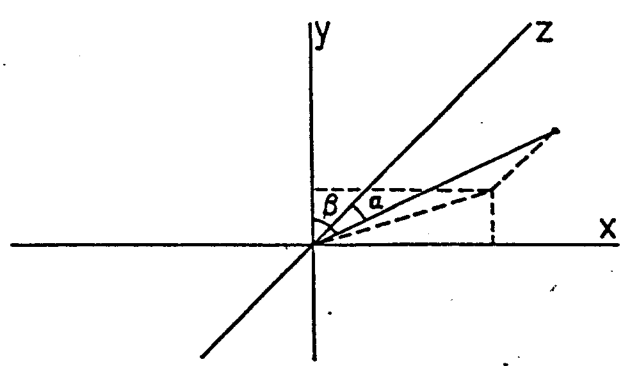
(b) ANGULAR DEFINITIONS FOR VARYING ROLL ANGLE



$$x = \cos\alpha$$
$$y = \sin\alpha \cos\beta$$
$$z = \sin\alpha \sin\beta$$

$$\int_{\alpha=0}^{\pi} \int_{\beta=-\pi/2}^{\pi/2} B(\alpha,\beta) \sin\alpha \, d\alpha \, d\beta$$

(c) ANGULAR DEFINITIONS FOR VARYING PITCH ANGLE



$$x = \sin\alpha \sin\beta$$
$$y = \sin\alpha \cos\beta$$
$$z = \cos\alpha$$

$$\int_{\alpha=0}^{\pi} \int_{\beta=-\pi/2}^{\pi/2} B(\alpha,\beta) \sin\alpha \, d\alpha \, d\beta$$

FOR ROLL

$$\sin\theta \cos\phi = \cos\alpha$$
$$\cos\theta = \sin\alpha \cos\beta$$
$$\sin\theta \sin\phi = \sin\alpha \sin\beta$$

FOR PITCH

$$\sin\theta \cos\phi = \sin\alpha \sin\beta$$
$$\cos\theta = \sin\alpha \cos\beta$$
$$\sin\theta \sin\phi = \cos\alpha$$

Figure 8 Relative sensitivity against change of transducer orientation between transmit and receive for both Pitch and Roll

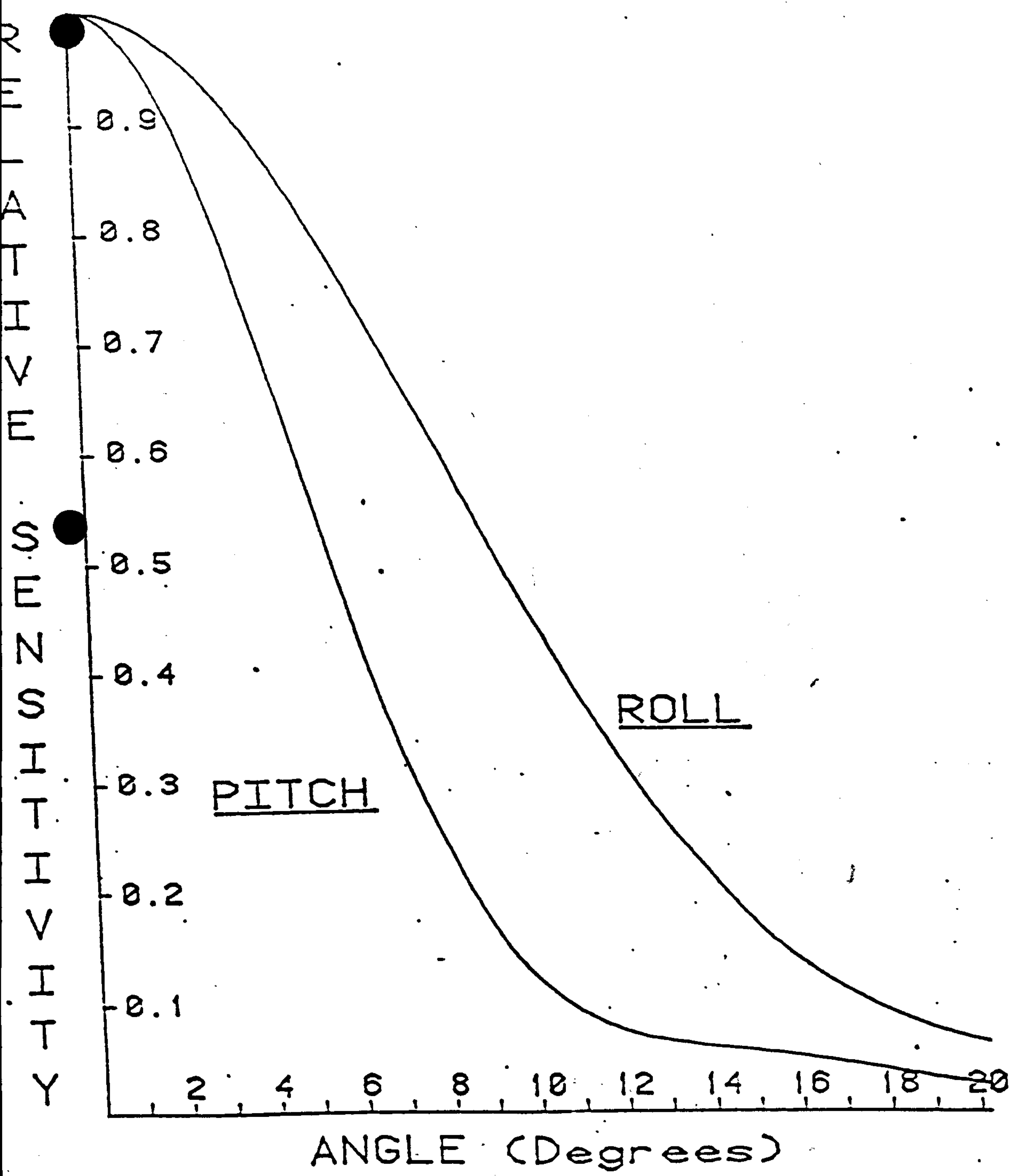


Figure 9 Relative sensitivity against depth for fixed rates of Transducer Pitch

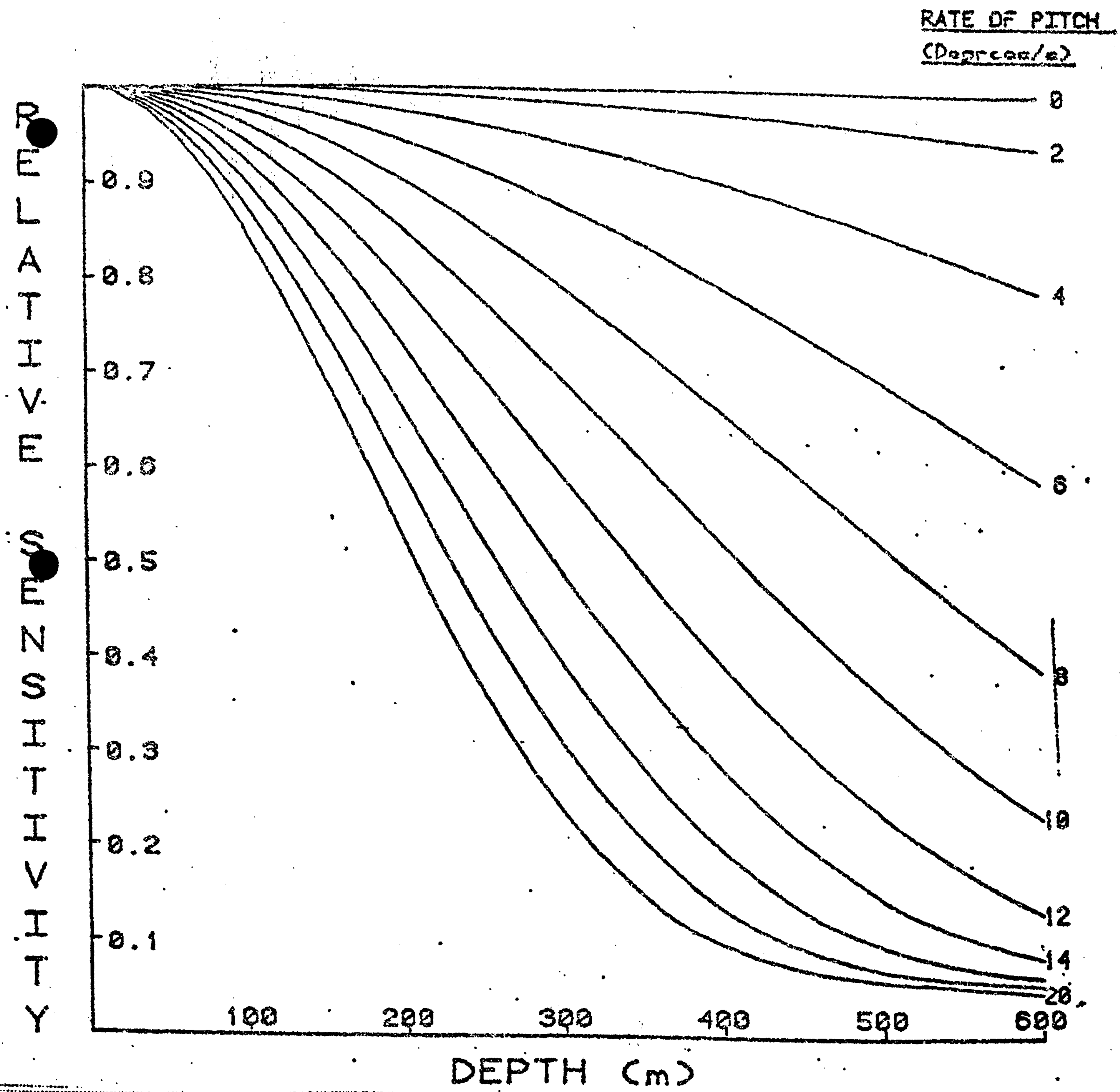


Figure 10 Relative sensitivity against depth for fixed water of Transducer Roll