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COMPARATIVE ANALYSIS OF SPLIT BEAM DATA

by

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ABSTRACT

Split beam data can provide high quality, in situ, fish target strength estimates, however a careful calibration is required to realize this potential. In some cases a standard target has been used to make a large number of measurements that cover the entire beam area of interest, then a general three dimensional surface is locally fitted to provide an expression for the beam pattern and a target strength calibration for all points. We use a simpler method that takes advantage of the known beam shape and requires relatively few data points. We also describe a new approach that optimizes the backscattering cross section, rather than the beam pattern estimation process. Preliminary work indicates that the attainable accuracy is comparable to that obtained with more elaborate methods.

INTRODUCTION

Standard targets are now used routinely to calibrate echo sounders with single beam transducers (Foote et.al. 1981). They also have been used to calibrate split beam echo sounders and to determine the beam pattern of the actual hull mounted transducer (Degenbol and Lewy 1987, Reynisson 1987a, Reynisson 1987b.

An uncalibrated split beam echo sounder measures relative backscattering cross section and relative beam angles. A complete calibration for cross section and beam angles requires that the actual position of the calibration sphere with respect to the transducer axis be known (Reynisson 1987b). This is a very demanding measurement. Calibration for backscattering cross section only is much simpler (Degenbol and Lewy 1987). In this case the split beam system will accurately measure backscattering cross section but yield relative angles only, these however are generally sufficiently accurate to reliably determine the physical position of the target.

Traditionally either calibration depends on a large number of measurements that are distributed uniformly over the entire beam surface of interest. A general three dimensional surface is fitted to the measured echo peak amplitudes and angles to produce a series of local estimates for the beam pattern $b(\theta,\phi)$ and the gain constant. Degenbol (1987) for example uses a bicubic spline algorithm to fit the "20 log amplitude" as a function of angles. This approach is appealing in its generality but ignores the well known basic beam shape.
The penalty is that many well distributed data points are required for the entire beam surface. There are also difficulties at the beam periphery due to the rapidly decreasing signal to noise at larger angles.

It is our hypothesis that split beam measurements can be adequately described by a conventional beam pattern function. Small and slowly varying deviations from the ideal beam pattern may be corrected by slight modifications to this function. This results in a simple calibration procedure that requires relatively few data points and computations. It will be sufficient to make measurements along a small number of tracks across the beam rather than over the entire surface. In addition we point out that the objective of the calibration must be clearly defined since fitting for beam pattern or backscattering cross section estimation will yield different results.

SPLIT BEAM CALIBRATION MODEL

The measured echo intensity i (V^2) from a single target like a calibration sphere can be described by:

$$i = g\, b(\theta,\phi)\, \sigma/4\pi \,, \qquad (1)$$

where g is the overall systems gain $(V/m)^2$, $b(\theta,\phi)$ the beam gain (one-way power) and σ the backscattering cross section (m^2). Its relation to target strength is (Urick 1975):

$$TS = 10 \log \sigma/4\pi \,. \qquad (2)$$

For a circular piston transducer the beam gain is given by

$$b(\theta) = \left(\frac{2\, J_1(ka \sin(\theta))}{ka \sin(\theta)}\right)^2 . \qquad (3)$$

Where J_1 is the Bessel function of the first kind, θ the beam angle, $k = 2\pi f/c$ and a the effective transducer radius (m).

For convenience and computational ease we have used an approximate beam gain function which is given by approximating the second order expansion of the square root of b(θ) by an exponential function (Appendix 1):

$$b(\theta) \sim \exp -\left(\frac{ka}{2}\sin(\theta)\right)^2 . \qquad (4)$$

Our echo sounder measures the fore/aft angle α and starboard/port angle ß (Figure 1). The transformation to spherical coordinates θ and ϕ is given by:

$$\tan(\theta) = \left(\tan^2(\alpha) + \tan^2(\beta)\right)^{1/2} \qquad (5)$$

$$\tan(\theta) = \frac{\tan(\beta)}{\tan(\alpha)} \qquad (6)$$

Equivalent expressions for θ are some times used (e.g. Degenbol 1987, Foote et.al. 1986). When polar coordinates are employed to describe the angles that are measured by the split beam echo sounder (Bodholt 1986, Ehrenberg 1981) then the conversion equations use sinθ, sinα and sinß.

Equations (1) and (4) yields a simple expression to estimate the beam gain b(θ):

$$v \sim (g_1 \sigma / 4\pi)^{1/2}\, b(ka_1, \theta - \theta_1) . \qquad (7)$$

Where v and θ are the measured peak amplitude and off axis angle and σ is the known backscattering cross section for the calibration sphere. The parameters g_1, ka_1 and θ_1 are estimated by least squares non linear regression. The offset angle θ_1 is required to produce a good fit and represents an idiosyncracy of the echo sounder we used. Note that the model so far is independent of ϕ.

Normally the estimated gain and beam pattern are used to produce a calibration curve or equation for the echo sounder, in order to convert measured amplitudes and angles from unknown targets to backscattering cross section estimates. We do not recommend this procedure as it optimizes the beam pattern fit and not the target strength calibration.

For optimal backscattering estimation we use the backscatter calibration model:

$$\sigma \sim \frac{4\pi\, v^2}{g_1\, b^2(ka_1, \theta - \theta_1)} \qquad (8)$$

METHODS

The measurements were made with a Simrad ES 400 split beam echo sounder (Foote et.al. 1984). It has a 38 kHz transducer with nearly cylindrical beam pattern with $\theta \sim 4°$ at the half power point. Three lines were used to suspend the calibration sphere (Cu, 60 mm ϕ, -33.7 dB) at a range of 20.4 m below the hull mounted transducer on the Norwegian research vessel R/V Eldjarn. The echo sounder was operated with the internal transmitter.

We use the parallel output of the split beam echo sounder and store the binary data on an IBM AT compatible computer. For each 0.1 m range increment the binary file records range r, echo amplitude v, fore/aft angle α and starboard/port angle β.

Programs were written in Turbo Basic (1987) to analyze the digitized echo. For each ping the appropriate peak was selected and its maximum amplitude and the angles on its leading slope were stored (Figure 2). From these the mean angles were computed.

Finally, the measured peak amplitudes and angles are fitted to the beam pattern or backscatter model, equation 7 or 8. This is done by a none linear regression algorithm that is part of a PC based statistical package (Statgraphics 1987). This software is also used to plot the results for examination and presentation.

RESULTS

Five data sets of approximately two hundred echoes each were collected by moving the calibration sphere along different tracks (Figure 3). In particular we note track one and two which lie approximately across and along ship's respectively. Each covers an angle of ±5° and data points are fairly even distribution with respect to θ. We also note track 5 which was collected with a nearly stationary target, to demonstrate the local variability of the measured amplitudes and angles.

The beam pattern model (equation 7) and the backscatter model (equation 8) were fitted to subsets of our data consisting of track 1, 2, 1+2 and finally 1-5. The estimated beam pattern for track 1+2 (Figure 4) describes the data well. This is amplified by the residuals (Figure 5).

To optimise the factors for target strength calibration the same data are fitted to the known, constant backscattering cross section of the calibration sphere (Figure 6). Except for a shift in the ordinate a residual plot would look identical. All tracks were fitted to either model to yield estimates for the gain factor g_1, the beam parameter ka_1 and the angular offset θ_1. These as well as the relative standard errors are listed in Table 1.

Table 1
Estimated gain factor g_1 and beam pattern constants ka_1, θ_1. The model abbreviations b and σ indicate optimal beam pattern and backscatter fitting respectively, n gives the number of amplitudes used. E9 represents 10^9.

Model	Track	n	g_1	+-%	ka_1	+-%	θ_1	+-%
b	1	155	7.614E9	0.54	27.23	0.40	-0.133	7.3
b	2	156	7.566E9	0.40	26.66	0.28	-0.112	6.1
b	1+2	311	7.578E9	0.35	26.91	0.25	-0.124	4.9
b	1-5	802	7.393E9	0.15	26.73	0.15	-0.107	4.2
σ	1	155	7.824E9	0.93	27.66	0.37	-0.155	6.5
σ	2	156	7.618E9	0.75	26.75	0.29	-0.105	7.2
σ	1+2	311	7.681E9	0.68	27.09	0.27	-0.127	5.6
σ	1-5	802	7.453E9	0.29	26.94	0.14	-0.115	4.0

DISCUSSION

The good fit between the beam pattern model and the data shown in Figure 4 is typical. It however suggests a slight sagging of $b(\theta)$ near ±3.5°, the effective half power points. This is due to our approximate beam pattern function. The exact beam pattern equation (3) would provide a better fit for the large angular range used here. In practice the acceptance angle would usually be limited between the -3 dB points and the observed deviation would be quite negligible.

No data points are shown at the apex of the beam pattern (Figure 4). This indicates that the target did not pass through the beam centre; its nearest approach was ~0.2°. Even without the central data the beam pattern is well defined, an even larger central θ range could be missing as the shape of the beam pattern function is given.

The optimal calibration fit (Figure 6) indicates the same trends. However an increasing difference is evident between the known and estimated backscattering cross section for larger θ. This is in contrast to the beam pattern fit which shows almost constant residuals for all θ (Figure 5). The increasing errors are explained by the quadratic and inverse nature of equation 8. In practice they reflect the well know fact that off axis target strengths are harder to measure than on axis.

To check our calculations we used the calibration factors from track 1+2 (Table 1, Figure 6) to estimate the target strength of the calibration target. A plot of these ofcourse is identical to Figure 6. It is interesting to note the mean of the measured backscattering cross sections $\sigma/4\pi$ = (4.21 ±0.02)E-4, it is significantly different from that for the calibration target of -33.7 dB = 4.27E-4. This is not surprising as our fit is optimal in the least squares sense while the average is a linear operation. The difference between the two values is 0.06 dB and will diminish when the accepted echoes are limited by the -3 dB points. The difference will totally disappear when a linear distance measure rather than distance square is used for fitting.

The relative standard errors given in Table 1 indicate the high precision of our parameter estimates. The largest error on the eight gl estimates is only 0.9% (0.04 dB) and those for ka_1 are even smaller. Errors in θ_1 do not exceed 7% (0.3 dB), this relatively large value indicates that our functions are quite insensitive to this parameter.

For each model several target tracks were analysed, omitting track 1-5 the variation between g_1 estimates is of the order of 0.05 dB. This is similar to the difference between models for this parameter estimate based on track 1+2. Off axis the difference in models will be more significant.

Near the acoustic axis an estimated backscattering cross section will be dominated by the errors in g_1 and a^2. We feel that gl is reproducible to 0.05 dB when a few hundred echoes are used. Observations of the almost stationary target (Figure 3, track 5) provide an estimate for the relative standard deviation for each measured a^2 of 1.5% (0.06 dB). A larger value is expected for off axis and smaller echoes.

To illustrate the effective difference between the estimated parameters (Table 1) we have plotted the normalized calibration factor (Figure 7). It is based on equation (8) and uses the backscatter calibration from track 1+2 as a reference. As expected the data from track 1 and 2 lie on either side of the straight line that represents track 1+2. For small θ a maximum difference of 2% is observed while off axis much larger deviations occur. This suggests that the beam pattern equations for track 1 and 2 are indeed slightly different. We also show the beam pattern calibration from track 1+2, even at the -3 dB points it deviates strongly from the strait line. These deviations are important when targets outside the half power points <u>must</u> be measured.

Our data points are nearly ideally distributed for the beam pattern fit (Figure 4). For the backscatter fit we however would like to have an increasing number of points (proportional to θ) as θ increases to reflect the larger frequency of fish targets in the beam periphery. In addition it also is desirable to have at least three or more tracks that cross the beam systematically, not just two as in this particular case. Work on more complete data sets is in progress.

We have observed an angular off set $\theta_1 \sim -0.1°$, this is of the same magnitude but not equivalent to the offset in α and β found by Bodholt (1986) for an identical split beam system.

We have deliberately chosen a simple beam pattern and calibration model and found it adequate to describe our data.

However several improvements are possible and may be desirable when more measurements are available:

1. Exact beam pattern model, e.g. circular piston or rectangular.
2. Include a small θ dependence to correct for rotational asymmetries. A small ϕ dependence is suggested by our data and those presented by Reynisson (1987a).
3. Use the angles α and β rather than θ and ϕ. This is suggested by the above-mentioned angular offset (Bodholt 1986).

The calibration method presented here is ofcourse applicable to a dual beam system. However it also could be used for the calibration of a single beam transducer or echo sounder when the angles α and β have been measured geometrically, as is usually the case when a calibration facility is used. Fitting a beam pattern or target strength calibration model to a range of observations will certainly provide a better calibration than a single on-axis measurement.

We have realized from calibration exercises and fish data that a beam threshold must be applied in order to maintain the signal-to-noise ratio and stability in the angle determination particularly for small echoes. In practice we therefore concentrate on obtaining the correct beam gain matrix within the -3 dB points, rather than to stretch the observation volume and calibration procedures to larger angles where poor backscattering cross section estimates and severe threshold biasing are inevitable.

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APPENDIX 1 -- Approximate beam pattern equation:

The directivity of a circular piston transducer is given by:

$$b^{\frac{1}{2}}(\theta) = d(\theta) = \left(\frac{2\ J_1(x)}{x}\right) .$$

For convenience define: $x = ka \sin(\theta)$ with $k = 2\pi\ f/c$

Using the Taylor expansion for $J_1(x)$ yields:

$$d(\theta) = 1 - \frac{x^2}{8} + \frac{x^4}{192} - \frac{x^6}{9216} +$$

The first two terms are identical to a Taylor expansion of the exponential function, thus:

$$d(\theta) \sim \exp\left(- \frac{1}{8}\ x^2\right).$$

The approximation is useful for θ between the half power points, i.e. $x \leq 1.614$.

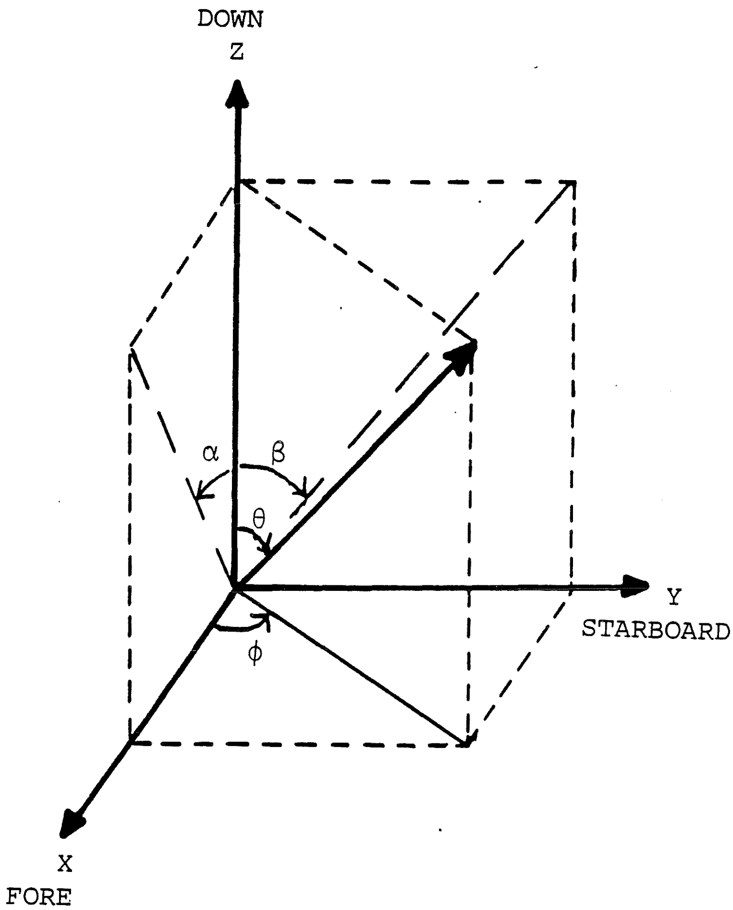

Figure 1. Used coordinate system. The fore/aft angle α and starboard/port angle β are measured in the x/z and Y/Z plane respectively. Spherical coordinates θ and ϕ are also shown.

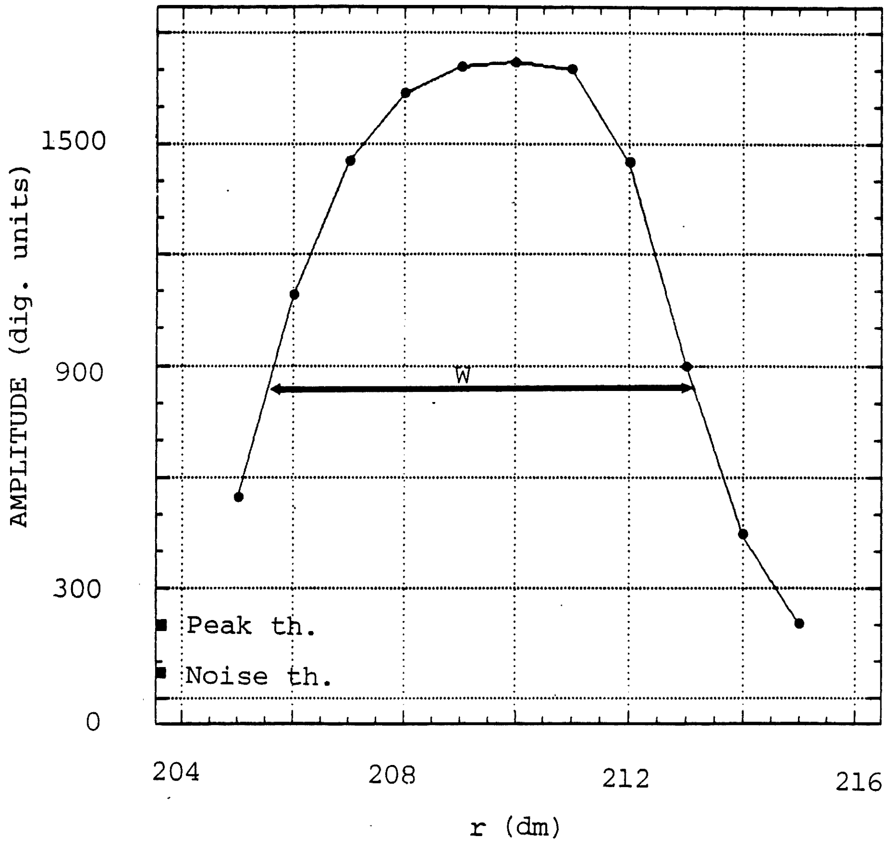

Figure 2. Single pulse from the sphere at 20.4 m depth. Only data above the noise threshold are collected. Small dots indicate actual data points, with angle data available on the rising part of the pulse. A single-target peak must exeed the peak threshold, and is characterized by the peak amplitude, width at half amplitude, W, angles α and β and their standard deviation.

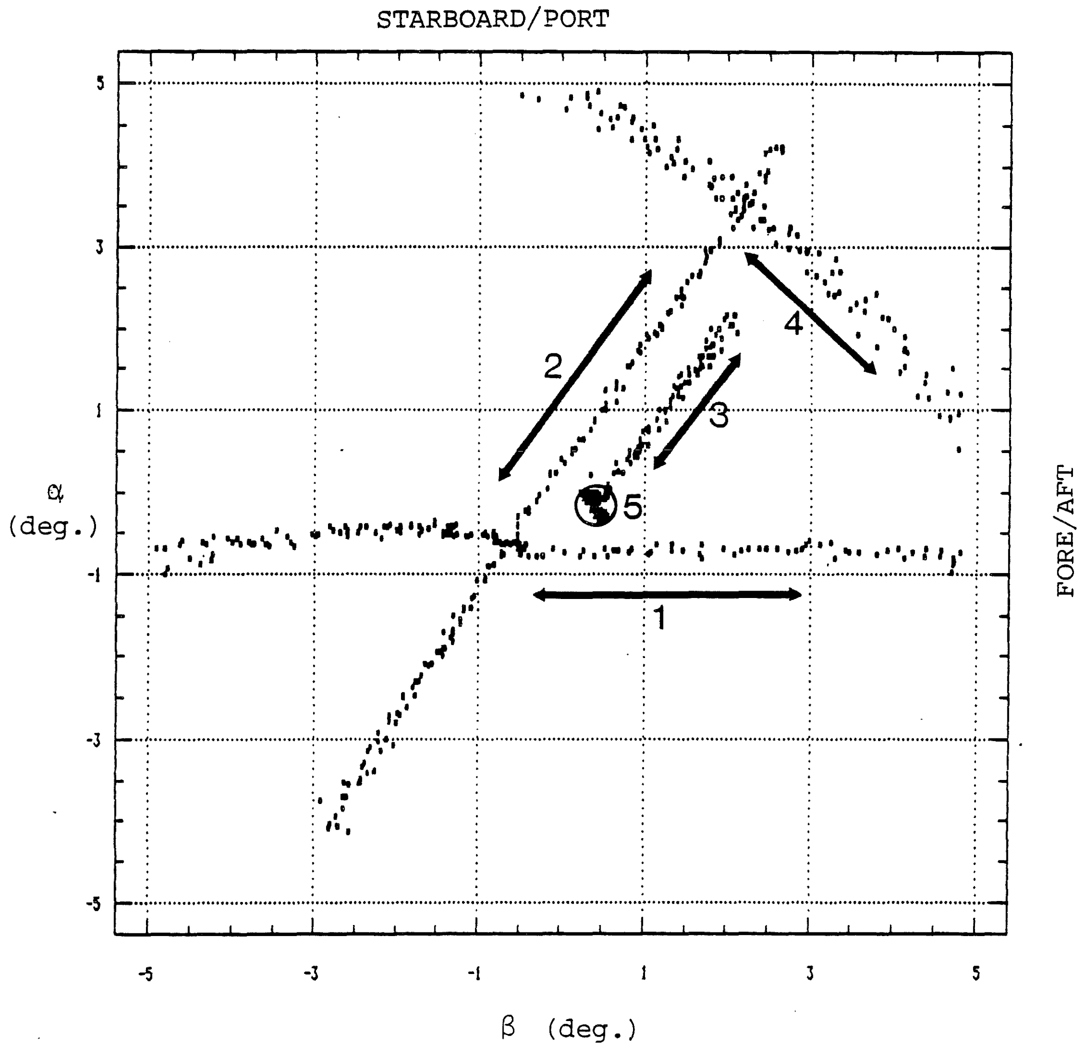

Figure 3. A plot of α versus β gives the target position as seen by the split-beam echo sounder. The numbers one through five identify different paths of the calibration sphere. Note that track no. 5 was recorded with a nearly stationary target.

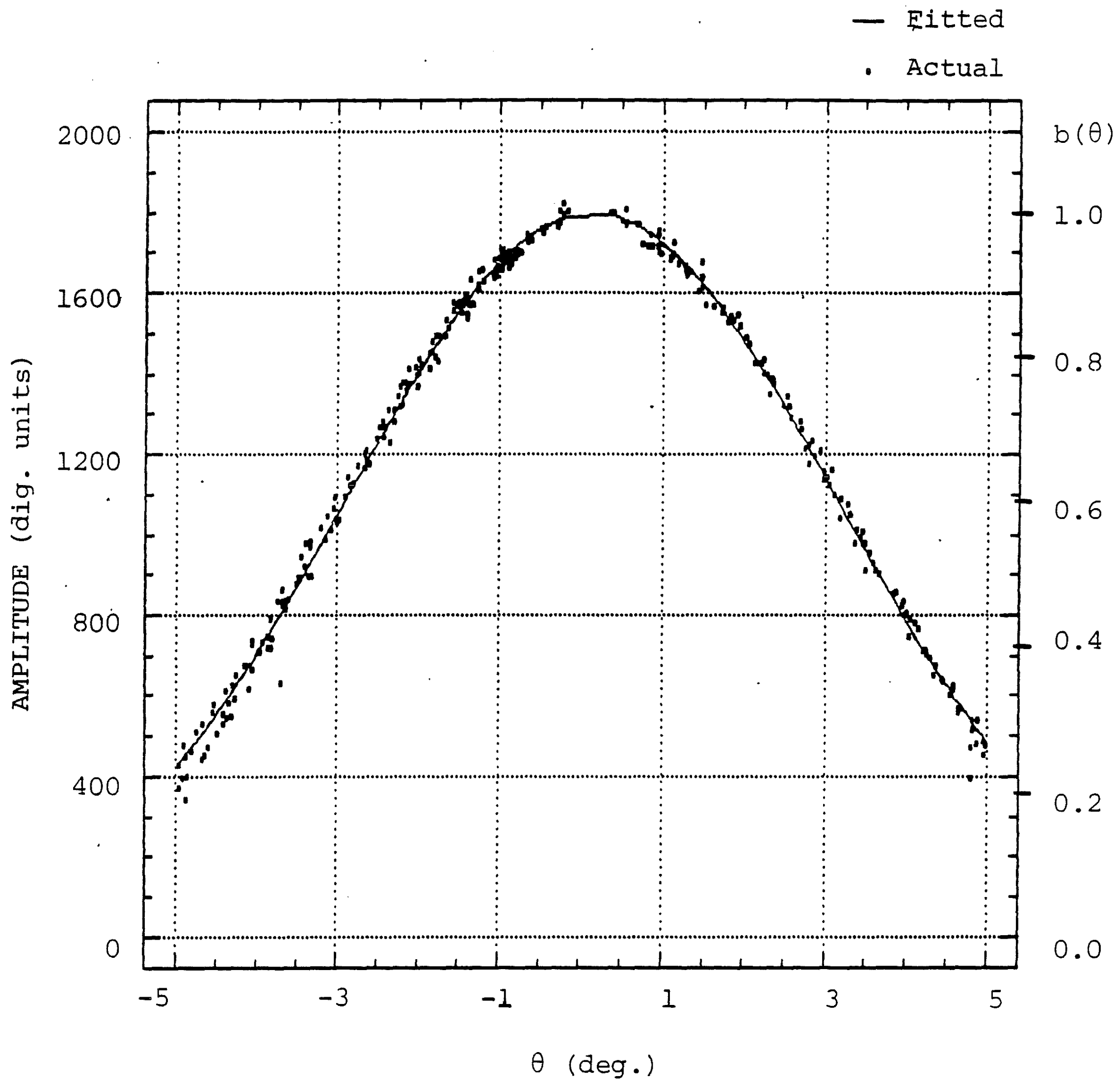

Figure 4. The approximate beam pattern, fitted to the data from track one and two.

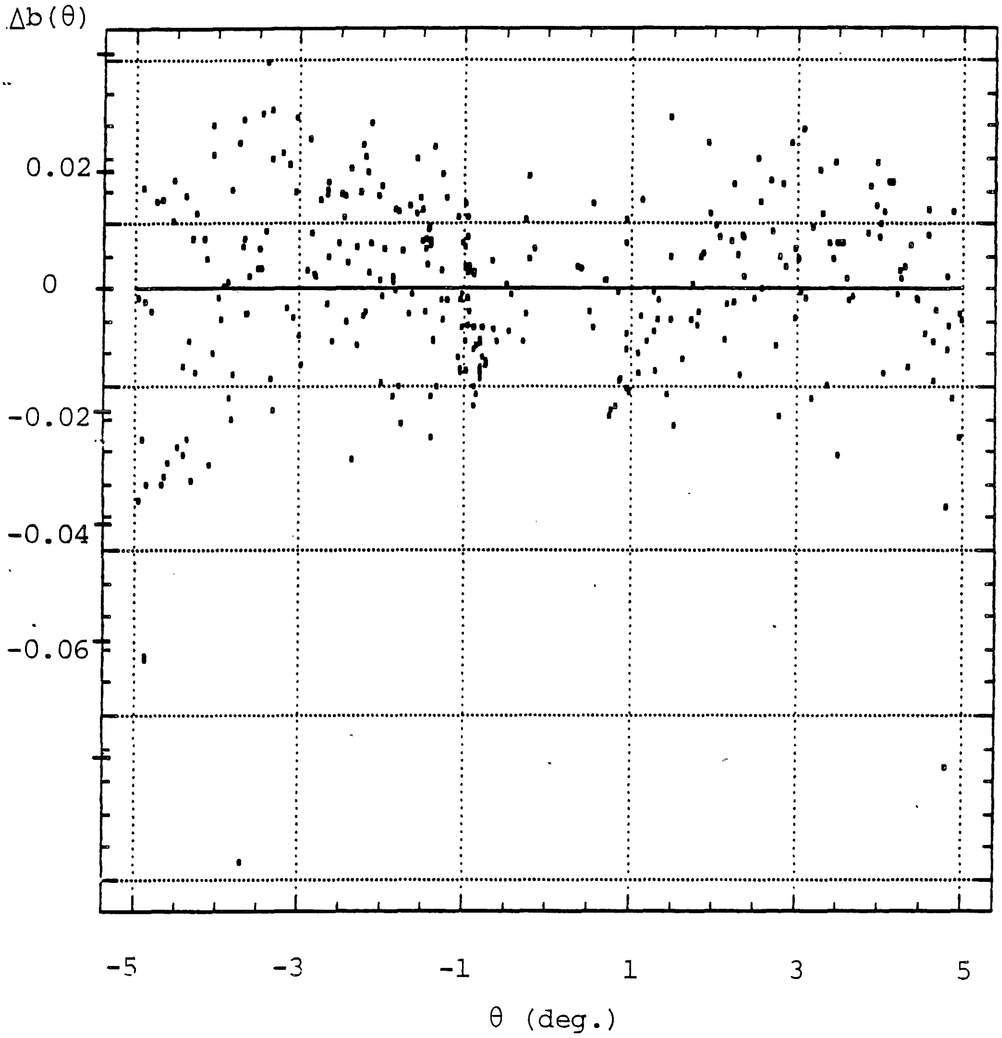

Figure 5. The residuals, $\Delta b(\theta)$, from the fit shown in Fig.4

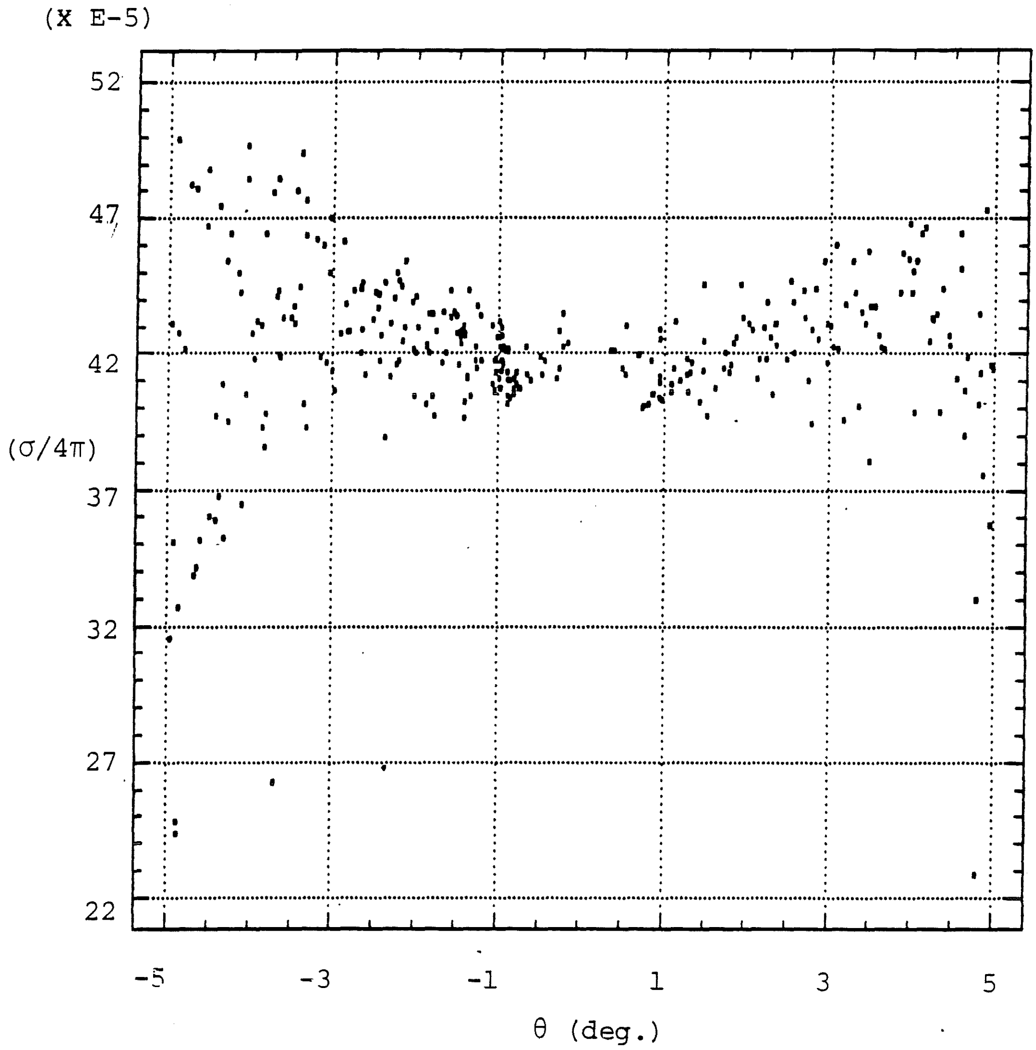

Figure 6. The data from track 1 and two are fitted by the backscatter model.
The calibration sphere has a TS = -33.7 dB, or a σ/4π= 42.7E-5.

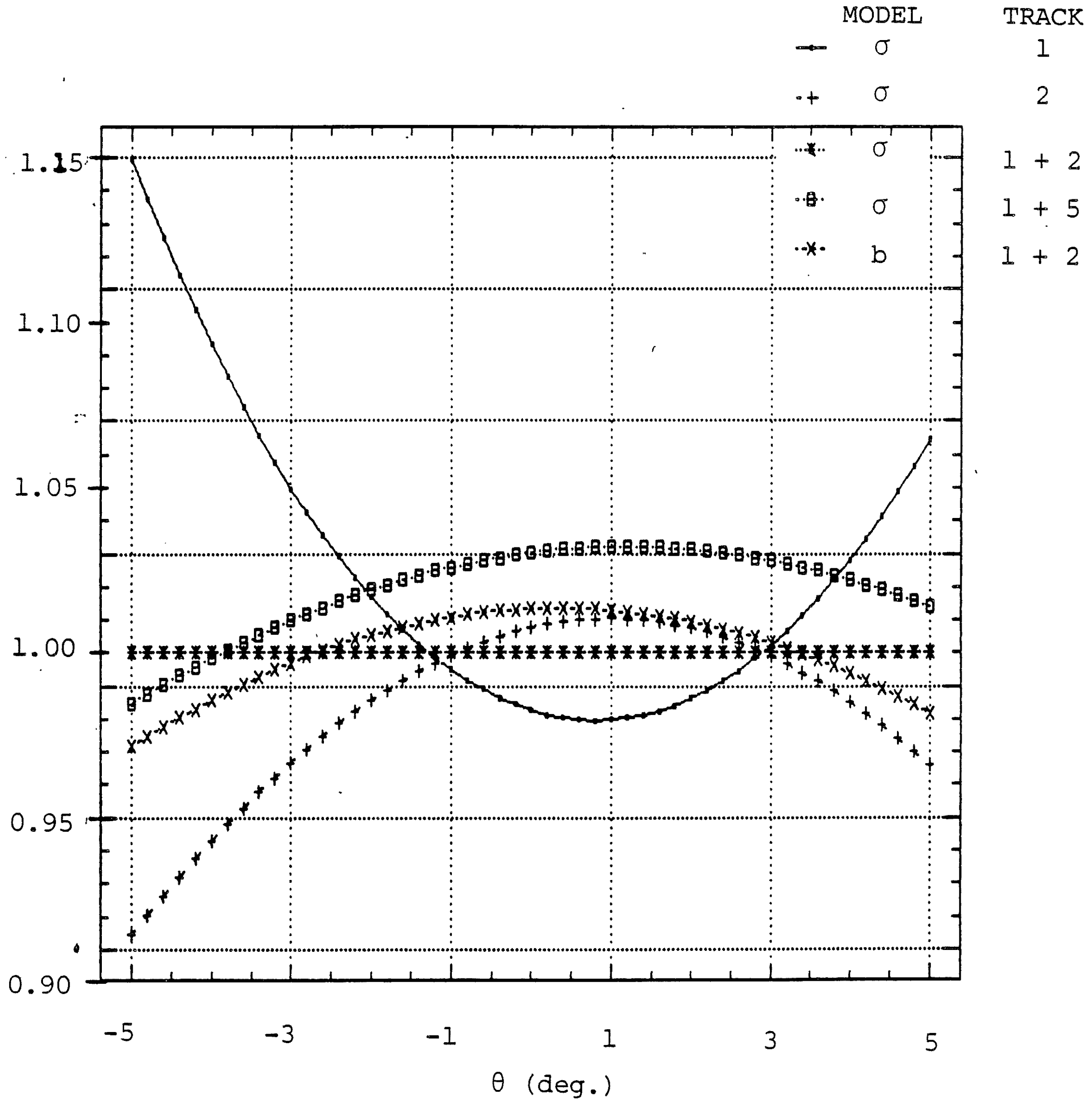

Figure 7. Relative calibration factors from equation 4, normalized with respect to data from track 1 + 2, using the backscatter model.