Leak Detection Surveys Using a Digital Correlator

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Abstract

This paper describes a new method of surveying water distribution systems for leaks based on digital correlation. Digital correlation allows computerized analysis and storage of acoustic data recorded during a survey. Leaks are detected and pinpointed without the need for skilled interpretation of the recordings in the field. The general objective is to develop a surveying method that maximizes recovery of lost water, increases time-efficiency, and is fully accessible to small utilities and non-expert users.

1. Introduction

Leakage from water distribution systems is increasingly important. The cost in the US of unbilled distributed water is on the order of $1 – 2 billion per year (figures extrapolated from data given in reference [1]). The total cost is considerably higher when factors such as property damage, liability, and investment in limited water resources are included.

A method to reduce water loss is needed that is (a) capable of pinpointing underground leaks, (b) time-efficient, and (c) easy to implement. Present listening survey methods, from the ground surface with geophones and from valves and hydrants, have significant limitations. Sonic leak detection is very subjective. Quiet leaks produce only very subtle differences that are easily missed by experienced surveyors. Loud leaks create sound over a wide area and are often difficult to pinpoint. Surveying is often performed at night when daytime environmental noise levels impede listening.

Digital correlation offers several advantages over conventional surveying methods. The correlator can pinpoint leak sounds with a single measurement performed over significant distances. Leak sounds below the threshold of human hearing can be readily detected. Loud leaks are accurately pinpointed. Advanced signal processing can distinguish between true leak sounds and other sounds, such as traffic and wind, that may obscure leak noise. Computerized techniques can also define automatically the precise frequency spectrum of leak noise and optimize its detection and localization.

Without a leak detection program in place, most leaks are discovered when either water surfaces, pipeline pressure drops, or infrastructural damage is observed. At this point, according to the American Water Works Association (AWWA) the leak has been developing typically over two years [2].

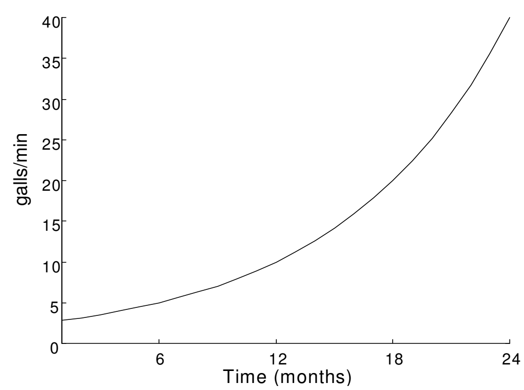

Figure 1.

Figure 1 shows how water loss increases during the lifetime of a typical leak. Initially, leakage is less than 1 gallon per minute (1 gpm). As the leak size steadily increases over time, the loss rate rises exponentially. A typical mains leak may emit 10 – 100 gpm, costing on the order of $25,000 per year. A mains burst may lose over 500 gpm (costing on the order of $5,000 per week). (These figures assume pipe pressure of 70 pounds per square inch (psi) and a production cost of water of $1 per thousand gallons.)

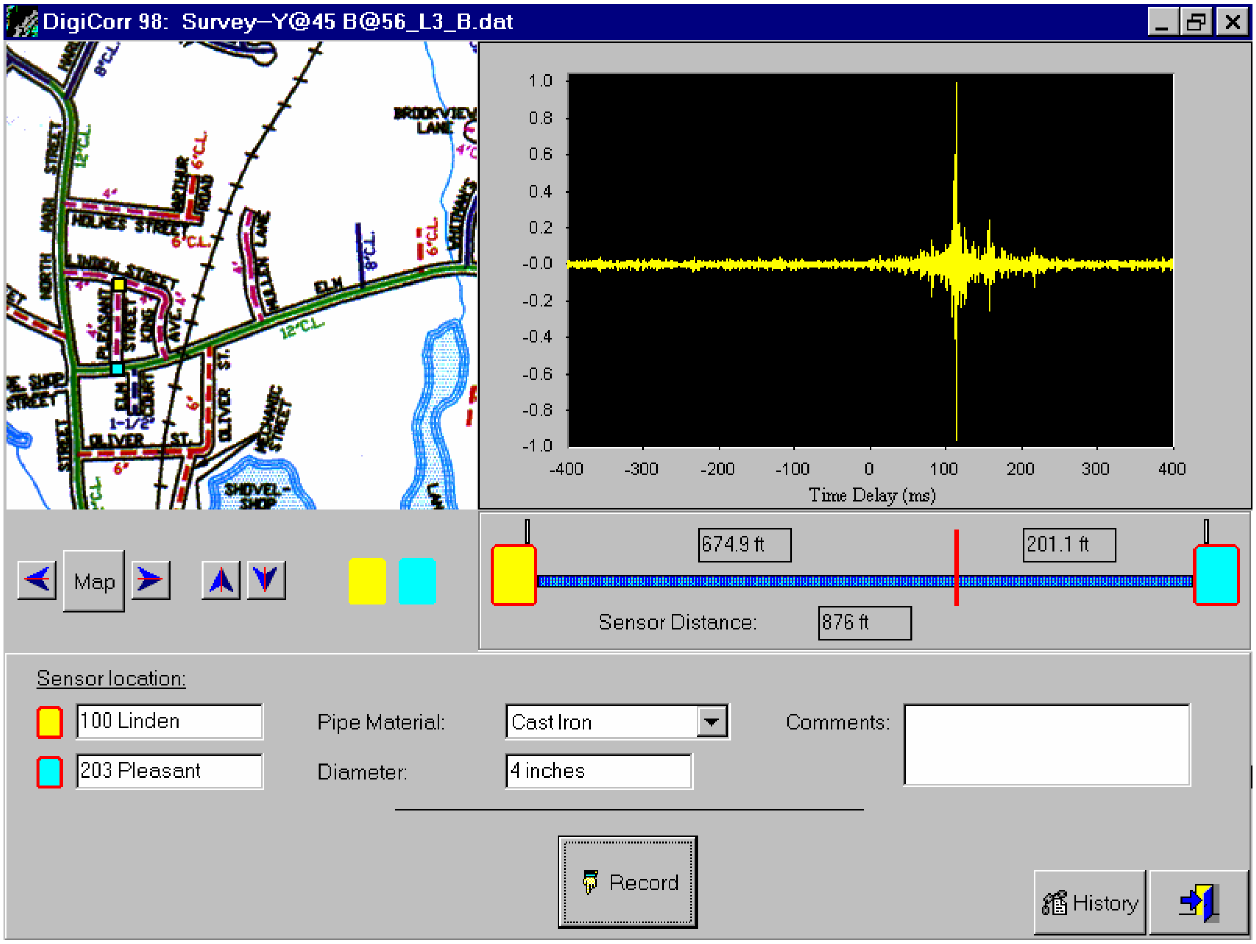

Figure 2.

Finding leaks early in their life cycle is valuable. Water loss is minimized. The production cost of all water that would have been lost during the lifetime of the leak is saved. The life of the distribution system can be extended, deferring capital expenditures by preempting mains breaks. Interruptions in service to consumers are also minimized.

2. Methods

2.1 Data Acquisition

Sensors are placed at convenient access points, such as gate valves or fire hydrants. A typical inter-sensor distance ranges from 300 to 1,200 feet. The preferred distance depends on the availability of access points, number of service connections to the main, and environmental noise levels (lower noise permits greater inter-sensor distances).

The survey software has an easy-to-use, Windows™-based interface to the recording process. Sensor locations are entered as addresses or valve/hydrant numbers and marked on a map of the distribution system (Figure 2). The user also selects pipeline material and diameter, and may enter comments, such as apparent local water usage that may influence the correlation result. The user then starts the recording. Sixty seconds of data are recorded, analyzed, compressed and automatically saved. The figure shows a sample correlation recorded in February 1998 in Cardiff, Wales. The sensors were placed 876 feet apart. The major peak represents a previously unknown leak detected at 674.9 feet from the yellow sensor. The second peak (to the right) represents seepage from valve packing. The small third peak (to the left) represents usage. The peak was temporary and its location is coincident with a service line.

2.2 Signal Processing

Recorded data is analyzed in real-time using advanced digital signal processing methods. Leak noise present at both sensors is statistically coherent.

This property is used to estimate the difference in time for the leak sound to travel to each sensor through the water in the pipe. The measured time difference is converted to a distance using the velocity of sound propagation, calculated from a knowledge of the pipe's material and size. Each peak in the sample correlation function of Figure 2 represents a noise source at a particular location in the pipe. It is therefore possible to localize multiple leaks and consistent water usage.

2.3 Analysis and Interpretation

A typical survey of 100 miles of mains will produce on the order of 1,000 recorded data files. These files are analyzed comprehensively at the end of the survey using computerized batch processing. At this time it is possible to introduce more variables than can be reasonably considered in the field. Examples include: 1) comparing correlations obtained from several locations in a locality, 2) analyzing the confidence (likelihood of a leak) and persistence (continuous presence of leak sound) of a particular correlation result, 3) multi-peak analysis, and 4) distinguishing correlations due to leaks or to usage.

2.4 Follow-Up Methods

After analysis, a set of recording sites are selected for further investigation. Pinpointing of the suspected leak at each site is then confirmed. Confirmation usually starts by listening with a geophone at the suspected leak site. Often a geophone can confirm the leak location to within 3 feet of the correlation result. Sometimes no leak noise is audible at ground surface, due to the depth of the pipe or the soil conditions (e.g. heavy clay attenuates sound). In this case, listening is conducted at nearby service points, such as curb stops and meters. A bar hole may also be drilled to the pipe under rare conditions. Excavation may be needed to confirm the most challenging leak sites.

3. Results

A total of five surveys have been started as of July, 1999. Of these, two have been completed (Mt. Vernon, NY and Chicopee, MA) and three are ongoing (Westchester Joint Water Works, NY; Easton, MA; and Maynard, MA). Results of the two completed surveys will be discussed below.

Table 1 shows the Unaccounted-For Water (UFW), characteristics of the water distribution system, and recovered leakage for Mt. Vernon, New York. The setting is urban with high daytime environmental noise levels. A total of 565 gpm of water loss was recovered. This figure was estimated by one of us (John Francett: Heath Consultants, Houston, TX), with confirmation where possible during excavation.

Mount Vernon, New York	
Estimated UFW before survey:	18%
Distribution System:	
Mains surveyed	105 miles
Number of Connections	20,000
Total water pumped	10 million gallons/day
Mains leaks:	4
Total leakage (est.)	255 gpm
% of total leakage (vol.)	45%
Service Leaks:	17
Total leakage (est.)	254 gpm
% of total leakage (vol.)	45%
Valve & Leaks:	1
Total leakage (est.)	6 gpm
% of total leakage (vol.)	1%
Hydrant Leaks:	10
Total leakage (est.)	50 gpm
% of total leakage (vol.)	9%
Total Leakage:	**565 gpm**

Table 1.

Results from Chicopee, MA are shown in Table 2. The setting is suburban.

Chicopee, Massachusetts	
Estimated UFW before survey:	9%
Distribution System:	
Mains surveyed	240 miles
Number of connections	16,500
Total water pumped	6.8 million gallons/day
Mains leaks:	3
Total leakage (est.)	158 gpm
% of total leakage (vol.)	69%
Hydrant leaks:	1
Total leakage (est.)	2 gpm
% of total leakage (vol.)	1%
Total Leakage:	**160 gpm**

Table 2.

Table 3 shows the typical number of miles of mains surveyed each day for digital correlation. An estimate is also given for conventional listening surveys.

Productivity of Surveys	
Digital correlation:	
Mt. Vernon (urban)	6 miles / day
Chicopee (suburban)	8 miles /day
Range	3 – 13 miles / day
Geophone survey:	3 – 5 miles / day (typical)
Hydrant + valve survey:	7 – 9 miles / day (typical)

Table 3.

4. Discussion

4.1 Performance at Detecting Leaks

In Mt. Vernon, the estimated leakage recovered was 813,600 gallons/day. This represents 8.1% of the average total water pumped. Under the assumption that 65% of Unaccounted For Water is due to leakage, the recovered leakage represents 69.5% of the total leakage in the system before the survey.

At Chicopee, the recovered water loss was 230,400 gallons/day, representing 3.4% of the average total water pumped. Under the same assumptions as above, the recovered leakage represents 59.5% of the total leakage present in the system. Although the UFW rate at Chicopee was significantly lower before the survey, the estimated residual (post-survey) leakage is similar in both towns, as shown in Table 4.

Comparison of Residual Leakage in Mt. Vernon, NY and Chicopee, MA		
	Mt. Vernon, NY	Chicopee, MA
Estimated residual leakage	357,047 gallons/day	163,446 gallons/day
% of average water pumped	3.6%	2.4%
Leakage per mile of water mains	3,400 gallons/day	681 gallons/day
Leakage per service connection	17.9 gallons/day	9.9 gallons/day

Table 4.

This analysis suggests a definition of the *sensitivity* of the method of digital correlation, defined as the percentage of *recoverable* leakage detected. This statistic is not possible to measure precisely because the extent of true leakage is unknown. However, according to the AWWA [1], 75% of leakage is economically recoverable. The remainder is more likely to consist of seepage and smaller leaks that may be difficult to pinpoint even after excavation. Using this definition, the sensitivity – percentage of recoverable water loss that was actually recovered – was 78% (that is, 59.5/0.75) in Chicopee and 93% (69.5/0.75) in Mt. Vernon.

Factors that affect sensitivity with digital correlation are primarily: (1) vibration-sensing quality of the access point (main line valves are preferred; hydrants and service connections are often used), (2) inter-sensor distance (ideally ~500 feet), (3) the number of service connections and the amount of usage occurring during the measurement, and (4) ambient noise (a minor factor).

The *specificity* of the method could be defined as the percentage of measurements where there is no leak present and the correlation result is negative. This statistic exhibits a seasonal effect. False positive correlations can occur due to water usage. This is particularly the case during summertime, with sprinklers and compressors causing vibrations in the water mains. These effects can often be ruled out by observation. Automatic analysis methods, used after the data recording has been completed, further reduce the number of sites that must be investigated. In almost all cases, a leak will predominate over usage in the correlation function. Unlike typical noise, leaks are a turbulent noise source originating directly within the flow.

4.2 Economic Analysis

The tangible benefits of a successful leak detection program principally include the savings in production cost of lost water. To calculate the economic benefit of saved water, some assumptions are necessary. Some leaks are immediately catastrophic, resulting in a sudden mains break with no prior water loss. Other leaks are stable for many years. The factors that determine the life of a leak are complex, and include at least the condition and age of the pipe, pressure variations over time, and the corrosiveness of the soil. However, the *typical* leak has a life of 2 years (cf. Figure 1). It is reasonable to assume that the survey will find leaks with a random age distribution. Therefore, the remaining life expectancy of a discovered leak is typically 1 year. The size of the leak at the time of discovery is unimportant. The total water loss from the leak is heavily biased towards losses that occur at the end of the leak's life.

With these considerations, the discovered leakage is a significant under-estimate of the total water that would have been lost in the coming year. Table 5 shows the annual savings achieved, assuming that there would have been no increased losses in the coming year due to leaks enlarging.

Economic Analysis of Leak Surveys

	Mt. Vernon, NY	Chicopee, MA
Discovered leakage	565 gpm	160 gpm
Production cost of water (nominal)†	$1 per thousand gallons	$1 per thousand gallons
Total cost of survey‡	less than $20,000	less than $25,000
Annual savings	$297,900	$84,096

Table 5.

4.3 Time Efficiency of the Survey

The time efficiency of a digital correlation survey depends on how many personnel and vehicles are available, and the terrain to be surveyed. In our experience, 2 persons and 2 vehicles is optimal and can result in up to 13 miles of mains surveyed per day. Table 3 shows the figures achieved in the 2 surveys conducted. The initial experience with digital correlation surveys suggests that time-efficiency of the survey is comparable to a comprehensive geophone survey. However, an important consideration is that in the digital correlation survey, data recording and data analysis are separate functions. This eliminates the need for a skilled listening surveyor. In fact, utility personnel can be more productive than specialists because they are familiar with the distribution system.

4.4 Other Benefits of Surveying With Digital Correlation

The analysis of correlation data can be made very flexible with the capability of storing tens of thousands of recordings before a comprehensive analysis is performed. The digital correlation survey therefore effectively includes a comprehensive listening survey as a subset of its capabilities. Analysis and interpretation of leak noise correlations can be performed in the field, in the utility's office, or by a specialist. Automatic analysis capabilities allow all recordings to be analyzed together. This permits a higher level of interpretation, such as the ability to compare nearby sites for confirmation of suspected leaks.

Permanent archival of the data on a CD ROM permits a listening and correlation survey record to be maintained. This data can be used in a comparative analysis with data recorded in subsequent surveys. The archived data allows the utility to plan its own schedule for investigation and repair of suspected leaks.

5. Conclusion

Two surveys have been presented, using a new digital correlation method. The two distribution systems present an interesting contrast: Mt. Vernon is an older, urban system with typical water losses (pre-survey UFW was 18%); Chicopee is a newer suburban system (pre-survey UFW was 9%). There were 32 leaks found in Mt. Vernon versus 4 in Chicopee. Post-survey, both systems had similar estimated residual leakage of less than 4% of total water pumped. These preliminary results suggest that digital correlation is capable of controlling leakage in a cost-effective manner.

References

[1] Water and revenue losses: Unaccounted-for water. AWWA Research Foundation (Wallace, LP. ed.), 1987.
[2] Water audits and leak detection (AWWA M36), American Water Works Association, 1990.

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† Nominal cost assumed to facilitate comparisons
‡ Includes equipment, plus specialist and utility labor