DEVELOPMENT OF A PASSIVE SONAR SYSTEM FOR LOCALISATION OF AN UNDERGROUND ACOUSTIC SOURCE

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1. INTRODUCTION

The ability to detect and determine the position of an underground sound source is desirable both for civilian and military purposes, for example, for rescue following collapse of mining tunnels, or for the detection of covert underground operations [1,2,3]. Compared to the similar problem in air or in water there are a number of features which cause additional difficulties - the medium is likely to be inhomogeneous with unknown properties, objects which scatter sound are usually present, and there are practical difficulties in positioning (and moving) the acoustic sensors.

A suitable acoustic system might consist of a number of acoustic sensors positioned in the suspected locality of the sound source, as shown in Figure 1. The type of sensor employed depends on their location. Geophones are velocity-sensitive transducers intended for use at or just below the ground surface. Hydrophones are pressure sensitive and designed to operate in water; they are therefore suitable for locating in water-filled boreholes. The use of such boreholes offers the advantage that the interference from noise caused by activity on the surface is reduced; also, by placing the sensors at various depths a 3-dimensional arrangement can be obtained, more so than with an arrangement on the surface. The maximum operating depth of 300 m for the commonly-used spherical hydrophone [4] is more than adequate for the current application.

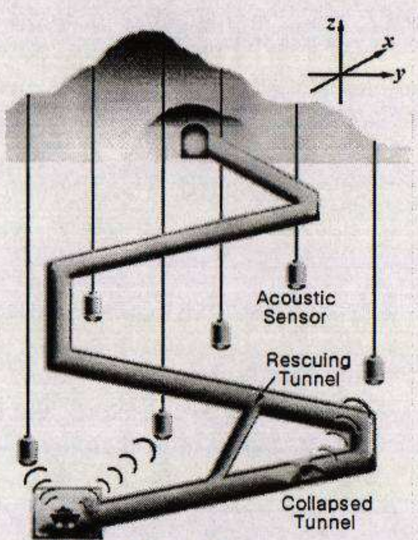

Figure 1. An underground passive SONAR system for rescue following collapse of mining tunnels.

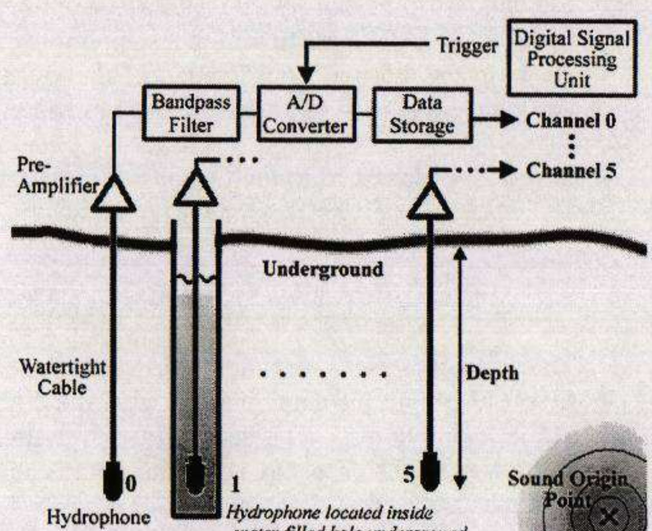

Figure 2. The overall layout of the underground experimental apparatus.

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In the work reported here, the underground material is granitic beyond a depth of just a few meters. The standard value for the wave propagation velocity in granite is about 6000 m/s [5] but there will be inevitable variations from this in practice, caused by inhomogeneities such as rock faults and rock-soil mixtures. Each hydrophone in the array of sensors will receive acoustic signals from the sound source which have propagated through a medium with uncertain sound speed and unknown attenuation, and possibly along more than one path. The information available is therefore restricted to the detected arrival times and perceived powers of the signal, without assumptions about the sound speed and rate of attenuation [6].

The aim of the work is to develop an underground acoustic system which detects and determines the location of an underground hammering sound, using an array of hydrophones positioned underground. Three algorithms for estimating the location are presented and their predictions are compared with the known location in a particular experiment.

2. EXPERIMENTAL ARRANGEMENT

The general layout of the electroacoustic system is shown in Figure 2. Six holes of diameter 150 mm were bored vertically into the ground to depths of between 80 m and 120 m in the vicinity of an existing underground tunnel. After drilling, these boreholes filled with water naturally. A hydrophone, Brüel and Kjær type 8106 [7], was placed at or near the bottom of each hole, with a 150 m watertight low-impedance core cable (B&K AC0101) providing the connection to the surface. To eliminate the 60 Hz ground noise caused by the potential difference between the ground surface and the hydrophone location [8], batteries were used to power all of the components of the system, and the cable to each hydrophone was completely shielded [9].

The output from each hydrophone was amplified by 60 dB for all six channels and then captured by a multi-chanel A/D storage unit at a sampling frequency of 10 kHz, using the DT-VEE software package [10]. In parallel with observation of the signals by a battery-operated digital storage oscilloscope, a headphone was used to monitor the sound within the boreholes.

Several locations within the tunnel were selected for the origin of the sound, which was produced by a 10 kg hammer being struck on the tunnel wall.

3. ALGORITHMS FOR LOCATING THE SOUND SOURCE

Three methods have been developed and tested for determining the location of the sound source. The first of these, a time-delay method, uses the differences in the detected arrival times of the sound signal at the hydrophones. The second, a power-attenuation method, uses the information provided by the relative strengths of the signals. The third is a hybrid method in which both the arrival times and signal strengths are used.

In all of the methods the position of the ith hydrophone (i = 0, 1,...., n-1) is denoted by cartesian coordinates (x_i, y_i, z_i) and the unknown location of the sound source by (x, y, z). The sound speed v and attenuation α (dB/m) are assumed to be constant, but also unknown. Solutions for x, y, z, v and α are

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sought by minimising cost functions. Although six hydrophones were used in the experimental work, the methods are not limited to this number and more could be used to improve the estimating power.

3.1 Time-delay method

Since the time at which the sound originates is unknown, all times in the problem are relative and one of the hydrophones, label i, is taken as the reference. ΔT_{ij} denotes the time of arrival, or time delay, of the signal at the jth hydrophone relative to its arrival at the reference hydrophone. Ideally, $r_j - r_i = \Delta T_{ij}.\nu$, where $r_i = \sqrt{(x_i - x)^2 + (y - y_i)^2 + (z - z_i)^2}$ is the distance from the sound source to the ith hydrophone. However, variations in ν and errors in measuring the arrival times mean that in general it will not be possible to satisfy this equation exactly. Instead, a solution is sought which minimises the sum of the squares of the residuals, given by the function

$$F_{1,i}(x, y, z, \nu) = \sum_{j=0, j\neq i}^{n-1} \left(r_j - r_i - \Delta T_{ij}.\nu\right)^2 \quad (1)$$

The time delays, ΔT_{ij} for j = 0, 1,...., n-1, are calculated using unbiased cross-correlation [11] between the signal from each hydrophone and that from the reference. Errors in determining these time delays may be caused by propagation effects and by the presence of other noise sources in the environment.

3.2 Power-attenuation method

The acoustic waves radiated by the sound source are assumed to be attenuated geometrically according to the inverse square of distance and by the medium at a rate of α dB/m, so that the intensity at distance r is given by

$$I(r) = 10^{\alpha(1-r)} I_0 / r^2 \quad (2)$$

where I_0 is the intensity at 1 m from the source [12]. The material attenuation coefficient, α, is unknown but is assumed to be constant.

The recorded signals consist of samples of discrete pressures $P(k)$, k = 0, 1,..., N-1. If P_{s+n} denotes a sample containing the signal from the sound source together with background noise, and P_n a sample of background noise only, then the time-averaged acoustic intensity of the signal from the sound source can be calculated using

$$\varepsilon I = \frac{1}{N}\sum_{k=0}^{N-1} P_{s+n}^2(k) - \frac{1}{N}\sum_{k=0}^{N-1} P_n^2(k) \quad (3)$$

where ε is a constant, equal to $\rho_0 \nu$ for a plane wave. The power ratio ΔP_{ij} of the jth hydrophone relative to the reference hydrophone is defined as $I(r_j)/I(r_i)$. According to the attenuation formula of Eq. (2) this ratio theoretically should equal $\left(r_i^2/r_j^2\right)10^{\alpha(r_i - r_j)}$. The cost function to be minimised is therefore

$$F_{2,i}(x, y, z, \alpha) = \sum_{j=0, j\neq i}^{n-1} \left(\Delta P_{ij} - \frac{r_i^2}{r_j^2} 10^{\alpha(r_i - r_j)}\right)^2 \quad (4)$$

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3.3 Hybrid method

Full use of the available information - both time delay and power-attenuation - may be made by taking a weighted sum of the above cost functions:

$$F_{3,i}(x,y,z,v,\alpha)=\sum_{j=0,j\neq i}^{n-1}\left\{\left(r_j-r_i-\Delta T_{ij}.v\right)^2+\kappa.\left(\Delta P_{ij}-\frac{r_i^2}{r_j^2}10^{\alpha(r_i-r_j)}\right)^2\right\} \quad (5)$$

where κ is a weighting factor. Various values of κ were used in the experiments, as reported below.

3.4 Optimisation

Because of the likelihood that local minima of the cost functions could lead to false solutions, two approaches have been used to estimate the variables x, y, z, v, and α. A coarse search of the variable space, within predetermined limits, is made to narrow down the region where the true minimum occurs. The Nelder-Meade simplex search algorithm [13,14] is used to refine this search. In this algorithm, a simplex in n-dimensional space is characterised by the n+1 distinct vectors defining the vertices of the simplex. At each step of the search, a new point in or near the current simplex is generated. The function value at the new point is compared with the function values at the vertices of the simplex and the new point replaces one of the vertices if it has a low function value, giving a new simplex. This step is repeated until the diameter of the simplex is less than a specified tolerance.

4. RESULTS AND DISCUSSION

The cartesian coordinates of the six hydrophones are listed in Table 1. The x- and y-coördinates are distances east and north respectively of a fixed reference point, while the z-coordinates are heights above mean sea level, determined from the known height of the ground surface and the depths of the boreholes. In practice there is some difficulty in determining precisely the x- and y-coordinates because of deviation from the vertical in the drilling operation. The hydrophone locations and hammering position are shown schematically in Figure 3.

Table 1. Hydrophone locations and hammering position

Sensor no.	x (m)	y (m)	z (m)	Distance from hammering position (m)
0	593.5	671.4	338.7	99.8
1	608.7	656.4	366.8	98.4
2	688.3	600.2	376.3	122.1
3	673.6	594.2	354.9	124.0
4	701.0	644.8	341.7	74.9
5	668.1	640.3	371.7	83.6
Hammer	682.0	717.3	342.3	0

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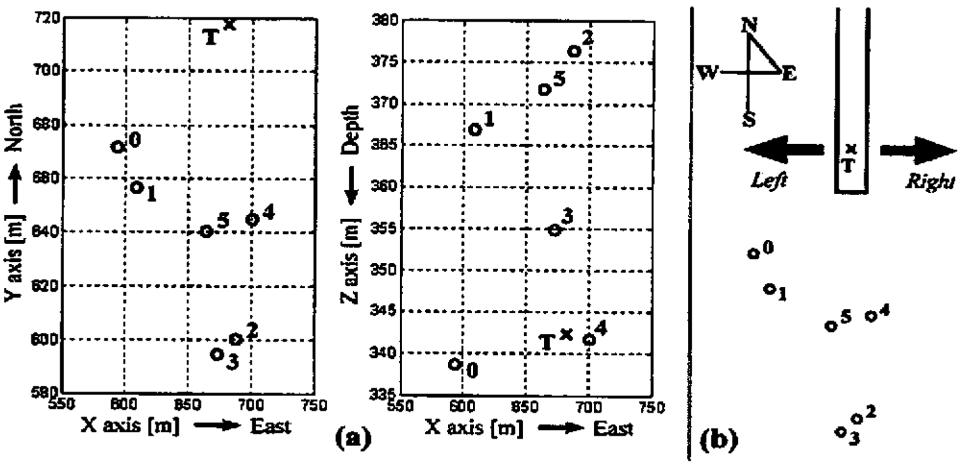

Figure 3. Schematic views of hydrophone locations (o) and hammering position (×)

Typical time responses and their corresponding FFT spectra, for hydrophones 1, 3 and 4, are shown in Figures 4 and 5 respectively. The time response for hydrophone 4 (the closest to the source) shows a clear second arrival of the hammering shock, believed to a reflection from the ground surface. Multiple paths may also result from refraction and scattering within the inhomogeneous medium, producing dispersion of the signal in time. This, together with environmental noise, leads to uncertainty in calculating time delays between the signals. Although the signals and their spectra are shown for the same hammering event, there are significant differences between the spectra, indicating that the attenuation is frequency-dependent.

4.1 Time-delay method

The measured time delays between the hydrophone signals, calculated using cross correlation [15], are listed in Table 2. Because of the sampling frequency of 10 kHz, the values could be calculated only to the nearest 0.1 ms. Ideally the values should be anti-symmetric ($\Delta T_{ji} = -\Delta T_{ij}$) and related by the equation $\Delta T_{kj} = \Delta T_{ij} - \Delta T_{ik}$; however, deviation from this ideal occurs because of noise and propagation effects on the signals. For comparison, the theoretical time delays, calculated for the known source position and assumed velocity of sound $v = 6000$ m/s, are shown in Table 3.

Table 2. Measured time delays (ms) between hydrophones

Obj. Ref.	0	1	2	3	4	5
0	0	0.2	4.3	4.4	-3.4	-1.2
1	-0.3	0	4.0	4.1	-4.2	-1.4
2	-4.3	-4.0	0	0.2	-8.1	-5.3
3	-4.4	-4.1	-0.1	0	-8.3	-5.5
4	3.4	4.3	8.0	8.2	0	2.8
5	1.2	1.4	5.2	5.5	-2.8	0

Table 3. Theoretical time delays (ms) for $v =$ 6000 m/s

Obj. Ref.	0	1	2	3	4	5
0	0	0.23	3.72	4.04	-4.14	-2.70
1	-0.23	0	3.95	4.27	-3.91	-2.47
2	-3.72	-3.95	0	0.32	-7.86	-6.42
3	-4.04	-4.27	-0.32	0	-8.18	-6.74
4	4.14	3.91	7.86	8.18	0	1.44
5	2.70	2.47	6.42	6.74	-1.44	0

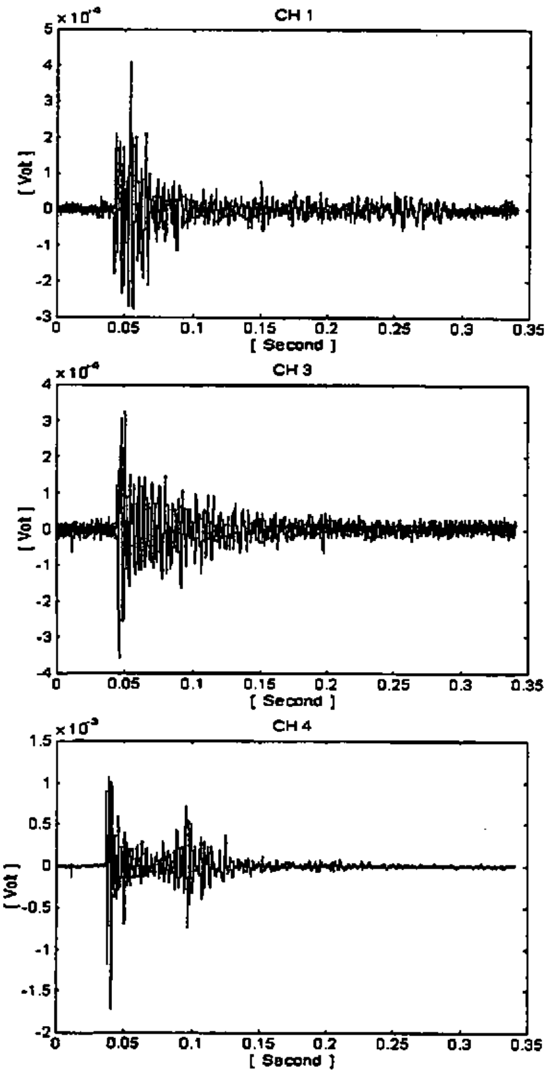

Figure 4. Typical time responses of the hydrophones for a single hammer blow

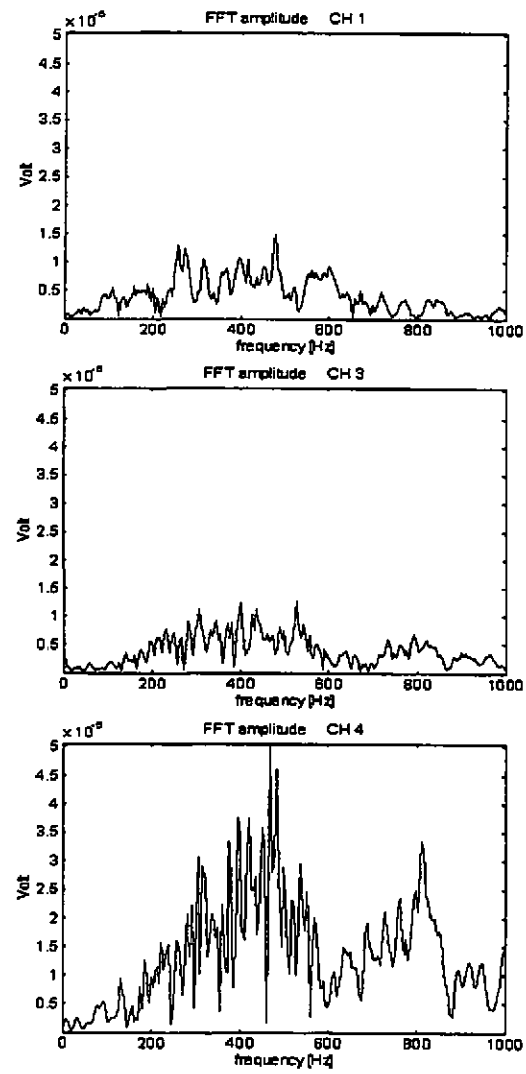

Figure 5. FFT spectra of the time responses shown in Figure 4.

The estimates of the location of the sound source obtained by minimising the time-delay function, Eq. (1), are given to the nearest metre in Table 4. The estimates vary because of the emphasis that the time-delay function places on the reference hydrophone. In this experiment it is possible to compare the measured (Table 2) and theoretical time delays (Table 3) and from the differences to determine a measure of reliability for each hydrophone. However, this relies on knowing the true location of the source and so is not feasible in general. An alternative approach is to recognise that the time-delay function, if divided by v^2, represents the sum of the squares of the discrepancies between the estimated and measured time delays. The optimised value of that function may therefore provide an assessment of the reliability of the measurements for each hydrophone. The values shown in the final column of Table 4 indicate that this provides a useful, if not infallible, guide - the lowest value of the time-delay function is that obtained when taking hydrophone 0 as the reference, and this corresponds to the best estimate. However, the correspondence is not universal; for example, using hydrophone 1 as reference produces a higher value of the function than in any other case but provides the second best estimate of the location.

In the experiment, the source is situated on one side (to the north) of the array of hydrophones. All of the positions estimated by the time-delay method are further from the array than the true location.

Table 4. Estimated positions of the sound source, distance from known location, and sound speed estimates using the time-delay method.

Reference hydrophone	Estimated location			Distance from true location	Estimated velocity	Time-delay function
	x (m)	y (m)	z (m)	r (m)	v (m/s)	(m^2)
0	684	727	332	14.3	6500	2.96
1	688	735	329	23.0	6330	9.14
2	694	746	326	35.3	6439	5.36
3	690	736	325	26.8	6390	4.64
4	689	737	320	30.6	6359	3.28
5	703	761	324	52.0	6637	7.78
True location	682.0	717.3	342.3	0	-	-

4.2 Power-attenuation method

The measured power factors for each hydrophone, given by the right hand side of Eq. (3), are plotted in Figure 6 (×) against distance from the known source location. Theoretical curves are also shown for a best-fit attenuation coefficient $\alpha = 0.0164$ (continuous line) and for upper and lower bounds, $\alpha = 0.0131$ and $\alpha = 0.0205$ respectively (broken lines). The power ratios between the hydrophones, determined from the measured power factors, are listed in Table 5. Corresponding theoretical power ratios, calculated for $\alpha = 0.0164$ and the known source location, are given in Table 6.

The greatest discrepancy occurs in the values relating sensors 1 and 2, where the measured power ratio of sensor 2 relative to sensor 1 is over five times the theoretical ratio. This is also illustrated in Figure 6, where the measured power factors for hydrophones 1 and 2 can be seen to lie at opposite extremes of the attenuation bounds. Further comparison of the measured and theoretical power ratios indicates that the discrepancy persists in all of the values with hydrophone 1 as the reference.

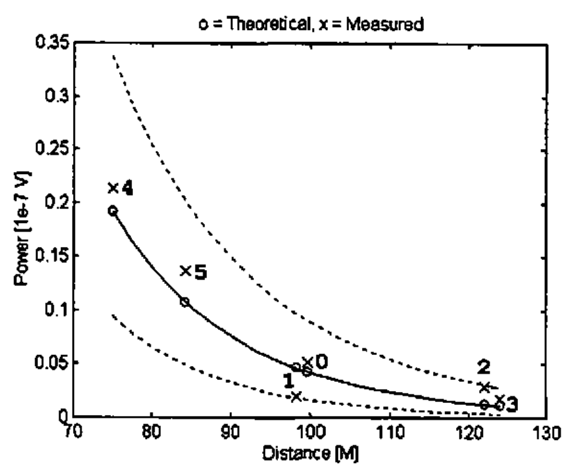

Figure 6. Measured acoustic power (X) and theoretical power (O) of the hammering shock *vs.* distance.
Continuous line: $\alpha = 0.0164$. Broken lines: (upper) $\alpha = 0.0131$, (lower) $\alpha = 0.0205$.

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Table 5. Measured power ratios (ΔP_{ij}) between hydrophones

Obj. Ref.	0	1	2	3	4	5
0	1.0	0.375	0.564	0.332	4.12	2.64
1	2.67	1.0	1.51	0.887	11.0	7.05
2	1.77	0.664	1.0	0.589	7.31	4.68
3	3.01	1.13	1.70	1.0	12.4	7.95
4	0.243	0.091	0.137	0.081	1.0	0.641
5	0.379	0.142	0.214	0.126	1.56	1.0

Table 6. Theoretical power ratios for $\alpha = 0.0164$ dB/m

Obj. Ref.	0	1	2	3	4	5
0	1.0	1.08	0.288	0.259	4.52	2.51
1	0.923	1.0	0.266	0.239	4.17	2.31
2	3.47	3.76	1.0	0.901	15.7	8.70
3	3.857	4.18	1.11	1.0	17.4	9.66
4	0.221	0.240	0.064	0.057	1.0	0.555
5	0.399	0.432	0.115	0.104	1.80	1.0

The solutions obtained for x, y, z and α using the power-attenuation method are given in Table 7. The optimised values of the power ratio function, Eq. (4), will tend to be smaller for reference hydrophones with high power and so for this method the values have been normalised by multiplying in each case by a factor proportional to the square of the measured power at the reference hydrophone. The highest value of this normalised function occurs for reference hydrophone 1 and this corresponds to the worst estimate of position. The values for reference hydrophones 2, 3, 4 and 5 are all similar although the estimates of the source location show considerable variation. The best estimate is that obtained with hydrophone 3 as reference. It should be mentioned that convergence to a solution is much slower for the power-attenuation method than for the time-delay method.

The estimated locations are all closer to the array of hydrophones than the true location, in contrast to the estimates obtained using the time-delay method.

Table 7. Estimated positions of the sound source, distance from known location and attenuation using the power-attenuation method.

Reference hydrophone	Estimated location			Distance from true location	Estimated attenuation	Power ratio	Normalised power ratio
	x (m)	y (m)	z (m)	r (m)	α (dB/m)	function	function
0	661	667	321	58.2	0.0170	0.51	1.37
1	661	652	325	70.4	0.0288	5.09	1.92
2	689	698	354	23.5	0.0081	1.24	1.06
3	690	711	355	16.4	0.0126	3.60	1.07
4	666	669	330	52.0	0.0130	0.022	1.00
5	669	674	334	45.6	0.0110	0.054	1.01
True location	682.0	717.3	342.3	0	-	-	-

4.3 Hybrid method

As already observed, the time-delay method generally overestimates the values of x and y whereas the power-attenuation method underestimates these values; both methods generally underestimate z. It may be expected, therefore, that the hybrid method should give intermediate values, improving the estimates of x and y. This is borne out in most cases by the estimates for the source location obtained using the hybrid method and shown in Table 8. A sample of different values for the weight κ has been tried and further work needs to be done to determine an appropriate weight for each case.

Table 8. Estimated positions of the sound source, distance from known location, sound speed and attenuation using the hybrid method.

Reference hydrophone	Weight κ	Estimated location x (m)	y (m)	z (m)	Distance from true location r (m)	Estimated velocity v (m/s)	Estimated attenuation α (dB/m)
0	20	681	721	333	9.9	6460	0.0246
1	7	680	717	338	5.1	6388	0.0412
2	125	688	717	338	7.2	6139	0.0130
3	23	685	720	339	5.3	6334	0.0175
4	600	692	742	325	31.5	6451	0.0175
5	1300	678	712	340	6.6	6762	0.0206
True location	-	682.0	717.3	342.3	0	-	-

5. CONCLUSIONS

Three methods for estimating the location of an underground sound source using measurements from an array of hydrophones have been presented. In the experiment reported, where the source was on one side of the array, the time-delay method gave estimated locations further from the array, and the power-attenuation method gave locations closer to the array, than the true position. The hybrid method is capable of steering a middle path to give more accurate estimates. Of the three methods, the power-attenuation method was the slowest to converge.

Various matters remain to be addressed. All of the methods rely on the choice of a reference hydrophone; some attempt has been made to assess the reliability of the information provided by each hydrophone but this work needs to be extended to enable the choice to be made without prior knowledge of the location of the source. Alternatively the methods could be recast to be independent of such a choice. Another question concerns the weighting in the hybrid method in order to provide an appropriate balance between the time-delay and power-attenuation terms.

The experimental data could be improved by using higher sampling rates in recording the time signals and by using statistical averaging over a number of detections of sound from the sound source.

In the experiment reported the hydrophone sensitivity is sufficient to record the hammering shock up to a range of at least 250 m and the results suggest that an estimation of location can be made to within 30 m. The use of geophones in the suspected area may then be a feasible approach to determine the location more accurately [2,3].

Other features of the problem are more difficult to address. The assumption of uniform sound propagation velocity and attenuation coefficient is open to question and could be improved only with prior knowledge of the underground medium. Other propagation phenomena - reflection, reverberation, scattering, refraction - also need to be taken into account.

6. ACKNOWLEDGEMENTS

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