# ACTIVE ACOUSTIC METHODOLOGY FOR DETECTING SEWER LINE OBSTRUCTIONS

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## ABSTRACT

A challenge facing the industry is determining where and when to deploy limited cleaning resources for preventative maintenance within a utility's collection system. Setting up a cleaning program involves the recognition that many pipe segments scheduled for cleaning will only benefit marginally and some not at all from the cleaning action. This cost of over cleaning is significantly overshadowed by the alternative risk of insufficient maintenance resulting in sanitary system overflows. Charlotte-Mecklenburg Utilities (CMU) undertook a pilot project to assess a new diagnostic tool, the Sewer Line – Rapid Assessment Tool (SL-RAT™). The SL-RAT is an onsite diagnostic tool under development by InfoSense, Inc. It evaluates the aggregate blockage within a sanitary sewer pipe segment using a novel acoustic methodology. The CMU Pilot Project objectives were to assess both the technical and economic merits of integrating the SL-RAT into their preventative maintenance programs. The SL-RAT diagnostics capability allows cleaning requirements for pipe segments to be prioritized prior to conducting cleaning operations. Potential cost savings exist through several complementary mechanisms: reduced performance assessment costs, reduce cleaning-related overflows, and reduced non-value added cleaning effort. The CMU Pilot Project methodology involved conducting SL-RAT acoustic measurements and CCTV videos both prior to and after the cleaning operations. This enabled rigorous quantitative analysis of the SL-RAT's operation performance. These results formed the bases for both the technical and economic evaluations. Utilizing the SL-RAT within the cleaning operation revealed 39% to 81% of pipe segments along a problematic sewershed had room for improvement by cleaning. Results suggest the balance of line segments considered (19% to 61%) could be eliminated from the cleaning maintenance cycle without adverse performance impacts, corresponding to a net cost savings from 10% to 50% depending on the goals and approach for the cleaning operation.

## KEYWORDS

Sewer Line Inspection, Wastewater Operational Management, Sewer Line Pipe Blockage Assessment

## INTRODUCTION

**Overview:** A highly valuable tactic for improving preventative maintenance cost effectiveness is to identify where limited resources should be deployed during a cleaning operation. The industry has effective tools for cleaning and a growing set of in-pipe inspection tools. The inherent problem is the extensive size of the collection network and, missing the wrong pipe segment during cleaning, results in facing the consequences of a preventable overflow. The variability in the time between cleaning requirements for pipe segments precludes the effectiveness of a straightforward periodic cleaning regime. The fundamental trade-off for preventative cleaning programs is [Fishburne 10] – "Too frequent cleaning wastes resources and too little results in failure". This challenge motivated Charlotte-Mecklenburg Utilities (CMU) to undertake a pilot project to assess a new diagnostic tool, the Sewer Line – Rapid Assessment Tool (SL-RAT™). The SL-RAT is an onsite diagnostic tool under development by InfoSense, Inc. It assesses the aggregate blockage within a sanitary sewer pipe segment using a novel acoustic methodology [Howitt 09]. This diagnostic capability provides the support required to prioritize pipe segments within a cleaning operation. The objectives and the methodology for the *CMU Pilot Project* were established to allow quantitative analysis of the SL-RAT diagnostic capabilities. The technical findings of the project are presented in the Results Section and are used to develop the cost saving evaluation presented in the Discussion Section.

**SL-RAT Technology Overview:** The SL-RAT exploits the similarities and difference between water and sound transmission through a pipe segment in order to diagnose its blockage. This novel methodology is based on measuring the signal received from an active acoustic transmission through a pipe segment, Figure 1. The sound wave generated at the transmitter, propagates from the speaker to the receiving microphone located at the adjacent manhole. Diagnostics through multiple pipe segments are possible, as long as the combined pipe length is reasonable, i.e., less than approximately 500' to 800'. An important practical aspect of the SL-RAT is that both the speaker and the microphone are placed just within the opening of the manhole and never come in contact with the wastewater flow. The sound waves generated just below the entrance to the manhole naturally couple into connecting pipe segments, whether the depth of the manhole is 3' or greater than 20'. Unlike other acoustic technologies for sewer line inspection, the SL-RAT uses low frequency sonic waves and not ultrasound waves. Within pipes, ultrasound waves propagate a relatively short distance compared to sonic waves. Also, the SL-RAT directly measures the transmitted signal in order to evaluate the condition of an entire pipe segment versus ultrasound systems which measure the reflected signal in order to typically evaluate the flow rate or image a section of a pipe.

A clean pipe segment is a natural acoustic waveguide [Philip 68]. As illustrated in Figure 1, commonly encountered sanitary sewer defects, such as roots, grease and sags naturally absorb or reflect acoustic energy. These defects change a pipe segment's acoustic properties and produce a measurable impact on the received signal at the microphone, i.e., the acoustic profile. Each pipe segment has an individual acoustic profile representative of its current state. The acoustic profile changes over time as the condition of the pipe segment varies. The SL-RAT detects these variations to provide a real time evaluation of the pipe segment's operating condition; the approach is illustrated in Figure 2. The acoustical profiles for two different sewer line segments are depicted in the graphs at the top of the figure. From the graph for Segment I, the signal pressure level (SPL) varies with time and frequency tracing out eight repeated stepped tone sequences from the transmitted signal. Based on the signal processing within the SL-RAT's acoustic receiver, the received acoustic profile is evaluated to obtain two assessment criteria:

- *SL-RAT Blockage Assessment* - Estimate of the aggregate blockage within the pipe segment between the acoustic transmitter and acoustic receiver.
- *SL-RAT Measurement Confidence* - Indicates the impact ambient noise has on evaluating the *SL-RAT Blockage Assessment*.

For Segment I, Figure 2, the *SL-RAT Blockage Assessment* is nearly 0 indicating the segment is estimated to have a low level of obstruction. The *SL-RAT Measurement Confidence* is 100 indicating ambient noise had no impact on the assessment. For Segment II, the transmitted signal is difficult to see within the graph. Based on CCTV inspection, the segment was significantly obstructed with a combination of roots and grease as illustrated in the corresponding snapshot. The *SL-RAT Blockage Assessment* for Segment II is 91 and its *SL-RAT Measurement Confidence* is 97. A blockage assessment of 91 indicates the pipe segment is estimated to be highly obstructed.

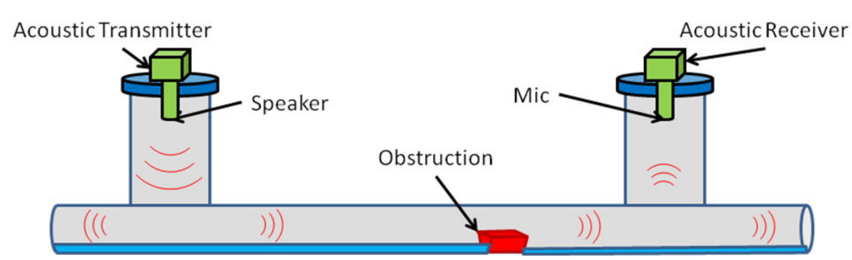


**Figure 1. Sewer Line – Rapid Assessment Tool (SL-RAT™) concept and operational procedure.**

Based on the two assessment criteria, the SL-RAT classifies the sewer line segment's condition as

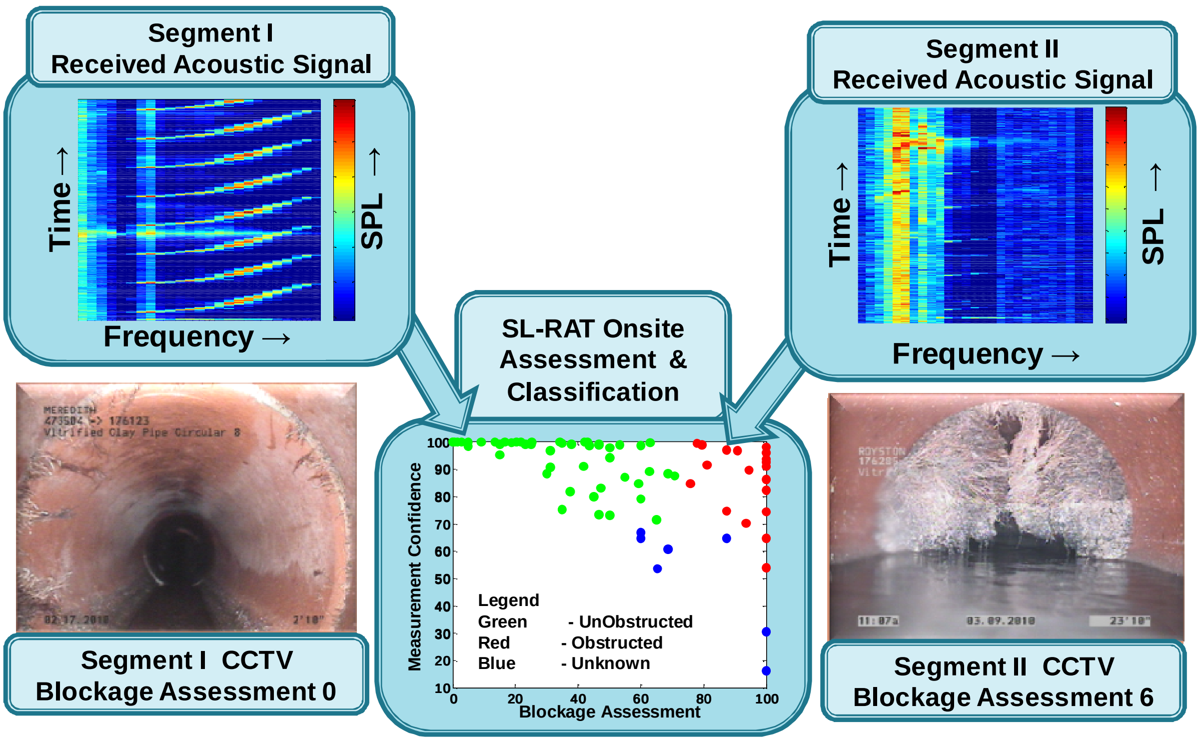


**Figure 2. SL-RAT functional overview, illustrating SL-RAT process for mapping the received acoustic signal to the assessment parameters which are in turn used to classify the sewer line segment.**

either: Obstructed, Unobstructed, or Unknown. The mapping between the assessment criteria and the classification is application dependent. The mapping is illustrated for Segment I and II in Figure 2 and the classification process is discussed in greater detail in the following sections.

For all the results presented in this paper, the SL-RAT does not use historic data for evaluating a pipe segment's current condition. There are no previously stored measurements for a pipe segment used to assess its current blockage. The assessment criteria evaluation and the classification are made strictly on the acoustic profile obtained from the measurement collected on site at the time of the test. This approach is a specific objective of the CMU Pilot Project, to evaluate InfoSense Inc.'s algorithm for assessing and classifying previously untested sewer line segments. It is anticipated using previous measurements from the same segment will improve the classification process and is currently being developed.

## METHODOLOGY

**CMU Basin Cleaning Pilot Project Objectives:** This paper focuses on the following *CMU Pilot Project* objectives.

1. Assess the ability of the SL-RAT acoustical tool to
    a. Reveal a state of partial obstruction in a pipe segment,
    b. Define the progression of partial to complete obstruction for a pipe segment.
2. Establish the suitability of the SL-RAT acoustical tool for CMU to realize operating cost savings and prevent system failures
    a. Economically identify pipe segments requiring maintenance (prioritization aid, failure prevention method),

b. Establish optimal maintenance cycles (sustainable failure prevention).

**<u>CMU Basin Cleaning Pilot Project Approach :</u>** The *CMU Pilot Project* was integrated into an ongoing preventative maintenance program which focuses cleaning and inspection resources into a consolidated area. The *CMU Pilot Project* was initiated in early February 2010 and the results presented in this paper are based on evaluation during the consolidated cleaning of Basin 17-100, Figure 3. The initial phase of the project was completed in June 2010 with the completion of the cleaning and subsequent pipe segment inspection using both CCTV and SL-RAT. The following summarizes steps used in the evaluation:

1. Use the following data collection sequence within the Consolidated Cleaning Area:
   a. Collect pre-cleaning acoustical profile of pipe segments
   b. Collect pre-cleaning video inspection of pipe segments
   c. Collect post-cleaning video inspection of pipe segments
   d. Collect post-cleaning acoustical profile of pipe segments
2. Analyze and assess acoustical profiles and compare with assessment based on video inspections.
3. Evaluate SL-RAT use by typical CMU staff to identify reduced capacity for pipe segments without a previous acoustical profile
   a. Define and analyze range of profiles for clean pipes,
   b. SL-RAT classification analysis: False Positive Rate and False Negative Rate
   c. Cost saving analysis.

# RESULTS

**<u>Overview:</u>** The results presented for the *CMU Pilot Project* focus on data and analysis required to support both the technical and economic objectives. The initial Result Section examines the use of the

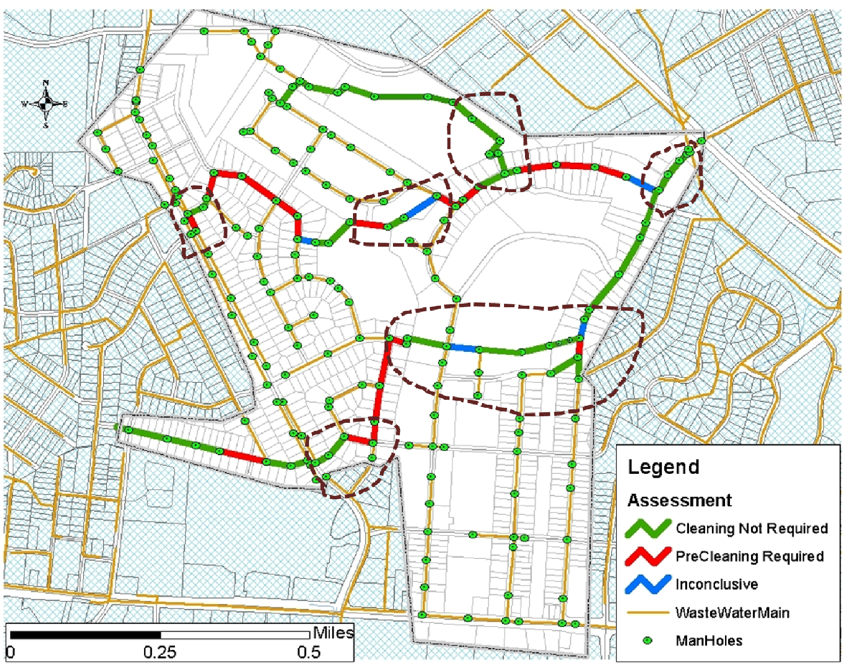


**Figure 3. GIS map for Basin 17-100, *CMU Pilot Project* location. Highlighted pipe segments represent locations evaluated with the SL-RAT. The highlighted color represents the SL-RAT classification based on the Pre-Cleaning requirements for prioritizing cleaning objectives. The sewer line segment's circled, indicate best guess segments requiring Pre-Cleaning based on historical data.**

SL-RAT to locate pre-cleaning locations for the Basin 17-100 Cleaning Project. The next two sections address the CMU technical objective of evaluating the SL-RAT classification rates. This is accomplished by comparing the SL-RAT assessment with CCTV based assessment for pipe segments evaluated during the project. In the last Result Section, the use of the SL-RAT as a cleaning verification tool is evaluated.

**Pre-Cleaning Assessment & GIS Integration:** CMU has found that pre-cleaning needs to be an integral part of a consolidated cleaning project in order to reduce the risk of spills during their systematic cleaning operation. Prior to Basin 17-100 cleaning operations an *Engineering Assessment* was made on which pipe segments were at high risk of being obstructed. These pipe segments were tagged for pre-cleaning and are indicated in Figure 3 by dashed circles. These pipe segments were then used to define the pipe segments included in the SL-RAT acoustic testing, Figure 3. The objective was then to compare the SL-RAT pre-cleaning assessment with the *Engineering Assessment*.

The scatter plot in Figure 4(a) depicts the SL-RAT assessment criteria prior-to-cleaning. Each point on the scatter plot represents the *SL-RAT Blockage Assessment* and the *SL-RAT Measurement Confidence* for one pipe segment. The color of each point represents the SL-RAT classification for the corresponding pipe segment. The SL-RAT assessment criteria prioritizes the pipe segments, then a decision is required to determine which pipe segments are sufficiently clean and which are not. An *SL-RAT Blockage Decision Threshold* is used in making the decision. For the pre-clean diagnostic application, the objective is to identify pipe segments which are likely to cause a spill during the cleaning operation. Given this objective, the *SL-RAT Blockage Decision Threshold* was set. How this threshold was determined is based on a rigorous analysis of the SL-RAT classification assessment as compared to the CCTV based assessment and is presented in the following two sections.

The sewer line segment SL-RAT assessment and classification results where integrated into CMU's current Geographic Information System (GIS) as depicted in Figure 3. GIS facilitates visually, spatially, and historically data analysis [Lo 02]. GIS systems are also very useful when it comes to maintaining and storing dynamic data for future analysis. With the data now having spatial reference in GIS, it is straight forward to visually compare the pre-clean locations based on the SL-RAT assessment and the *Engineering Assessment*. There are regions of agreement between the two assessments, but in general the two sets are disjoint. In the following two sections we establish the reliability of the SL-RAT assessment process in both assessing and classifying sewer line segments.

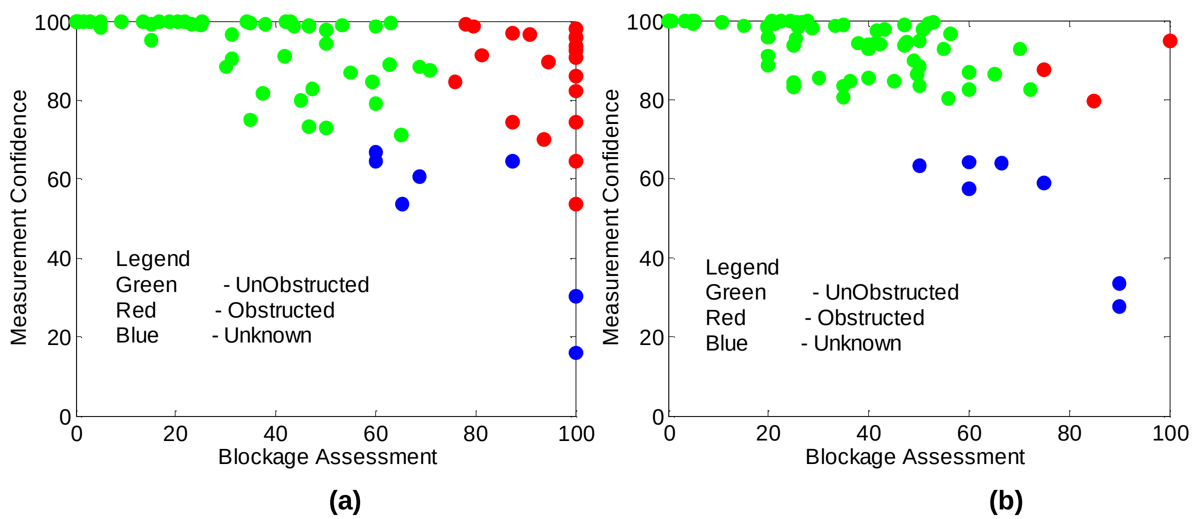


**Figure 4. Scatter plots for the SL-RAT assessment criteria results for the sewer line segments evaluated during the CMU Pilot Project (a) Prior-to-Cleaning and (b) After Cleaning.**

**SL-RAT Blockage Assessment & CCTV Blockage Assessment Comparison:** An important aspect of the methodology employed in the *CMU Pilot Project* was collecting CCTV videos both prior-to and after cleaning the pipe segments. This approach allowed us to directly investigate the technical feasibility of the SL-RAT and provides hard data for developing the economic justification. In order to make a comparative analysis between the CCTV and the SL-RAT, the CCTV videos were independently reviewed to assess the aggregate blockage within each pipe segment, i.e., *CCTV Blockage Assessment*. A rank order was used in the assessment with 0 indicating a pipe segment was essentially clean and 10 indicating the pipe segment was substantially obstructed. Two examples are given in Figure 2 where Segment I's CCTV video showed the pipe segment in excellent condition as represented by the snapshot; its *CCTV Blockage Assessment* is 0. For Segment II, the CCTV robot encountered several substantial root fiber growths as indicated by the snapshot; the root growths had not formed into root balls. For Segment II, *CCTV Blockage Assessment* is 6.

The scatter plot in Figure 5(a) provides a comparison based on the two assessments. Each point on the plot represents the *CCTV Blockage Assessment* versus the *SL-RAT Blockage Assessment* for one pipe segment. If the two assessment where identical, then all the points would lie along the diagonal line from (0,0) to (10,100). As observed in Figure 5(a), almost all points in the scatter plot lie in the triangle above the diagonal. This implies the *SL-RAT Blockage Assessment* will tend to be more conservative than the *CCTV Blockage Assessment*. These implications are evaluated in the next section.

**Misclassification Rate & False Alarm Rate:** The quantitative comparison between the *CCTV Blockage Assessment* and the *SL-RAT Blockage Assessment* is used to evaluate the SL-RAT's classification capability. This was accomplished by using a standard approach for evaluating classification algorithms [Duda 01] which is to determine the SL-RAT's misclassification rate and the false alarm rate where

- Misclassification Rate – Rate of classifying a segment requiring cleaning as one that does not require cleaning.
- False Alarm Rate – Rate of classifying a segment that does not require cleaning as one that requires cleaning.

The *SL-RAT Blockage Assessment* is evaluated against the *CCTV Blockage Assessment* which is assumed to be ground truth [Duda 01]. In order to accomplish this we need to classify each pipe

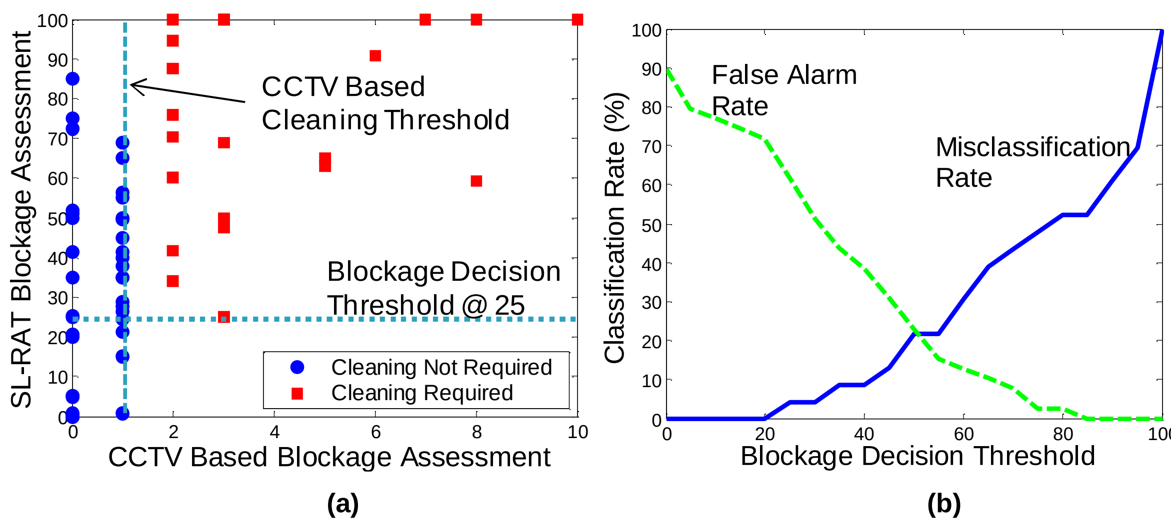


**Figure 5. (a)Scatter plot comparing the CCTV Blockage Assessment with the SL-RAT Blockage Assessment for sewer line segments within the CMU Basin Cleaning Pilot Project with the *CCTV Based Cleaning Threshold* set to 1. (b) SL-RAT False Alarm Rate and Misclassification Rate versus the Blockage Decision Threshold based on the scatter plot in (a) with the *CCTV Based Cleaning Threshold* set to 1.**

segment based on the ground truth. We therefore define the *CCTV Based Cleaning Threshold* to discriminate between pipe segments requiring cleaning and those that do not based on the *CCTV Blockage Assessment*. This is illustrated in Figure 5(a) where the *CCTV Based Cleaning Threshold* is set to 1. Setting the threshold to 1 means all pipe segments are classified as requiring cleaning except those which are clean or may have a minor degree of root fibers at joints. This cleaning objective is consistent with the consolidated cleaning project goal to be inclusive. For comparison, the *CCTV Based Cleaning Threshold* was set much higher to 5 for the pre-cleaning operation. This classified pipe segments which have a considerable degree of obstruction as requiring cleaning, e.g., Segment II in Figure 2 has a *CCTV Blockage Assessment* of 6.

With the *CCTV Based Cleaning Threshold* set to 1, each pipe segment is classified as either requiring cleaning or not as depicted in Figure 5(a). Based on a threshold of 1, approximately 52% of pipe segments do not require cleaning and 48% do require cleaning. Evaluating the SL-RAT misclassification rate and false alarm rate is based on selecting the *SL-RAT Blockage Decision Threshold* and evaluating the corresponding classification error rates. The *SL-RAT Blockage Decision Threshold* is the threshold used by the SL-RAT to discriminate between pipe segments estimated to require cleaning and not. As illustrated in the figure, for a *SL-RAT Blockage Decision Threshold* of 25, no pipe segments requiring cleaning (red points) fall below 25; therefore the misclassification rate is 0%. Correspondingly, 64% of the pipe segments designated as not requiring cleaning (blue points) fall above the *SL-RAT Blockage Decision Threshold*; therefore, the false alarm rate is 64%. Figure 5(b), provides graphs for both the SL-RAT false alarm rate and misclassification rate as the *SL-RAT Blockage Decision Threshold* is varied. As illustrated in the figure, a blockage decision threshold of 59 is optimal in the sense it jointly minimizes both the false alarm rate and the misclassification rate. This assumes both errors convey the same risk. For cleaning operations this is not the case, false alarms can be tolerated. Misclassifications, especially a misclassification of an obstructed pipe segment presents a high risk for failure. The current CMU Basin Cleaning Operation can be viewed as being based on 100% false alarm rate with 0% misclassification rate classification or decision process. The goal for using the SL-RAT is to maintain the cleaning operation's target misclassification rate while reducing the false alarm rate. This trade-off will be further explored in the Discussion Section where we evaluate cost saving benefits versus risk. The SL-RAT with supporting evidence from the *CMU Pilot Project* provides the bases for evaluating trade-offs for performing cleaning operations with a managed risk assessment.

**SL-RAT Cleaning Verification:** Comparing the prior-to and post-cleaning scatter plots in Figures 4(a) and 4(b), the general shift of the data points towards the upper left indicates the cleaning operation significantly impacted the *SL-RAT Blockage Assessment*. To evaluate the SL-RAT, as a cleaning verification tool, we determined the percent improvement for each segment due to the cleaning operation and examined their relative rate of occurrence, Figure 6. In evaluating the results, it was noted that an *SL-RAT Blockage Assessment* less than 50 prior-to-cleaning remained in the same range after cleaning. Therefore, to reduce trivial results we mapped these to 0% improvement. Based on the results depicted in the figure, 43.5% of the pipe segments exhibited significant improvement due to the cleaning operation with most lying between 20% to 60% improvement.

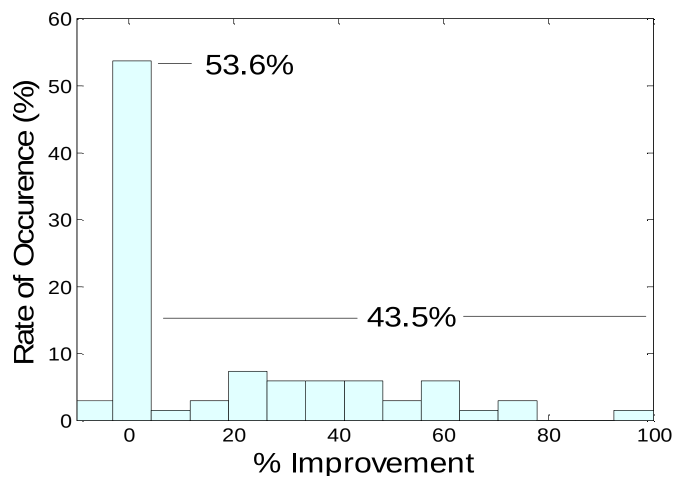


**Figure 6. Histogram showing the distribution of the percent improvement in the SL-RAT Blockage Assessment due to the sewer line segment being cleaned.**

The results in Figure 6 are suggestive that acoustics can be used as a verification tool, in addition to diagnostic tool prior-to-cleaning. The results also suggest historical profiling of pipe segments is beneficial. To illustrate, a given pipe segment has a pre- and post cleaning *SL-RAT Blockage Assessment* of 70 and 30, respectively. If in 9 months the pipe segment is inspected and is measured to have *SL-RAT Blockage Assessment* of 60, this is highly suggestive the pipe condition has deteriorated.

# DISCUSSION

**Cost Savings Analysis:** From the Results Section there is strong evidence that the technical objectives for the initial phase of the *CMU Pilot Project* have been established. In the Discussion Section, we build upon the *CMU Pilot Project* results to establish an economic justification for integrating the SL-RAT into a cleaning operation as a diagnostic tool. The economic justification is established by estimating the cost savings by comparing the estimated total cost of the *Current Basin Cleaning Operation* to the estimated total cost of the *Proposed Basin Cleaning Operation.* For the *Proposed Basin Cleaning Operation*, the SL-RAT is used to identify sewer line segments that do not require cleaning. These segments are excluded from the cleaning and CCTV operation. In the last section of the Discussion, we generalize the discussion and examine using the SL-RAT under several different cleaning operation scenarios.

***Current Basin Cleaning Operation* Cost per Foot:** The *Current Basin Cleaning Operation* is based on cleaning an entire basin followed by CCTV inspection to verify the cleaning operation. For the evaluation we have used average costs per foot for both the CCTV crew inspection and the cleaning crew operation, Table I. To generalize the results, we have used typical industry numbers and not specific values from the CMU Basin Cleaning Project. To simplify the evaluation, we have excluded the cost for easement cleaning and clearing. Using these assumptions, the *Current Basin Cleaning Operation* cost per foot of sewer line pipe is $2.00/ft.

**Table I. Estimated SL-RAT Cost Savings**

| | |
|---|---|
| CCTV Crew Cost per Foot | $1.00/ft |
| Cleaning Crew Cost per Foot | $1.00/ft |
| Total Cost per Foot for Current Basin Cleaning Operations | $2.00/ft |
| SL-RAT Cost per Foot (see Table II) | $0.09/ft |
| SL-RAT False Alarm Rate | 64% |
| % Reduction in Segments Requiring Cleaning based on SL-RAT Blockage Assessment | 19% |
| Cost Saving per Foot | $0.28/ft |

**SL-RAT Pipe Segment Inspection Cost per Foot:** To estimate the SL-RAT cost savings, we need to estimate the cost for an SL-RAT Crew. The assumptions used are given in Table II where the values in the table reflect typical industry values. The onsite work hours per day has been selected conservatively. The average number of segments inspected per hour using the SL-RAT is based on CMU/InfoSense field experience using the SL-RAT during the course of the *CMU Pilot Project*. The inspected segments per hour varied from 4 to 10 with 6 being the average. Using the values from Table I, the SL-RAT operational cost per foot is

$$\frac{2\times 68000+24000}{251\times 5.5\times 6\times 220}=\$0.09/\text{ft} \tag{1}$$

**Assessing Sewer Line Segments using the SL-RAT:** The cost saving analysis for the *Proposed Basin Cleaning Operation* needs to balance the cost increase associated with using the SL-RAT with the cost savings obtained by reducing the number of segments to be cleaned. Ideally, we would eliminate all segments requiring minimal maintenance. Within the *CMU Pilot Project* approximately 52% of the segments were identified as not requiring cleaning, when the *CCTV Based Decision Threshold* was set to 1. Setting the decision threshold to 1 should have minimal or no impact on the Basin Cleaning Projects cleaning objective and would ideally reduce the cost by approximately 52%. Achieving this ideal cost savings needs to be balanced against the risk associated with removing a segment from the cleaning cycle. Using the classification rates established in the Results Section for the SL-RAT, the *SL-RAT Blockage Decision Threshold* can be used to trade-off risk and cost savings, or in other words misclassification and false alarm, Figure 5.

**Table II. Assumption used for Evaluating SL-RAT Cost Per Foot**

| | |
|---|---|
| Number of Crew Members | 2 |
| Annual Fully Loaded Salary | $68,000 |
| Annual Equipment Costs (Including Truck & SL-RAT) | $24,000 |
| Work Days Per Year | 251 |
| Onsite Work Hours Per Day | 5.5 |
| SL- RAT Average Number of Segments Inspected Per Hour | 6 |
| Average Sewer Line Segment Length in feet | 220 |
| Cost Per Foot | $0.09/ft |

The following illustrates the concept for using the SL-RAT to balance the trade-off in identifying segments to be removed from the cleaning operation while managing the risk. Let's assume the cleaning objective requires the *CCTV Based Decision Threshold* to be 1. From the graph in Figure 5, using an *SL-RAT Blockage Decision Threshold* of 25 results in a misclassification rate of 0, meaning all segments requiring cleaning are correctly identified; risk is minimized. Correspondingly, the false alarm rate is 64% resulting in 64% of the segments not requiring cleaning to be cleaned. This does not yield the ideal 52% reduction; it does result in nearly 19% $[(1-0.64)\times 0.52]$ reduction with essentially no risk. Recall, the Current Basin Cleaning Operation is based on cleaning all pipe segments with CCTV verification. Removing 19% of the pipe segments from the cleaning cycle is significant and will be shown to provide a substantial cost savings benefit.

***Basin Cleaning Operation* Cost Saving Evaluation:** The cost saving is appraised based on evaluating the difference between the total costs estimated for the *Current Basin Cleaning Operation* and the total costs estimated for the *Proposed Basin Cleaning Operation* using the SL-RAT. Based on the discussion presented in the previous sections and summarized in Table I

$$\text{Current CMU Basin Cleaning} = \$2.00/\text{ft} \times \text{Number Feet}, \tag{2}$$

$$\text{Proposed Basin Cleaning} = [\$0.09/\text{ft} + (0.81)(\$2.00/\text{ft})] \times \text{Number Feet}, \tag{3}$$

$$\begin{aligned}\text{Cost Savings} &= [\$2.00/\text{ft} - [\$0.09/\text{ft} + (0.81)(\$2.00/\text{ft})]] \times \text{Number Feet} \\ &= \$0.28/\text{ft} \times \text{Number Feet}.\end{aligned} \tag{4}$$

**Generalize Cost Savings Using SL-RAT:** We extend the cost saving analysis to evaluate three cleaning operation scenarios and three different cleaning objectives. For all nine cases, the baseline approach is compared with the same cleaning operation using the SL-RAT diagnostics prior-to-cleaning. Varying the cleaning objective examines different priority levels in removing pipe segments from the cleaning operation. The range of the cleaning objective is from removing essentially only clean pipe segments (*CCTV Based Cleaning Threshold* set to 1) to removing up to slightly obstructed pipe segments (*CCTV Based Cleaning Threshold* set to 3). To illustrate *CCTV Based Cleaning Threshold* of 3, it is between Segment I and Segment II in Figure 2. The three cleaning operation scenarios are (1) Cleaning with CCTV Verification – this is the same scenario used in the previous sections with a baseline cost of $2/ft; (2) Cleaning Only with No Verification – baseline cost $1/ft; (3) Cleaning Only with SL-RAT Verification – baseline cost $1.09/ft. The assumptions used for the cost analysis are the following: (1) The *SL-RAT Blockage Decision Threshold* was set based on the minimum value which maintained a 0 misclassification rate given the *CCTV Based Cleaning Threshold;* (2) The SL-RAT is used to diagnose and remove from the cleaning operation pipe segments which are estimated to be clean, based on the *SL-RAT Blockage Decision Threshold*. The estimated cost saving evaluation is summarized in Table III. As noted from the table, cost savings significantly increase when the *CCTV Based Cleaning Threshold* is set to 3. With this setting, the corresponding *SL-RAT Blockage Decision Threshold* increased with a significant decrease in the false alarm rate.

## CONCLUSIONS

Under the *CMU Pilot Project*, the technical and cost savings for using the SL-RAT as a diagnostic tool were evaluated. The methodology employed during the project allowed for quantitative analysis of the SL-RAT's diagnostic performance. The SL-RAT effectively prioritizes pipe segments allowing the operator to trade-off cleaning objectives for cost savings in a systemic and quantified approach. Table III provides examples of this for three cleaning operation scenarios. Specifically, the estimated SL-RAT cost savings for the Clean Only scenario are between \$0.10/ft and \$0.52/ft for baseline cleaning operation costing \$1/ft. The SL-RAT provides a 10% to over 50% estimated savings where the variation is based on the operator defined cleaning objectives. Similar estimated savings are obtained for the other two scenarios.

**Table III. Comparison of Cleaning Operation Programs Based on Using the SL-RAT**

| **All Cleaning Operation Programs Based on SL-RAT Diagnostics Prior to Cleaning** | Cleaning Objective: Remove Only Pipes Diagnosed as Clean | | Slightly Obstructed |
|---|---|---|---|
| CCTV Based Cleaning Threshold (0 to 10 range) | 1 | 2 | 3 |
| Percentage of Pipe Segments Not Requiring Cleaning | 52% | 72% | 86% |
| *SL-RAT Blockage Decision Threshold* | 25 | 25 | 59 |
| % Reduction in Segments Requiring Cleaning | 19% | 21% | 61% |
| Cost Savings: Cleaning with CCTV Verification | \$0.28/ft | \$0.33/ft | \$1.1/ft |
| Cost Savings: Cleaning Only no Verification | \$0.10/ft | \$0.12/ft | \$0.52/ft |
| Cost Savings: Cleaning with SL-RAT Verification | \$0.11/ft | \$0.14/ft | \$0.58/ft |

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