Locating leaks from water supply pipes using the passive acoustic method

A. Lockwood, T. Murray, G. Stuart and L. Scudder

ABSTRACT

Acoustic techniques for locating water leaks make use of the noise created by water leaking from a pipe; most require contact with the pipe network. This paper reports on the location of leaks in urban environments using acoustic loggers at the ground surface itself, remote from the pipe. An increase in the root-mean-squared (RMS) acoustic signal amplitude of ~7.5 to ~12.5 dB above background was detected above leaks from both plastic and metal pipes. The peak frequency of the acoustic signal was ~750 Hz above a metal pipe, decreasing to ~400 Hz at a distance of 1 m. Plastic pipes had a lower source leak frequency (below 700 Hz) and dropped to ~350 Hz at 1 m. Background noise was predominantly below 150 Hz, which was suppressed using a high pass filter. The RMS signal amplitude directly above the leak decreased with increasing pipe depth, but was detectable for all pipe depths (0.4–1.0 m) covered in this work. An array of acoustic sensors at the surface can successfully detect and locate leaks without direct access to the pipe network, providing a robust and rapid leak location method.

Key words | shallow acoustic, urban environment, water leak location, water supply

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INTRODUCTION

The provision of drinkable water is regarded as a basic right in the developed world and considerable time and money is expended in supplying and maintaining this food grade product (Pickerill & Malthus 1998). The reduction of leakage from the potable water network is an important element in the strategy to achieve sustainable use of this essential resource (Pilcher 2003). Water leakage levels are often given as a percentage of distribution input, and values of 30% are not unheard of (e.g. Jowitt 1995; Torsun 1998). The key to a successful leakage management programme is the rapid location and subsequent repair of leaks from the network (Farley & Trow 2003). Rapid leak location and repair both reduces the water lost (i.e. wastage) from the network and the damage caused by the water from the leak (Pilcher 2003). Accurate and precise location of water leaks is the most important aspect of the leak to water companies; this is followed by the size of the leak and finally the depth to the pipe itself.

This paper reports on the use of an array of surface acoustic recorders to detect leaks from water pipes and investigates the variables involved by analysing a number of case studies. This technique removes the dependency of the acoustic method on the need for access to the pipe. It has particular advantages when applied to leaks from plastic pipes, where fittings may not be closely enough spaced for standard leak location techniques to be successful, as the acoustic attenuation in plastic pipes is greater than that suffered in metal pipes (Hunaidi *et al.* 1999; Farley & Trow 2003).

Acoustic methods of leak detection make use of the sound waves created when pressurised water is forced out through holes and cracks in the water pipe network (Liston & Liston 1992). These bi-directional vibrations propagate through the water and along the pipe wall (Grunwell & Ratcliffe 1981; Muggleton *et al.* 2002; Covas *et al.* 2004), and radially out into the subsurface (Pickerill & Malthus 1998).

The water industry uses several different acoustic methods to locate leaks; at the most basic level one end of a simple metal rod is placed on a fitting and the operator listens to an ear piece at the other end (Pilcher 2003). Inaccuracies can be caused by variable ground and leak conditions (Liston & Liston 1992). More sophisticated techniques use the acoustic correlation method; this requires acoustic sensors (e.g. accelerometers) placed directly on the fittings of the pipe (Fantozzi & Fontana 2001; Farley & Trow 2003). The difference in time taken for the acoustic waves (assumed to be single mode and non-dispersive (Long *et al.* 2003)) to travel directly from the leak to the receivers through the pipe is measured by cross-correlating the signals (Smith 1994; Tafuri 2000; Long *et al.* 2003). Assuming the velocity of propagation, the position of the leak can be estimated to within a metre if signals taken at two points bracketing the leak are taken (Fantozzi & Fantana 2001). Technology has advanced to such a level that the processing can be quickly completed using a small hand-held field computer (Golby & Woodward 1999; Fantozzi *et al.* 1993).

Leak location using the cross-correlation method can be performed on a metal pipe with direct access several tens of metres away from the source (Fantozzi & Fontana 2001). However, the distance between recording sensors needs to be greatly reduced for plastic pipes because of their high acoustic attenuation (Hunaidi *et al.* 1999). Such pipes are being increasingly installed in new limbs to modern water networks. Therefore, a greater number of access points are required to carry out a standard acoustic leak location survey of a plastic pipe section, when compared to metallic pipes, meaning that the method may be unable to be applied.

Acoustic emission spectra

The acoustic characteristics (e.g. characteristic frequency and amplitude) of leak signals at a distance from the leak are a function of the leak source and the effects of propagation through the subsurface. The source properties (i.e. vibrations from a leak) are dependent on the pipe size and shape, water flow rate and water pressure (Hunaidi & Chu 1999), and also on the properties of the fluid such as viscosity and density (Wassef *et al.* 1985), and the pipe material (Hunaidi *et al.* 2000). The recorded signal is dependent on the response of the recording instrument. The propagation effects depend on the geological material through which the signal is propagating (Sheriff & Geldart 1995) and the season (Hunaidi & Chu 1999). Propagation velocities and acoustic attenuation vary for different rock types: however, in general, the aerated zone above the water-saturated region (i.e. the water table) has acoustic velocities of about 300–600 m/s for loose unconsolidated sediments (Reynolds 1997). This is considerably slower than the acoustic propagation velocity in water, which is ~1500 m/s. The absorption of acoustic energy is often greater in loose unconsolidated sediments of the near-surface weathered layer (Sheriff & Geldart 1995).

Results from work investigating the frequency content of leak noise can be disaggregated into those measured under realistic fieldwork conditions and those measured in the laboratory. Under fieldwork conditions, Liston & Liston (1992) observed that two distinct frequency ranges were emitted by leaks from metallic pipes, one in the range 500–800 Hz and the other in the 20–250 Hz range. Hunaidi *et al.* (2000) studied the acoustic emission spectra from plastic pipes using hydrophones located inside the pipe and found that the majority of the frequency content for a 150 mm diameter PVC pipe was lower than 50 Hz, whereas outside the pipe the frequency content was seen to be in the sub-150 Hz range using accelerometers. Muggleton *et al.* (2002) also concluded that leak noise from a simulated plastic distribution network leak is concentrated at frequencies lower than 100 Hz. These values are considerably lower than those observed for metal pipes by Liston & Liston (1992).

In the laboratory Wassef *et al.* (1985) performed experiments using a short section of pipe, free standing in air, whereas work by Hunaidi *et al.* (2000) used buried pipes several tens of metres long at a test site, approaching more realistic conditions. The difference between laboratory and "in-field" results is evident in the frequencies obtained in the laboratory by Wassef *et al.* (1985) and Feng (1996), which were in the kHz range. Clearly there is a great deal of discrepancy in the results obtained from studies in the field and studies performed in the laboratory. However, frequencies obtained under fieldwork conditions (Liston & Liston 1992; Hunaidi & Chu 1999) are all lower than 1000 Hz,

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suggesting that the higher frequencies of the signal have been attenuated in buried pipes as the signal travels from the source point (i.e. the leak).

Wassef *et al.* (1985) found that, as the fluid pressure is reduced, the frequency peak from the leak shifts upwards; this was seen to be the case for various diameters of leak holes. However, for a constant pressure, an increase in the diameter of the hole had the effect of reducing the peak frequency and increasing the relative amplitude of the signal. As the point source became more elongated and formed a crack, the aspect ratio became important. Wassef *et al.* (1985) showed that, as the crack became much longer than its width, the frequency spectrum became continuous, with distinct peaks of higher amplitude; these peaks diminished at the higher frequencies. The peaks represent the fundamental and harmonic resonant frequencies across the width of the slit.

Changes in the pipe fluid flow rate have a greater effect on the amplitude than the frequency content. Hunaidi & Chu (1999) found that the amplitude of the signal at 7.5 l/min was 50 times that of the signal when the flow rate was 3.5 l/min, but the frequency content showed negligible differences. The fluid properties are only of interest when dealing with two distinctively different systems. Mixed systems (i.e. water and air) are of no interest during this investigation because the pipe is assumed to be fully flooded with water.

Below 5 Hz, noise is seen to be dominant (Hunaidi & Chu 1999), although Krylov (1996) indicates that airborne environmental noise, with distinct peaks, can be detected up to about 100 Hz. These frequencies are often associated with the harmonics of the electrical network and may cause problems if the noise peaks overlap with those from the leak.

PROPAGATION OF ACOUSTIC ENERGY THROUGH THE GROUND

The propagation of an acoustic wave through the subsurface is dependent on the material through which it is passing, with the lithology, porosity, density, compaction and interstial fluid of greatest importance (Sheriff & Geldart 1995). These factors are not independent of each other and a change in one will often have a direct change in another.

The frequency content of the acoustic wave will also affect how it propagates, as a result of the attenuation of the higher frequencies of the acoustic signal (Bourbié *et al.* 1987). This attenuation effect will be of importance when dealing with high frequencies given off by water leaks, as the high frequency leak signals, e.g. ~500–800 Hz (Liston & Liston 1992), will be attenuated more readily.

The loss of amplitude with distance travelled by an acoustic wave occurs in three main ways: spherical divergence, intrinsic attenuation and scattering. The original energy, E, transmitted outwards from the source becomes distributed over the area of a spherical wavefront ($4\pi r^2$), the radius (r) of which expands with time (spherical divergence). Therefore, the energy diminishes in proportion to $1/r^2$ and the amplitude in proportion to $1/r$ (Sheriff & Geldart 1995). The intrinsic attenuation is the energy absorbed due to the elastic imperfections of the medium. The energy is transferred into heat by the friction of individual particles moving against each other as the acoustic waves pass (Sheriff 1991). Unconsolidated material will cause greater amounts of intrinsic attenuation. Scattering is the reflection, refraction and diffraction of the incident seismic waves at boundaries with the host medium. These boundaries are often objects in the medium, i.e. rocks and boulders (Reynolds 1997). The level of scattering is dependent on the size and number of scatterers, as well as the wavelength of the acoustic wave.

Hunaidi *et al.* (1999) found that the freezing of the ground to a depth of about 1.5 m in winter attenuated the leak signal. In winter those frequencies higher than 10 Hz were reduced. The shift in the peak frequency from 55 to 65 Hz, was thought to be caused by the change in coupling between the ground and the pipe in winter. The propagation velocity of the signal was seen to be raised from 482 m/s in summer to 515 m/s in winter (Hunaidi *et al.* 1999).

SURVEY PARAMETERS

Instruments used

The instruments used to collect the acoustic data were the commercially available Radcom SoundSens™ logger pods (Radcom Technologies Inc. 2003). These sensors employ piezo compression accelerometers, which operate between 1–2750 Hz with a sensitivity of 58 V/g (volts per unit of gravity). The default sampling rate is 4800 Hz. The loggers apply a high pass filter with a 2 Hz cut-off frequency and have a flat response up to a 2400 Hz anti-alias cut-off filter. A 55 Hz notch filter designed to remove the effects of electrical mains noise is also applied in the instrument.

In the conventional mode of operation the loggers are magnetically mounted directly onto the pipe (Radcom Technologies Inc. 2003). However, to investigate the acoustic signal observable at the surface the loggers were placed directly onto the ground. Five loggers were used for data acquisition, with a sixth logger placed at a distance from the pipe, but on the same surface as the other five loggers. This logger was used as a reference to take account of variations in the background noise and, hence, normalise the data from the other loggers.

Survey areas

Surveys were performed over 17 case study leaks in and around Leeds, West Yorkshire, UK at sites previously identified by Yorkshire Water PLC using the acoustic correlation method (S Edgley, personal communication, 2003). All of the surveys were performed in areas with either a tarmac or a paving slab cover. Data were acquired with the five signal loggers placed 0.2 m apart in a line with the midpoint above the presumed location of the pipe, while the reference logger was positioned several metres away from the survey area. Survey lines were oriented so that each line of five loggers were oriented perpendicular to the estimated orientation of the pipe. Data were collected for 20 s at each survey point. The loggers were typically moved 0.2 m along the length of the pipe to the next survey location and another 20 s of data were recorded. Progressively moving the loggers created a 0.2 m × 0.2 m grid positioned above the long axis of the pipe and allowed a relatively large survey area to be covered while keeping the resolution of the survey high enough to pin-point the location of the leak.

Once the data had been acquired, the sites were excavated to repair the water leak, which provided ground truth for the results. Information about the nature of the leak (e.g. size, position and type), pipe (e.g. position, depth and orientation) and subsurface material and conditions, including the presence of a cavity, were noted. Eight case studies are presented in this paper, as they offer a representative selection of leaks, covering different pipe materials (plastic and metal) and depths (Table 1).

Data processing

The time series were detrended and the frequency spectra of a series of moving windows of 512 samples (i.e. 0.107 s) windows were calculated. Since there was no overlap between consecutive windows this resulted in 187 discrete time window spectra. The average frequency spectrum at each survey location was calculated as well as the frequency spectra for the reference logger for the same time period. All of the case studies showed a significant increase in noise amplitude below ~150 Hz. Therefore, a 180 Hz high pass tenth-order Butterworth filter was applied to each of the data sets to remove this.

The root-mean-squared (RMS) amplitude for a sliding 2 s window was calculated for the filtered data, and the mean and standard deviation of the RMS amplitude was determined for each geographic point. Any 2 s time period within the whole 20 s sample with an RMS signal amplitude value greater than two standard deviations from the mean was removed. If sections were removed from the time series the same 2 s section was removed from the reference logger record. The mean RMS amplitudes were then normalised by dividing the amplitude obtained at each position by the RMS amplitude from the reference logger for the same time period. The signal amplitude results were converted to the dB scale.

RESULTS

Frequency variation

Figure 1 shows the variation in frequency content of the signal received by loggers above a 4-inch cast iron pipe at the Poole Crescent leak (Table 1), together with the frequency content for one of the reference loggers. The solid black lines are the frequency content from the signal logger positions at increasing distance along the ground, parallel to the pipe (marked with distances in metres). The dashed black line is from the logger directly above the leak. The grey/black dashed line is the frequency content of ambient noise, obtained from a reference logger. This leak is

Table 1 | A summary of the case studies performed. The names of the streets in the Leeds Metropolitan area on which the leaks were found and the depth and type of pipe are shown. The ground conditions were obtained when the leaks were excavated for repair

Leak location	Pipe type	Pipe depth (m)	Ground conditions	Peak leak amplitude above noise (dB)
Poole Crescent	4″ cast iron	0.9	0.4 m deep sandy layer with pebbles over a clay rich sand with cobbles. Tarmac cover.	10.1
Church Lane	4″ cast iron	0.6	Sticky fine grained clay with areas of gravel under a 0.05 m fine grained sand layer. Covered by 0.09 m tarmac layer.	12.5
Low Lane	3″ cast iron	0.85	Made ground with cobbles, up to 0.4 m, in a sand and clay matrix. Covered by tarmac.	12
Talbot View	3″ cast iron	1	Tarmac and gravel base layer over a 0.2 m clay layer with pebbles up to 0.08 m, over a sandy layer with cobbles.	9.3
Aire View Terrace	1″ steel	0.8	Gravel (up to 0.3 m) and clay mixed under a 0.1 m tarmac cover.	9.5
Green Road	1″ plastic	0.4	Fine sands and gravels with pebbles up to 0.03 m in size under a 0.07 m thick tarmac cover.	9.9
Church Avenue	1″ plastic	0.7	Mixed fine sands and gravel areas with pebbles up to 0.2 m in size, under a 0.05 m thick paving slab cover.	7.3
North Hill Road	1″ plastic	0.4	Sandy gravel layer below a 0.07 m thick tarmac cover, containing pebbles up to 0.1 in length.	9.4

from a 4-inch cast iron pipe, buried at a depth of 0.9 m (see Table 1 for details).

These data are from signal loggers positioned directly above the pipe, arranged at increasing distances from the point above the leak. The frequency content of the reference logger shows that the ambient noise is only significant in the frequency range below 150 Hz (Figure 1). The frequency spectrum of the logger positioned directly above the leak (referred to as the leak signal from here on) has a raised flat response from ~400 Hz to ~850 Hz. Between ~850 Hz and ~920 Hz there is a significant increase in the magnitude of the frequency peak. This is larger in magnitude than the peaks from the other logger positions. At increasing distances from the leak this dominant peak has a reduced frequency and amplitude. However, these peaks are often of greater magnitude than the signal observed from the leak at the same frequency. The frequency peak from the leak is observable across the extent of the survey area, and in the data from the loggers parallel to, and directly above the pipe the frequency peak could be observed at the logger positioned 1.2 m away from leak.

The unfiltered acoustic results from a second survey above a 1-inch plastic survey pipe at Green Road are shown in Figure 2. Again, the solid black lines are the frequency content from the signal logger positions at increasing distances along the pipe and the grey/black dashed line is the ambient noise recorded on a reference logger. These data show a similar high frequency peak (but at ~620 Hz for this case study) with a region of higher magnitude frequencies, with the plateau of leak noise extending down to about 490 Hz. Again, there is a pronounced peak at the higher frequency end of this plataeu, ranging from about 550 Hz to 630 Hz. This plateau and peak region has been interpreted as the acoustic signal from the leak. At increasing distances from the leak, the magnitude of the frequency content is reduced and the peaks become less

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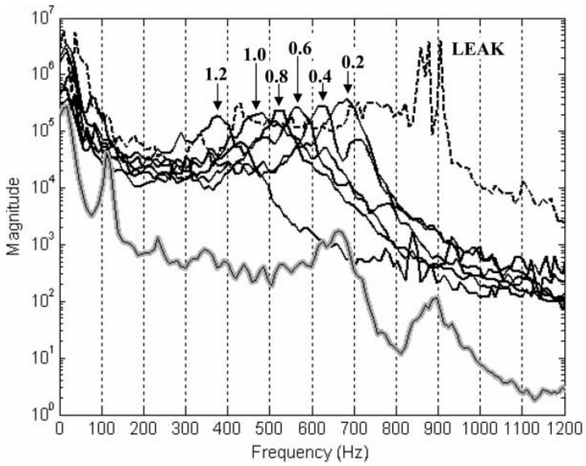

Figure 1 | Frequency spectra of unfiltered acoustic data from the Poole Crescent leak. The solid black lines are the frequency content from the signal logger positions at increasing distance along the ground, parallel to the pipe (marked with distances in metres). Noisy sections of the time series have been removed using the method described in the text. The dashed black line is from the logger directly above the leak. The grey/black dashed line is the frequency content of ambient noise, obtained from a reference logger. This leak is from a 4-inch cast iron pipe, buried at a depth of 0.9 m (see Table 1 for details). The raised flat response and peak of the leak signal and the drop in frequency with distance is evident. The increase in magnitude of the ambient noise at frequencies lower than ~150 Hz can also be seen.

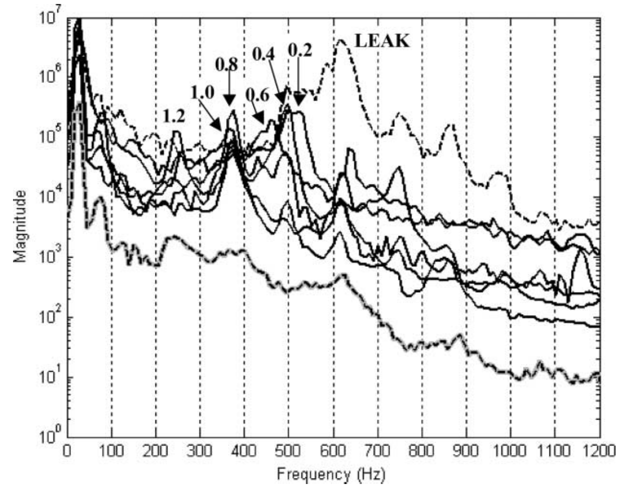

Figure 2 | Frequency spectra of unfiltered acoustic data from the Green Road leak. The solid black lines are the frequency content from the signal logger positions at increasing distances parallel to the pipe (marked with distances in metres). Noisy sections of the time series have been removed using the method described in the text. The grey/black dashed line is the ambient noise recorded on a reference logger. This leak is from a 1-inch plastic service pipe, buried at a depth of 0.6 m (see Table 1 for details).

pronounced. All of the loggers show an increase in frequency content at ~370 Hz. The level of the noise is significantly below that of the signal from the leak, although at frequencies below ~100 Hz the noise magnitude increases.

The results from all of the acoustic surveys show that the loggers positioned at the surface above the pipe have a broader higher frequency content than the corresponding reference logger. At each logger position the raised signal covered a range of frequencies; usually at the higher frequency end of the leak signal range there was also a peak of significantly increased magnitude. At increased distances from the leak this peak was seen at progressively lower frequencies. Figure 3 shows the frequency of the highest amplitude (greater than 150 Hz) peak at each survey location for the eight case studies. The frequency peak from loggers directly above the leak position (i.e. leak signal) are observed to be greater for the metal pipes (shown as solid lines in Figure 3). These frequencies were higher than 750 Hz, while the equivalent peaks above the plastic pipes (shown as dashed lines in Figure 3) were lower than 700 Hz (Figure 3). All of the case studies show a drop in the peak frequency of the leak signal with an increase in the distance from the leak position (Figure 3). In general the frequency drop was greater for metal pipes (~400 Hz) than it was for plastic pipes (~300 Hz) (Figure 3). The signal from the leak was observable above the background noise up to ~1.2 m from the point directly above the leak. This frequency peak observed directly above the leak was greater for the 3- and 4-inch diameter cast iron pipes surveyed than for 1-inch diameter service pipes surveyed during this work (Figure 3).

None of the case studies show the magnitude of the frequency of the recorded signal from the leak levelling out and reaching a similar level to that of the reference logger at a distance of ~1.2 m (Figure 1). At frequencies other than the leak peak the magnitude of the frequencies measured approaches (and sometimes coincides with) that of the background. This result shows that the reference loggers were positioned sufficiently far away from the influence of the leak.

The results from loggers positioned perpendicular to the pipe also show a drop in frequency magnitude at increasing distances from the point above the leak. The results from the Poole Crescent survey (Figure 4) show that the peak associated with each logger position (shown as solid lines in Figure 4) is not as pronounced as the peak for the same

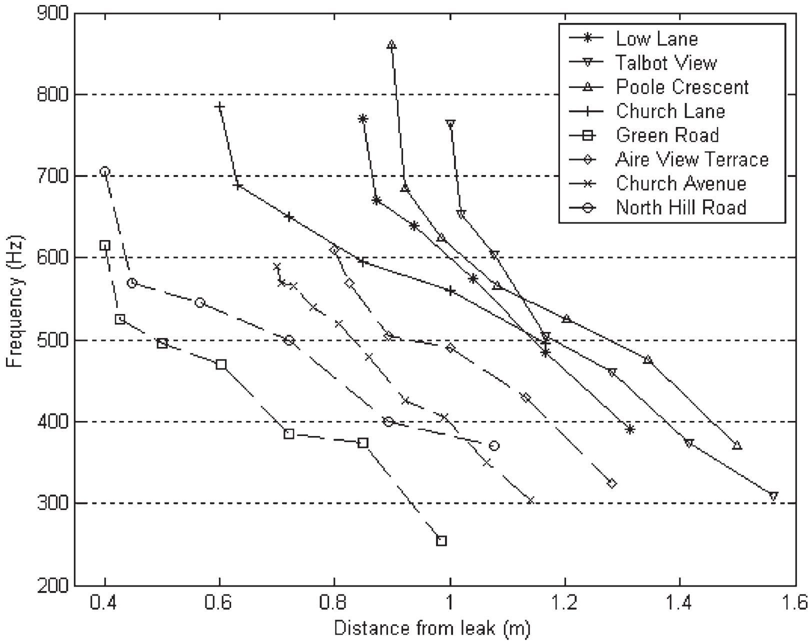

Figure 3 | The frequency of the highest amplitude (greater than 150 Hz) at each survey location for the eight case studies. These data are taken from loggers positioned parallel to the pipe at positions directly above the pipe crest. The peak amplitude from the logger directly above the leak is of higher frequency for metallic pipes (solid lines) than for plastic pipes (dashed lines), with that of the metallic pipes being higher than ~760 Hz and that of the plastic pipes being lower than ~700 Hz.

distance along the pipe and is much broader in nature. The dashed black line is the signal from the logger directly above the leak. The grey/black dashed line is the frequency content of ambient noise, obtained from a reference logger. The frequency reduction of the peak with distance is greater perpendicular to the pipe (Figure 4), when compared to the data from parallel to the pipe (Figure 1).

Amplitude variation

The variation in RMS signal amplitude over the Poole Crescent survey area shows an anomalous acoustic high at the right end of the survey (Figure 5). This area is 10 decibels (dB) above the background values. These data have had a 180 Hz high pass filter applied. Readings were taken in a 0.2×0.2 m grid, as denoted by the dots. The position of the reference logger has been marked with a black star. This acoustic high is positioned directly above the estimated position of the 4-inch cast iron pipe (marked with a dashed line in Figure 5) and has, therefore, been interpreted as the noise emanating from the leak. The ground truth confirmed the position of the leak (marked with a white star in Figure 5) to within 0.1 m of the acoustic signal high. The depth to the pipe could also be measured accurately during excavation.

The results from the survey performed over a 1-inch plastic pipe at the Green Road leak (Figure 6) also show an

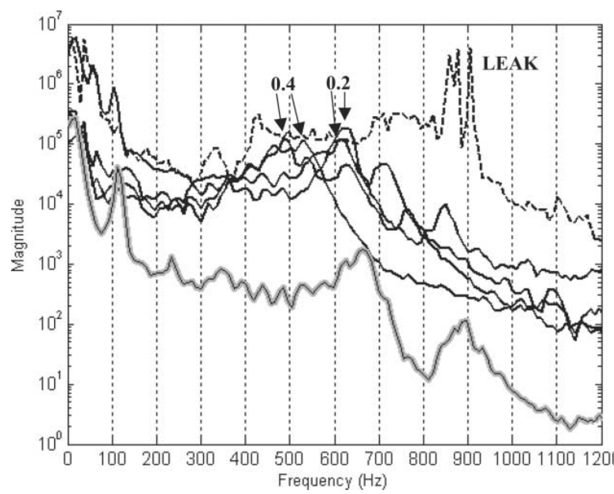

Figure 4 | Frequency spectra of unfiltered acoustic data from the Poole Crescent leak. The solid black lines are the signal logger located at increasing distances perpendicular to the pipe (marked with distances in metres). Noisy sections of the time series have been removed using the method described in the text. The dashed black line is the signal from the logger directly above the leak. The grey/black dashed line is the frequency content of ambient noise, obtained from a reference logger. This leak is from a 4-inch cast iron pipe buried at a depth of 0.9 m.

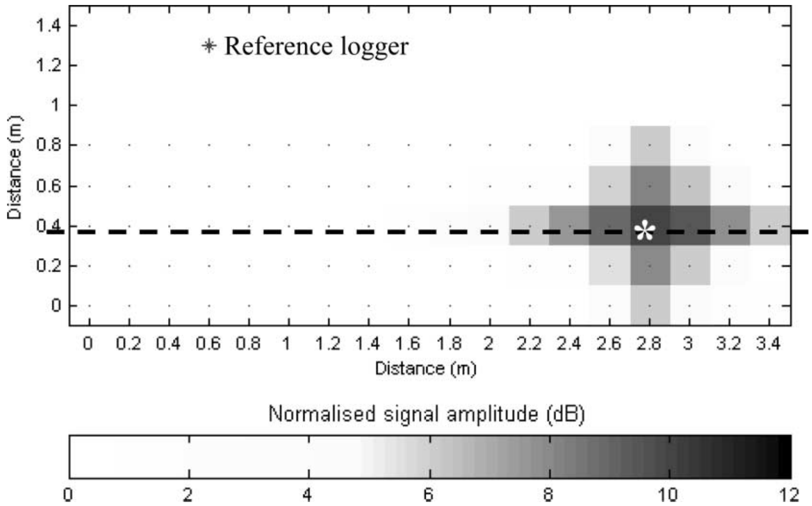

Figure 5 | Plan view of the variation in the RMS signal amplitude over the Poole Crescent leak survey area, shown in decibels. These data have had a 180 Hz high pass filter applied. The position of the 4-inch cast iron pipe is shown with a dashed line, and the increase in signal above the pipe at the right is obvious. Readings were taken on a 0.2 m × 0.2 m grid, as denoted by the dots. The position of the leak, as confirmed by the ground truth, is marked with a white star. The position of the reference logger has been marked with a black star and is annotated.

acoustic high above the estimated position of the pipe. These data have had a 180 Hz high pass filter applied. Readings were taken over a 0.15 m × 0.15 m grid. At a point directly above the leak the signal is about 10 dB higher than the background values; again, this has been interpreted as the sound given off by the leak. The ground truth confirmed the position of the pipe (marked with a dashed line in Figure 6) and the leak (marked with a white star in Figure 6). As expected, the area of increased acoustic signal was positioned, to within ±0.1 m horizontally, above the failure point on the pipe identified on excavation.

For all of the case studies performed the largest RMS signal amplitude is seen directly (±0.1 m) above the position of the leak and decreases with distance (Figure 7). In each case the location of the leak was confirmed during excavation and repair. The pipe type and depth, and the ground conditions, affect the distance at which the leak can be detected. In some cases, the increased amplitude in signal caused by the leak was detected up to a maximum of ~1.5 m on either side of the leak along the pipe axis (Figures 5, 6 and 7). This value is significantly less (~0.4 m) when looking at the drop in the signal amplitude perpendicular to the pipe (Figures 6 and 7). However, these values are dependent on ground conditions and are easily affected by buried objects, such as kerb stones and valve chambers. After applying a high pass frequency filter with a 180 Hz cut-off, the amplitude of the signal recorded over the leak, above the background noise, ranges from ~7 to ~13 dB.

In general, higher amplitudes are observed above the leaks from cast iron pipes buried at shallower depths (Figure 8); plastic pipes also follow a similar trend but have lower overall amplitudes than the cast iron pipes. The 1-inch steel pipe falls between the two groups, but is closer to the cast iron set.

DISCUSSION

The acoustic method of leak location has a proven track record (e.g. Grunwell 1993; Fantozzi & Fontana 2001; Farley & Trow 2003). However, this work has improved the accuracy of the method by using a reference logger to reduce noise and has removed the need for access to the pipe. The results from the case studies have shown that, even with pipes of different composition, diameter, pressure, depth and variable ground conditions the acoustic signal from the leak is observable. In this study, because the data sets presented are from real leaks, the relationships between these five parameters are complex. However, general interpretations can be drawn from the data.

The peak frequency for cast iron transmission mains pipes, observed at a point directly above the leak and for a

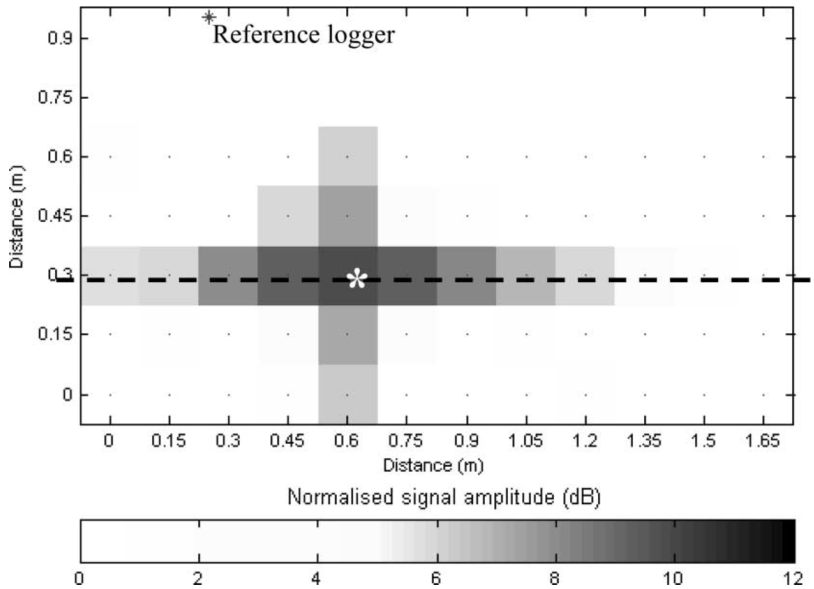

Figure 6 | Plan view of the variation in the RMS signal amplitude over the Green Road leak survey area, shown in decibels. These data have had a 180 Hz high pass filter applied. The position of the 1-inch plastic pipe is shown with a dashed line, and the increase in signal above the pipe at the centre of the survey is obvious. Readings were taken over a 0.15 m × 0.15 m grid. The position of the leak, as confirmed by the ground truth, is marked with a white star. The position of the reference logger has been marked with a black star and is annotated.

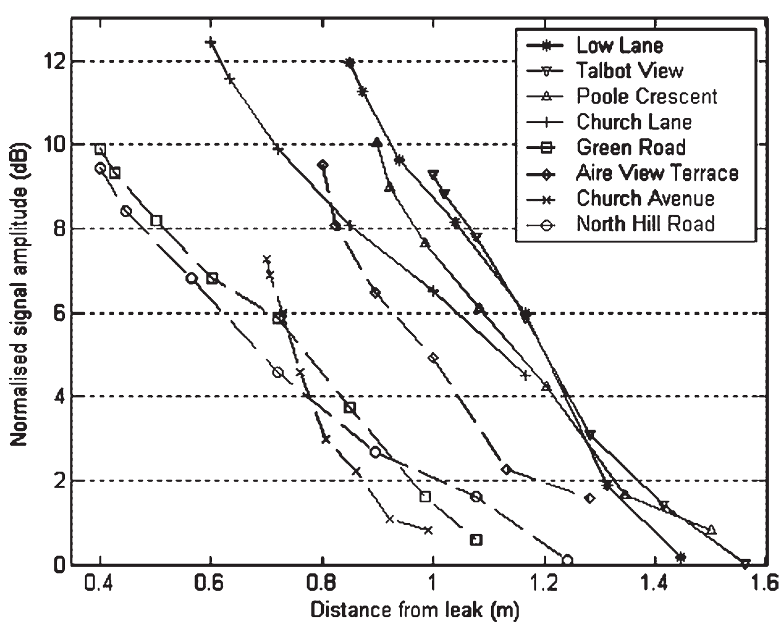

Figure 7 | The variation in RMS signal amplitude with increasing distance from the leak; a 180 Hz high pass filter has been applied. These data are from loggers positioned parallel to and directly above the pipe. The amplitudes are given in decibels (dB). Far away from the effects of the leak the dB ratio should be zero. The greatest RMS signal amplitude is seen directly above the leak and this drops away with increasing distance from the leak.

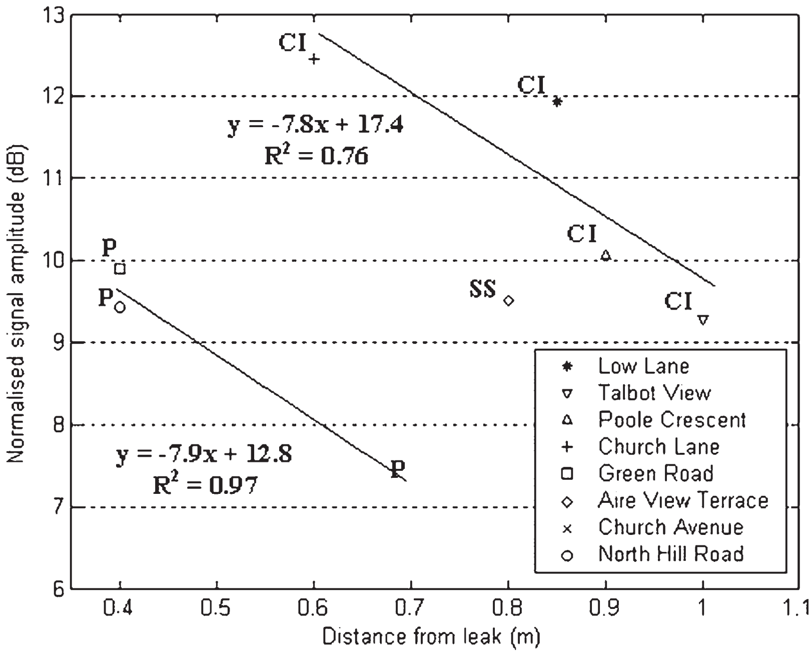

Figure 8 | The RMS signal amplitude from the loggers positioned on the ground at a point directly above the leak position. The data from cast iron pipes (CI) and plastic pipes (P) show a decrease in amplitude with an increase in the depth of the pipe. There is only a single stainless steel pipe (SS). Trend lines for the cast iron pipes and the plastic pipes are shown with regression equations and R^2 values.

given depth, is higher than that of the smaller diameter plastic pipes (Figure 3). The leak signals obtained also exhibit a region of increased frequency content, covering a range of frequencies: these are usually in the region of 500–900 Hz and are similar in frequency content to those obtained by Liston & Liston (1992). The complex double nature of the signal (i.e. a peak and associated range) suggests two modes of propagation of the leak signal, and that the signal observed at the surface is a combination of a signal that travels directly to the surface from the leak and a signal that propagates along the pipe and then to the surface. The reduction in the frequency with distance from the leak is attributed to the attenuation of the direct signal from the leak, while the dominant peak is caused by the signal that travels along the pipe and then to the surface. This theory of a dual propagation is supported by the results from the loggers perpendicular to the pipe, which show a drop in magnitude and frequency content with increasing distance but the dominant peak seen parallel to the pipe is not as pronounced (i.e. the source is elongated along the pipe).

This technique suffers, like all acoustic surveys, from ambient noise (e.g. cars, pedestrians, air conditioning units, etc.). During these case studies noise was only a significant problem below ~150 Hz. The use of the reference logger helped increase the signal-to-noise ratio by allowing a suitable band pass filter to be applied to the data. Tailoring of the filter to the data allows the specific noise conditions of the site to be accounted for.

The use of the normalising reference logger increases the signal-to-noise ratio from ~8 dB above background to over 12 dB, increasing the distance at which the leak can be detected to a maximum of ~1.5 m, with an accuracy of ±0.1 m. This is an order-of-magnitude improvement on leak location when compared to previous methods (Fantozzi & Fontana 2001), suggesting that, although time-consuming to implement and process, the data obtained using the reference logger increases the precision of the method. During quiet periods (e.g. middle of the night) the use of the reference logger may be considered excessive, costing time and money to perform. However, the use of a reference logger makes this method a viable alternative to the acoustic cross-correlation method during noisier periods (e.g. during the day).

The amplitude of the observed signal is linked to the burial depth of the pipe (i.e. the shallower the pipe the greater the amplitude), if all other parameters are the same (Figure 8). In general, the amplitude of the signal directly above the leak is greater for metal pipes when compared to plastic pipes. However, pipes at shallower depths have higher amplitude acoustic signals. This would be expected, as the closer to the leak the louder it should be. This makes it possible to calculate the amplitude of the leaks at their source. For 3- or 4-inch cast iron pipes this value is ~17.5 dB and is ~13 dB for 1-inch diameter plastic pipes. It is not known if this difference is a function of pipe type or diameter, or a combination of the two. However, the 1-inch steel pipe plots nearer the metal pipe set (Figure 8), away from the plastic pipes with the same diameter, suggesting that the difference is probably linked to the pipe type, i.e. leaks from metal pipes make more noise.

Varying ground conditions should affect both the amplitude and the frequency of the signal obtained at the surface. The case studies shown here (Table 1) indicate that no correlation can be drawn from the ground conditions around the leak and either the amplitude or the frequency content of the observed signal. Different case studies in areas with similar geology exhibit different frequency spectra and amplitude plots. Too few case studies with a water-filled cavity adjacent to the leak were encountered to know if any correlation was present.

CONCLUSION

The results from this work have shown that, by using acoustic loggers placed at the ground surface, the noise signature from a leak can be observed, and that this acoustic noise peak can be used to locate leaks, after processing, to within an accuracy of about ±0.1 m (depending on the survey resolution used). This accuracy is an order-of-magnitude improvement on the standard correlation method, which can locate leaks to within ~1 m (Farley & Trow 2003). Noise can often be problematic: however, the effect of this has been reduced by using one of the loggers to normalise the signal obtained from the other loggers. Frequency filtering can also be applied to remove the lower frequency (sub-180 Hz) noise, enhancing the signal from the leak. This work has shown that this method could be developed and used as an effective and accurate method for the location of water leaks. However, the time taken to remove the data from the loggers and processing would need to be addressed if this is to become a viable leak location technique, as at present the method is only suitable if the position of the leak is already known to within 1.5 m. However, the time taken to remove the data from the logger is a function of the instrument and not the method.

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