

> Itron white paper

Leak Detection Theory: Optimizing Performance with MLOG

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Introduction to Leak Detection Theory

Detecting leaks in a water distribution system is based upon measuring sound vibrations that travel down distribution pipes. MLOG acoustic sensors—or loggers—are spaced out along the distribution system adjacent to water meters. These loggers sense any vibrations, record the sound vibrations and pass the data back to the mlogonline network monitoring system for analysis and diagnostics.

The accuracy of the MLOG system to correctly identify all leaks and ignore non-leak noise is determined by the number of loggers deployed and diagnostic parameters set within mlogonline.

Leak Predictability

The MLOG system is an acoustic diagnostic system for detecting water leaks. The performance of the MLOG system is probabilistic in the sense that sometimes it will correctly identify leaks and sometimes it will not.

The four possible predictive outcomes of the system are shown in the 2x2 confusion matrix below. (For simplicity, a yellow logger indication is ignored in the matrix.)

	Actual leak	Actual no leak	threshold value
Predict leak-red logger	True Positive	False Positive	←
Predict no leak-green logger	False Negative	True Negative	

- **True Positive (TP):** An actual leak is detected. There is a leak and the logger is red. This is a good result.
- **False Negative (FN):** An actual leak is not detected. There is a leak and the logger is green. This result is bad in that water loss will continue until the leak is positively detected.
- **False Positive (FP):** There is no leak, but the logger is red. This will cause pinpointing activities (and associated expense) with DigiCorr, Zcorr and DLD to occur for an area where no leak exists. This is a bad result.
- **True Negative (TN):** There is no leak and the logger is green. This is a good result.

To understand the operation of the system, sensitivity and predictive value are defined below.

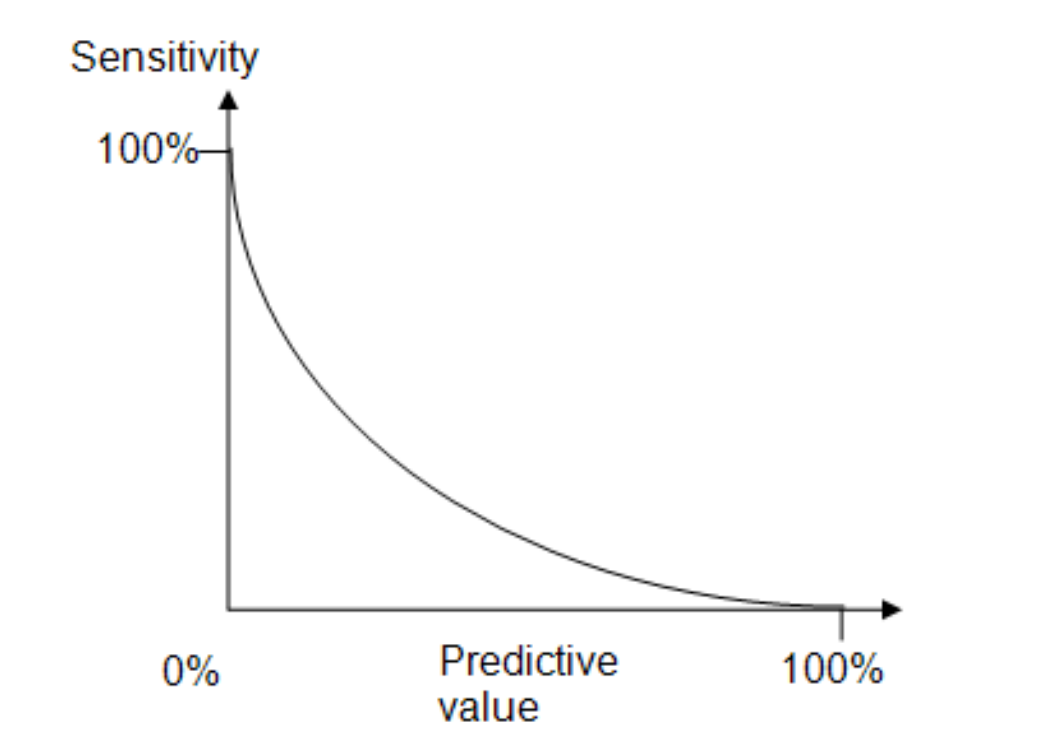
- **Sensitivity** is defined as the percentage of all leaks detected by the MLOG system. We want this number to be high.

$$\text{Sensitivity} = \frac{TP}{TP + FN}$$

- **Predictive Value** is defined as the likelihood that a red MLOG indicates an actual leak. We also want this number to be high.

$$\text{Predictive Value} = \frac{TP}{TP + FP}$$

Sensitivity and predictive value trade off against each other as illustrated in the **Receiver-Operating Curve (ROC)**, shown below.



To illustrate this curve, consider the example where every MLOG has a red status. While the sensitivity would be 100 percent (all leaks found) there would be no predictive value as not all red MLOGs would be associated with real leaks. Similarly, if most MLOGs had a green status the predictive value would be high (very few false positives), but the sensitivity would be lower because many leaks would be missed.

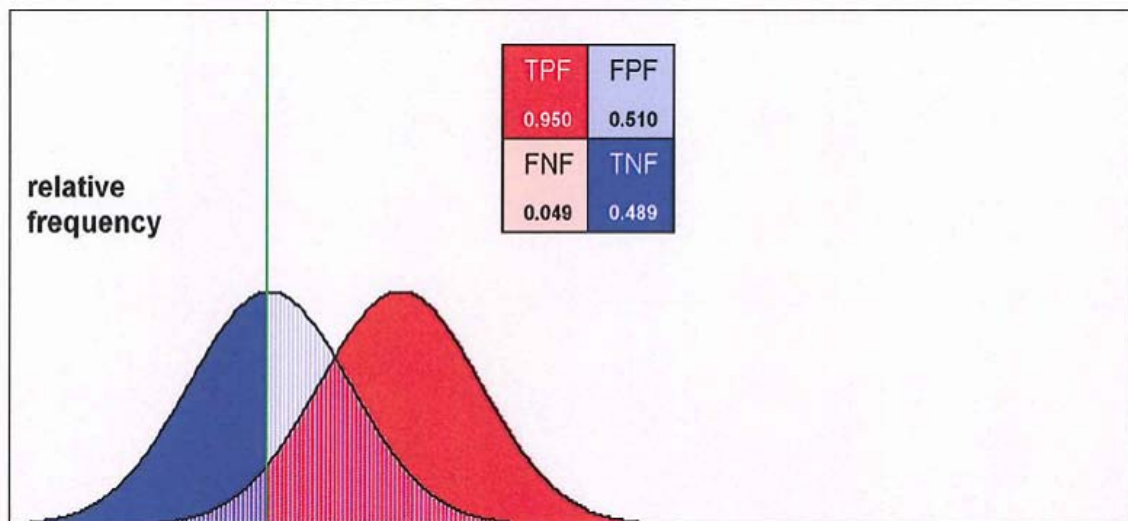
There is a value known as leak index that is calculated in the analysis engine of the mlogonline network monitoring system. This value is used to set the threshold where the MLOG status changes from green to yellow and yellow to red. If the threshold is set high in the 2x2 confusion matrix or on the ROC curve shown above, the number of false positives goes down (you have a higher predictive value) but the number of true positives also goes down (you have a lower sensitivity).

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The leak sensors are essentially measuring sound vibrations in the pipe. You can imagine on a section of pipe where a leak sensor is attached, one of two vibration distributions: the vibration spectrum where a leak is present or the vibration spectrum where no leak is present. These potential vibration distributions are shown in the graphs below.

- There is a distribution of sound (vibration) if there is no leak. The blue normal curve represents that distribution. The vibrations that the logger detects when there is no leak are all natural noises: traffic, regular water flow through the pipe, pump stations and so on.
- There is a distribution of sound vibration if there is a leak. This vibration signature will be different, represented by the red normal curve in the examples below.
- The green line represents the threshold value (leak index) set in mlogonline that differentiates between a green and a red logger (again ignoring the yellow logger).

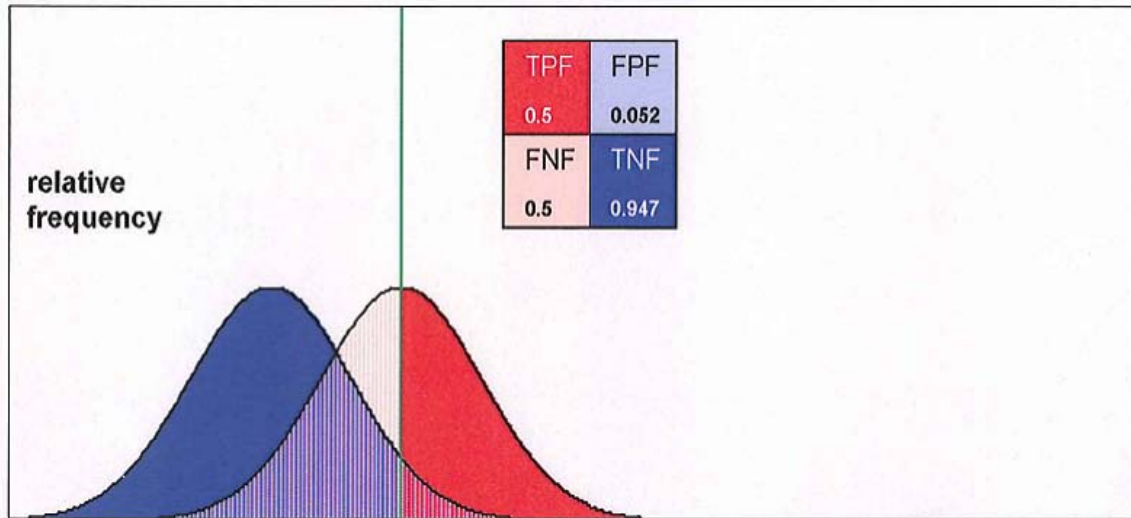
For the system to work the best, you want to set the threshold value so that it maximizes the area of the red curve above the threshold, while simultaneously maximizing the area of the blue curve below the threshold. For this example, the threshold (green line) should actually be set in the valley between the two curves.



With the threshold set somewhat low (more towards the left, as in the example), true positives (sensitivity) are 95 percent, but the false positives (predictive value) are also high at 51 percent. In other words, 95 percent of all real leaks would have a red logger, but 50% of the red loggers would not have an actual leak.



If the threshold value is set higher in mlogonline (moving the green line to the right) the number of false positives are reduced, but the true positives also go down. In the following curve, a higher threshold is set—true positives (sensitivity) are reduced to 50 percent and false positives (predictive value) are reduced to 5.2 percent. In other words, only 50 percent of all real leaks would have a red logger, but 90.6 percent of the red loggers would actually point to a real leak.



The MLOG system was designed to provide separation between the blue and red curves, allowing for an optimal threshold to be set: the sensitivity and frequency response of the vibration sensor was optimized and innovative filtering was applied to the vibration signals. The threshold values were carefully identified to select the best operating point on the ROC. The system also minimizes false positives by recording and reporting data during the quietest vibration periods on the water distribution period, specifically during the night. Mlogonline also identifies which loggers are near known noise generators (such as those near pump stations or other known environmental influences) to account for their vibration distributions.

Minimizing false negatives requires that loggers be close to the leaks. The distance between loggers and the leaks directly impacts the system's ability to differentiate between a leak and random noise; the greater the distance, the lower the predictive value. To improve the performance of the system, more loggers need to be deployed to get closer to each leak. A cost tradeoff analysis must be done with the customer to determine their tolerance for false negatives balanced with their equipment budget.

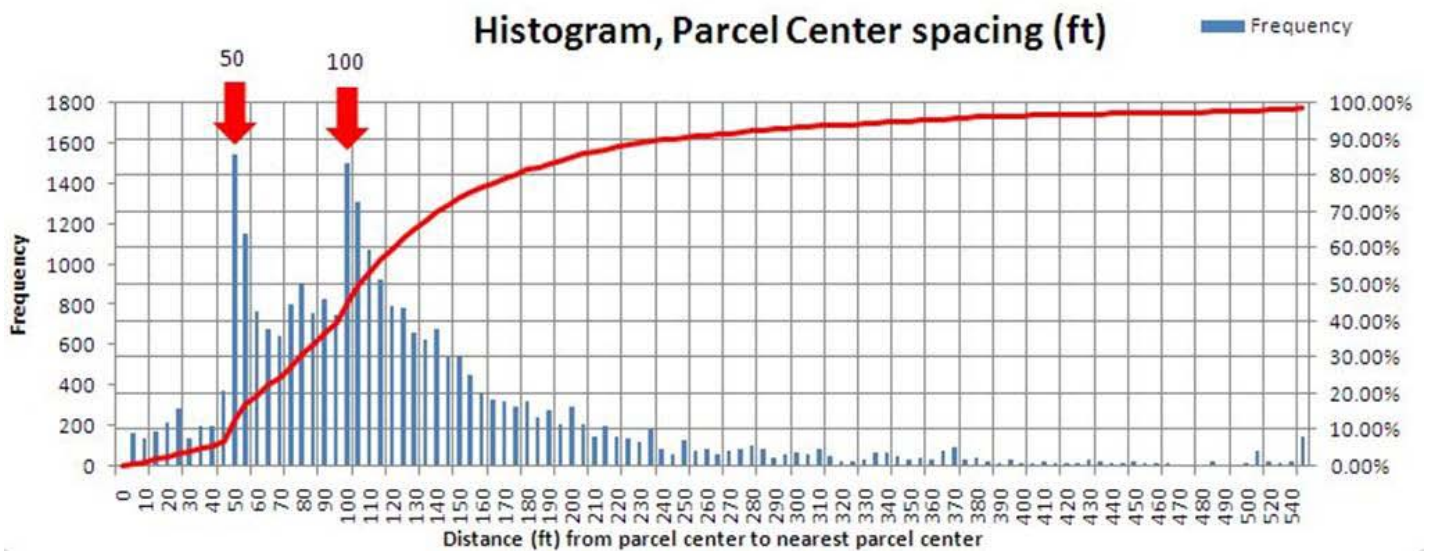
The 10:1 Rule of Thumb Assumption

The following rules of thumb have been used in the bid process for logger placement based upon the installation guidelines developed over time.

- Logger spacing when main line is metal: 400-500 feet
- Logger spacing when main line is cement or plastic: 150-250 feet
- Logger spacing (metal mains with greater than 8-inch diameter): 250 feet or less
- Loggers placed on street corners when deployment is not 1:1
- Logger spacing (metal mains with less than 60 pounds per square inch of pressure): 250 feet or less, although there is no way to get this information at the current time
- Loggers placed at lowest elevation points in distribution system
- Loggers placed on the service line on the main side of the water meter

It is easy to think about deployment in terms of one logger for every ten water meters, (a simple 10:1 ratio). But this assumption depends entirely upon the spacing between the meters or houses and the material of the main pipe in the street.

Shown below is data from Kingsport, Tenn., showing its parcel spacing. There is much variation in the distance between houses—and therefore meter locations. This is based upon actual data for the utility's 35,000 meters.





Assuming houses are on both sides of the street, and using the 50 foot and 100 foot parcel spacing peaks in the analysis above, the following meter to logger ratios meet the install guidelines as a first approximation.

	Metal pipe 50ft parcel	Plastic pipe 50ft parcel	Metal pipe 100ft parcel	Plastic pipe 100ft parcel
400 ft min. spacing	18:1		9:1	
500 ft spacing	22:1		11:1	
150 ft min. spacing		8:1		4:1
250 ft spacing		12:1		6:1

Based upon the Kingsport data and the recommended spacing between loggers, a 10:1 ratio is appropriate with any type of pipe if the parcel spacing is 50 feet. With 100 foot parcel spacing, a 10:1 ratio only works on metal pipe. A ratio less than 10:1 is required for plastic pipe.

In the case of Kingsport, following all of the deployment rules and accounting for parcel to parcel spacing, pipe materials, street corners, low points and so on, it was recommended to deploy 10,786 loggers to adequately cover the 35,355 meters for a ratio of 3.2:1—a far cry from the 10:1 rule. This is driven by the high percentage of plastic pipe and the large parcel spacing in Kingsport. Another recent MLOG deployment with different distance and material variables resulted in a 7.5:1 ratio. These examples illustrate that each deployment will vary and using the 10:1 rule of thumb should be avoided. Complete system analysis, propagation studies and bids should be performed in order to maximize system performance.

System Accuracy

Based upon the information in the system design reviews, as well as in individual papers referenced below, a simple model has been established to predict the performance of the system in some applications.

- For metal mains the rule of thumb for logger spacing is 400-500 feet, which equates to roughly 12:1 services per MLOG in a 100 foot parcel spacing environment.
- For cement or plastic mains, logger spacing should be 150-200 feet, requiring roughly a 5:1 deployment ratio to get the same performance as metal pipe.

The table below shows some rules of thumb relative to performance. In theory, we predict that getting closer to the service line, where 70-80 percent of water system leaks occur, will improve the performance of the system—although at a higher cost.

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Installing more loggers will:

- Increase sensitivity, meaning that more actual leaks will be found.
- Increase predictive value, meaning more red loggers will indicate an actual leak.
- Minimize false positives, eliminating unnecessary pinpointing.
- Minimize false negatives, with continued unaccounted-for water.

Mains pipe material	Meters per logger, 100 ft parcel spacing	Sensitivity	Predictive value
Metal	12:1	70%	33%
Metal	5:1	81%	40%
Metal	1:1	95%	50%
Plastic, cement	5:1	70%	33%
Plastic, cement	1:1	81%	40%

Limited Real-World Data Available to Validate Model

In a paper written on April 26, 2006, it is suggested based upon 73 red logger locations visited and 25 true leaks repaired in the Connellsville, Penn., territory serviced by American Water that the sensitivity of this early MLOG system was only 36 percent (based upon 9 true positives and 16 false negatives). The predictive value was between 21 and 40 percent. More data collected and analyzed in 2008 found that 97 leaks were found and 97 leaks were missed for a sensitivity of 50 percent. It would seem that this system is under-deployed if one expects the sensitivity of 70 percent and predictive value of 33 percent for the standard 10:1 rule of deployment.

More analysis of the system is required to support the model in the table above. Even though the sensitivity and predictive values were “low” in Connellsville, an estimated 90 percent of unaccounted-for water was mitigated during the first 200 days following the MLOG installation. American Water has ordered 4000 units for their Monterey, Cal., operation in 2008.

Tests and analysis to correlate the models described above against measured performance will continue at a few select customers to insure that the rules of thumb are accurate.

Summary

Detecting distribution system leaks is predictive science where many variables can impact an MLOG system’s performance. Deploy systems using in-depth propagation analysis, not quick rules of thumb like the 10:1 ratio. Use all information available to you make an informed decision on the appropriate amount of loggers necessary to meet your leak detection goals.



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Special thanks to Paul for his assistance in crafting the content of this document.

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