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Demonstration of Innovative Sewer System Inspection Technology: SL-RAT™

SCIENCE

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Demonstration of Innovative Sewer System Inspection Technology: SL-RAT™

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NOTICE

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development (ORD) National Risk Management Research Laboratory (NRMRL) Water Supply and Water Resources Division (WSWRD), funded and managed this technology demonstration through EPA Contract No. EP-C-11-006. This report has been both peer and administratively reviewed and approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use of a specific product.

Questions concerning this document or its application should be addressed to:

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Foreword

The U.S. Environmental Protection Agency (EPA) was charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, EPA is tasked with formulating and implementing actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To help meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to protect human health and the environment.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. NRMRL's solution-based research program is focused on (1) method and technology development and their cost effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; (2) protection of water quality in public water systems; (3) remediation of contaminated sites, sediments, and groundwater; (4) prevention and control of indoor air pollution; and (5) restoration of ecosystems.

This research provides solutions to environmental problems by developing and promoting technologies that protect and improve the environment. NRMRL's research advances scientific and engineering information to support regulatory and policy decisions, and provides the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels. NRMRL collaborates with both public and private sector partners to anticipate emerging challenges and foster the development of technologies that reduce the cost of regulatory compliance.

The information provided in this document will be of use to stakeholders such as state and federal regulators, Native American tribes, consultants, contractors, and other interested parties.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Abstract

The overall objective of this EPA-funded study was to demonstrate innovative a sewer line assessment technology that is designed for rapid deployment using portable equipment. This study focused on demonstration of a technology that is suitable for smaller diameter pipes (less than 12-inch diameter). The recently developed and commercially-available acoustic-based sewer pipe assessment technology demonstrated during this study was the Sewer Line – Rapid Assessment Tool (SL-RAT™) manufactured by InfoSense, Inc. (InfoSense) of North Carolina.

This technology can provide a rapid assessment of the need for pipe cleaning. Acoustic technologies require a minimal amount of equipment when compared to traditional closed-circuit television (CCTV) inspection systems. This acoustic based technology has the potential to provide information in a matter of minutes to assist an operator in determining whether a sewer pipe might be partially or fully blocked and require cleaning or renewal. The speed of the assessment, using minimal equipment, has the potential to result in significant cost-savings compared to traditional methods, such as CCTV inspection. It is generally known that smaller diameter pipes (i.e., less than or equal to 12-inch diameter) contribute to over 90 percent of the sewer main backups reported in a typical city (Sprague, J., 2007). This study hence focused on the demonstration of an acoustic technology that is suited for smaller diameter pipes.

This collaborative field demonstration of the SL-RAT was led by EPA's National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. EPA worked with the Metropolitan Sewer District of Greater Cincinnati (MSDGC) as a collaborative research partner to identify study locations, provide access to the study area sewer lines and to perform the related field work. Specifically, the data and information obtained from the following technologies were used in this demonstration project: SL-RAT; Pan-Tilt-Zooming pole-mounted camera (aka "camera on a stick") manufactured by Envirosight Quickview; and HD-digital scanning CCTV or the PANORAMO 3D Optical Pipeline Scanner manufactured by RapidView-IBAK.

The results of this demonstration of the SL-RAT show promise for the application of this technology as a tool for cost-effective, pre-cleaning assessment and post-cleaning quality assurance. The application of this technology in an overall collection system O&M program should enable wastewater utilities to optimize their sewer cleaning efforts and free up valuable resources to more effectively implement critical CMOM and asset management programs.

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Abbreviations & Acronyms

3-D	Three-dimension
ADS	ADS Environmental Services
ALSA	ALSA Tech LLC
ATV	All Terrain Vehicle
BC	Brown and Caldwell
CCTV	Closed-Circuit Television
CIP	Cast Iron Pipe
CMOM	Capacity, Management, Operation and Maintenance
CMU	Charlotte Mecklenburg Utility
DIP	Ductile Iron Pipe
EPA	U.S. Environmental Protection Agency
GPS	Global Positioning System
HD	High-Definition
IBAK	Ingenieur Büro Atlas, Kiel (manufacturer of RapidView and PANORAMO (CCTV))
I&I	Infiltration and Inflow
MSDGC	Metropolitan Sewer District of Greater Cincinnati
NASSCO	National Association of Sewer Service Contractors
NRMRL	National Risk Management Research Laboratory
O&M	Operation and Maintenance
ORD	Office of Research and Development
OSHA	Occupational Safety & Health Adminstration
PACP	Pipeline Assessment and Certification Program
PC	Personal Computer
POTW	Publicly Owned Treatment Works
PTSI	Pegasus Technical Services, Inc.
PVC	Poly-vinyl Chloride
QAPP	Quality Assurance Project Plan
RCP	Reinforced Concrete Pipe
RF	Radio Frequencies
RX	Receiver
SaaS	software-as-a-service
SL-DOG	Sewer Line Diagnostic OrGanizer
SL-RAT	Sewer Line – Rapid Assessment Tool
SPL	Sound Pressure Level
SSO	Sanitary Sewer Overflow
TX	Transmitter
USB	Universal Serial Bus
USDOT	United States Department of Transportation
VCP	Vitrified Clay Pipe
WERF	Water Environment Research Foundation
WSWRD	Water Supply and Water Resources Division

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Executive Summary

The focus on condition assessment of gravity wastewater collection systems (sewers) continues to broaden. Traditionally, the main focus of condition assessment of sewers has been directed at operational issues related to the collection and conveyance of flows to a facility for treatment and disposal. To address operational issues, attention has tended to concentrate on maintenance activities associated with the cleaning and removal of debris and foreign materials from collection system pipes. The combination of debris and extraneous wet-weather induced flows can result in less than desired levels of customer service and possibly cause raw sewage to overflow from the collection system or to result in basement backups.

Cleaning and inspecting sewer pipes is essential for utilities to operate and maintain a properly functioning system and minimize SSOs. The routine maintenance of a sewer system often includes sewer system cleaning, root removal/treatment, and cleaning/clearing of sewer mainline blockages. However, understanding where and when to perform cleaning activities in the most effective manner is not necessarily a straight forward task. In an attempt to direct maintenance staff and cleaning equipment to those pipes in a sewer system that require attention, some agencies identify cleaning needs by conducting inspection of the sewers prior to cleaning. Rapid assessment approaches and tools provide an avenue to significant pre-cleaning inspection cost savings that could be achieved through reduced inspection and non-productive cleaning costs.

The overall objective of this EPA funded study was to demonstrate a recently developed innovative acoustic-based sewer line assessment technology that is designed for rapid deployment using portable equipment. This technology can provide a rapid assessment of the need for pipe cleaning and an overall pipe-condition assessment. Acoustic technologies require a minimal amount of equipment when compared to closed-circuit television (CCTV) inspection systems. These acoustic based technologies have the potential to provide information in a matter of minutes to assist a utility in determining whether a sewer pipe might be partially or fully blocked and require cleaning or renewal.

Innovative inspection approaches are now emerging that take advantage of the advances in newly available observation and detection technologies and deployment strategies, such as acoustic- (sonic, ultrasonic) and light- (laser, infrared) based devices that have not traditionally been applied to sewer system investigation. These technologies are designed for rapid deployment using portable equipment and do not necessarily require a robotic transporter in order to capture data for the entire length of the pipe. The deployment of these non-traditional technologies, supported by emerging digital, modular, and robotics technologies has the potential to greatly expand the “reach” of sewer system inspection techniques, while reducing the overall cost of sewer inspections.

One commercially available line of emerging technology for the rapid assessment of gravity sewer lines is acoustic-based technology for sewer inspection. Acoustic energy naturally follows a pipe’s curvature.

Obstructions within the pipe will cause a portion of the acoustic energy to be reflected and absorbed. In addition, unless the obstruction is significantly dense, a portion of the acoustic energy also passes through. These inherent physical properties of acoustics within pipes provide the mechanisms for evaluating a pipe's condition. Based on these mechanisms, acoustic inspection technology may be capable of quickly evaluating the presence of blockages, features, and defects in the interior of sewer pipes and provide informed decisions relating to the need for cleaning or further inspection using other available technologies.

The SL-RAT is a portable, battery-operated, acoustic sewer inspection tool that provides blockage assessment in less than 3 minutes. The SL-RAT system is composed of two basic components: 1) the acoustic signal transmitter (TX) unit and 2) the acoustic signal receiver (RX) unit. Each SL-RAT system is deployed as a uniquely configured "pair" of TX and RX units. The TX unit provides the active acoustic transmission through the pipe and the RX unit provides the microphone and signal processing capabilities to listen for and interpret the received acoustic signal. The TX and RX units are typically deployed atop adjacent manholes on a sewer line.

Once deployed, the SL-RAT measures the dissipation of sound energy between the TX and RX units through the airspace within the pipe (i.e., the space between the wastewater flow and the pipe wall). Any single defect that completely obstructs the pipe will not allow the transmission of sound energy between the TX and RX units. Additionally, aggregate obstructions within the pipe – such as roots, grease, debris, joint offsets, hammered lateral connections, cross bores, pipe sags, high water levels etc. – will increase the sound energy dissipation. The SL-RAT measures this "energy gap" and then develops a blockage assessment. The overall blockage assessment by SL-RAT is provided in the form of a numeric output value on a scale of 0 (completely obstructed) to 10 (completely unobstructed).

MSDGC is responsible for the operation and maintenance of over 3,000 miles of sewer, with approximately 600 miles of those sewers being "off-road." These off-road sewers are typically inspected every 8 – 10 years and are difficult to access, and expensive to inspect. In addition to these "off-road" sewers, MSDGC also inspects and cleans on-road sewers on a proactive basis. For the purposes of this study, the following three Greater Cincinnati-area locations were identified and selected for this demonstration:

- Hunt Road – off-road sewers (see Appendix B for a detailed figure)
- Galia Drive – off-road sewers (see Appendix B for a detailed figure)
- Greenhills – on-road sewers (see Appendix B for a detailed figure)

These locations include a range of pipe sizes and a variety of pipe materials and were scheduled for cleaning and inspection during the study year. The selected study areas have sewer pipes ranging from 6- to 12-inch diameters. The SL-RAT system deployed in this evaluation is designed to work optimally in this pipe size range. For optimal evaluation of larger diameter pipes (i.e., greater than 18-inch diameter), adjustments to the SL-RAT algorithm implemented in the RX unit's firmware would likely be required.

A project-specific EPA required Quality Assurance Project Plan (QAPP) was developed and implemented by the project team. Each sewer pipe-segment was to be examined and assessed using selected acoustic methods, pole mounted camera, and CCTV prior to cleaning. If cleaning was considered necessary based on the inspections, the sewer segments were to be cleaned, examined, and assessed again after cleaning. Per the project's QAPP, the following strategy was specified for conducting the inspections. Sewer line branches were to be inspected by starting at the furthest downstream pipe segment, with the inspection regime systematically conducted to the furthest upstream pipe segment. This procedure was specified to ensure that if any material (or debris) was dislodged during testing, the material would flow downstream and not impact subsequent testing in the upstream pipe segments.

Besides providing a pipe condition and blockage assessment, the key advantage of implementing technologies such as SL-RAT is the rapid deployment feature using portable equipment that can result in significant cost savings to utilities. As mentioned previously, the Greenhills area within MSDGC was selected to evaluate the time it takes to conduct an acoustic assessment campaign using SL-RAT. As the goal of this study area was to evaluate the time required to perform the acoustic inspections, advanced planning and preparation was conducted to help mitigate issues associated with traffic control and location of manholes. This sub-study involved SL-RAT measurements at 53 pipe-segments covering approximately 9,500 linear feet of pipe in the Greenhills study area with pipe sizes of 8" and 10" diameters.

The emergence of acoustic sewer inspection technologies, like SL-RAT, as rapid deployment, low-cost, reliable, pre-cleaning assessment tools is focusing growing attention on the potential for more cost-effective sewer cleaning programs. Through the ease of deployment, reduction of cost, increases in reliability of these inspection approaches, combined with the potential for reducing the "cleaning of clean pipes," significant cost savings are attainable. As utilities apply these new inspection technologies, they can move towards implementing sewer cleaning programs that consist of planned directed and quick response, reactive cleaning. Also, these cost savings can be realized while improving collection system performance and the protection of public health and water quality.

The results of this demonstration project reveal the potential for more cost-effective sewer cleaning programs. The site specific pre-cleaning assessment inspection costs resulting from this project and MSDGC's historic practices for CCTV (on-road), CCTV (off-road), and SL-RAT (on- and off-road) are $1.68/ft., $2.03/ft., and $0.14/ft., respectively. So, for pre-cleaning assessment, the application of the SL-RAT can reduce MSDGC's costs by $1.54/ft. for on-road sewers and $1.89/ft. for off-road sewers. In addition, by moving to a sewer cleaning program predominated by planned directed cleaning, MSDGC can save $2.00/ft. by reducing its "cleaning of clean pipe." In total, when costs of conventional CCTV inspection and cleaning are combined, for each pipe segment that is deemed "clean" using the SL-RAT, MSDGC can save $3.54/ft. for on-road sewers and $3.89/ft. for off-road sewers.

The results of this demonstration of the SL-RAT show promise for its application as a tool for cost-effective, pre-cleaning assessment and post-cleaning quality assurance. The application of the SL-RAT in an overall collection system O&M program should enable wastewater utilities to optimize their sewer cleaning efforts and free up valuable resources to more effectively implement critical CMOM and asset management programs.

Section 1—INTRODUCTION

The focus on condition assessment of gravity wastewater collection systems (sewers) continues to broaden. As sewer system networks age, the risk of deterioration, blockages, and collapses becomes increasingly of concern. The consequences of these events and conditions can negatively impact a community's social, environmental and financial well-being. As a result, sewer system owners and operators worldwide are taking proactive measures to better maintain and improve the performance levels of their sewer systems. Sewer system owners and operators are progressively addressing operational issues prior to their occurrence, when possible, and obtaining information concerning the condition of their sewer system assets.

Traditionally, the main focus of condition assessment of sewers has been directed at operational issues related to the collection and conveyance of flows to a facility for treatment and disposal. To address operational issues, attention has tended to concentrate on maintenance activities associated with the cleaning and removal of debris and foreign materials from collection system pipes. The presence of debris and foreign material in sewer pipes reduces capacity and inhibits sewage from flowing through the system to the treatment facilities as intended. Additionally, attention has been directed towards the reduction of excessive hydraulic loading of sewers due to wet-weather induced infiltration and inflow (I&I) entering and over burdening the hydraulic capacity of the sewers and wastewater treatment plants. The combination of debris and extraneous wet-weather induced flows can result in less than desired levels of customer service and possibly cause raw sewage to overflow from the collection system or to result in basement backups. Unintended overflows from a wastewater collection system are commonly referred to as sanitary sewer overflows (SSOs).

Occasional unintentional discharges of raw sewage (i.e., SSOs) from municipal sanitary sewers occur in almost every system. SSOs result from a variety of causes, including but not limited to line blockages, line breaks, and sewer defects that allow storm water and groundwater to overload the system; lapses in sewer system operation and maintenance; power failures; inadequate sewer design; and vandalism. The U.S. Environmental Protection Agency (EPA) estimates that there are at least 23,000 - 75,000 SSOs per year (not including the sewage backups into buildings). The untreated sewage from these overflows can contaminate the nation's water resources, causing serious water quality problems. Sewage can also backup into basements, causing property damage and threatening public health (EPA, 2012).

1.1 Maintenance of Sanitary Sewers

Many avoidable SSOs are caused by inadequate operation or maintenance, inadequate system capacity, and improper system design and construction. These SSOs can be reduced or eliminated by the following practices (EPA, 2012):

- Sewer system cleaning and maintenance
- Reducing I&I through system rehabilitation and repairing broken or leaking service lines.
- Increasing or upgrading sewer, pump station, or sewage treatment plant capacity and reliability.
- Construction of wet-weather storage and high-rate treatment facilities to treat excess flows.

Cleaning and inspecting sewer pipes is essential for utilities to operate and maintain a properly functioning system and minimize SSOs; these activities further a community's reinvestment in its wastewater infrastructure (EPA, 1999). For many utilities, sewer cleaning and inspection programs are generally part of larger umbrella programs. These programs are commonly referred to by the utilities and regulatory agencies as capacity, management, operation and maintenance (CMOM) and asset management programs. Effective operation and maintenance (O&M) of a collection system is an essential element of any CMOM and asset management program (EPA, 2005).

The routine maintenance of a sewer system often includes sewer system cleaning, root removal/treatment, and cleaning/clearing of sewer mainline blockages. However, understanding where and when to perform cleaning activities in the most effective manner is not necessarily a straight forward task. Some agencies clean their sewer system as a matter of course without knowing in advance whether the system or portions of the system require cleaning. Pipes with blockages receive the same attention and resources as those with no actual cleaning needs. The use of staff and equipment is not optimized in this approach and staff time and resources that could be directed to other more productive O&M activities are lost.

In an attempt to direct maintenance staff and cleaning equipment to those pipes in a sewer system that require attention, some agencies identify cleaning needs by conducting inspection of the sewers prior to cleaning. These pre-cleaning inspections are conducted using various approaches and equipment to varying degrees of success, efficiency and speed.

The speed and cost associated with traditional methods for pre-cleaning inspections vary greatly. The rapid assessment of sewers to determine the need for cleaning and to possibly identify defects is an approach that is capturing wide attention of many wastewater utilities. Rapid assessment approaches and tools provide an avenue to significant pre-cleaning inspection cost savings that could be achieved through reduced inspection and non-productive cleaning costs.

The overall objective of this EPA funded study was to demonstrate a recently developed innovative acoustic-based sewer line assessment technology that is designed for rapid deployment using portable equipment. This technology can provide a rapid assessment of the need for pipe cleaning and an overall pipe-condition assessment. Acoustic technologies require a minimal amount of equipment when compared to closed-circuit television (CCTV) inspection systems. These acoustic based technologies have the potential to provide information in a matter of minutes to assist a utility in determining whether a sewer pipe might be partially or fully blocked and require cleaning or renewal. The speed of the assessment, using minimal equipment, has the potential to result in significant cost-savings compared to traditional methods, such as CCTV inspection. It is generally known that smaller diameter pipes (i.e., less than or equal to 12-inch diameter) contribute to over 90 percent of the sewer main backups reported in a typical city (Sprague, J., 2007). This study hence focused on the demonstration of a acoustic technology that is suited for smaller diameter pipes.

1.2 Sewer Line Inspection Techniques

The traditional sewer system inspection methodologies used for pre-cleaning assessment and inspection-based condition assessment are generally based on visual observations. Most inspections of sewer lines are performed primarily by one or more of the following established inspection techniques:

- Visual (historical)
- Lamping (historical)
- Pole/Stick Mounted Zooming Cameras
- CCTV
- Laser profiling
- Sonar assessment

The historical approaches to visually examining sewers have been used to varying degrees of success. In the past, before camera and robotic equipment were widely available, workers often entered a maintenance access point (manhole) and visually examined the pipes. This method of pipeline inspection is rarely used today due to worker safety considerations, limitations inherent to the inspection method, and the introduction of technologies that allow for remote, non-entry, camera-based inspections.

Workers have long used light sources lowered into sewer access structures or manholes in an attempt at illuminating the interior of a pipe. A second worker positioned at grade at an adjacent manhole then attempts to see if the light has reached the adjacent manhole. If light is observed, the pipe is assumed to be relatively free of obstructions. If light is not observed, the pipe is assumed to have a blockage that also obstructs flow. The pipe would then typically be cleaned in an attempt to remove the blockage. Inspection of a pipe in this manner has been referred to as lamping of lines or simply lamping. Many older sewer systems have lamp holes constructed in the sewers to facilitate this type of inspection. The fundamental issue with lamping of lines is that the entire inspection relies on whether light can visibly be seen from one access structure to the next. The inspectors cannot directly see whether a sewer pipe requires cleaning or if a structural defect exists. Such structural defects might include conditions such as misalignment of the pipeline, sags, protruding taps or a collapsed pipe. A variation of line lamping that has been used extensively is for a worker to enter a manhole and shine a bright light and view the pipe condition using a mirror or direct observation. The approach can be effective but only a small percentage of the line can be inspected.

More recently, cameras have been mounted on poles, much like a painter’s extension pole commonly referred to as cameras on a stick or pole-mounted cameras. A pole-mounted camera is lowered into the manhole by an operator standing at street level, and the camera operator directs the camera’s view into the pipes connected to the manhole. On an integrated monitor, the equipment operator remotely views at street level what the camera observes in the pipe. These cameras are now commonly equipped with operator controlled lighting and camera focus/zooming capabilities to augment the inspection in an attempt to view and inspect the entire pipe length between access structures.

Pole-mounted zooming cameras have been a significant advancement over lamping of lines. However, issues with lighting the entire length of the pipe between access structures and the ability to focus the camera lens at significant distances in poor lighting conditions limit the usefulness of these tools. Furthermore, if the pipe is misaligned and not straight, water vapor is present, or obstructions such as roots or other matter are present, the effectiveness of this tool is further diminished and limited.

Robotic platforms, mounted with camera-based technologies, have been in use for sewer inspections for more than 50 years. These robotic systems allow for CCTV camera equipment to be remotely operated, controlled, and monitored from ground level. The inspection images can be viewed immediately and transferred to data storage devices for viewing and evaluation at a later time. Advances in technology include self-propelled equipment, digital imaging and 360-degree field of view. The cameras are transported into the length of sewer pipes for direct visual inspection via the camera. These CCTV systems are now widely used and, over the course of the past 20 to 30 years, become the current industry standard for direct visual inspection of sewer pipes. A majority of utilities own and operate CCTV systems or have contract(s) for the provision of CCTV services.

The most common type of robotic CCTV inspection systems in use for inspection of public sewers requires vans, trucks, or similar vehicles for their operation. If sewers are located off-road, all wheel drive or four wheel drive vehicles may be required to access the manhole structures. A new vehicle equipped with a CCTV inspection system will typically cost between $100,000 and $200,000, and require a minimum crew of two persons. Custom off-road vehicles equipped with CCTV systems are even more expensive to own and operate. Figure 1-1 shows a custom off-road CCTV camera tractor owned and operated by the Metropolitan Sewer District of Greater Cincinnati (MSDGC).

Figure 1-1. Custom Off-road CCTV Camera Tractor (Courtesy: MSDGC).

The use of laser and sonar profiling technologies for the inspection and condition assessment of sewers has been introduced in recent years (EPA, 2009). Laser profiling technology is increasingly being used to inspect sewers. Laser profiling goes beyond visual inspection and allows for geometric measurements to be obtained. However, the adoption of laser profiling for pre-cleaning inspection is of limited added value beyond what CCTV can provide.

Unlike CCTV and laser technologies, sonar profiling equipment requires that the sensing apparatus be completely submerged and only provides an assessment of the pipe condition under the water level. Therefore, the equipment is often coupled with CCTV equipment so that the pipe above and below the water level can be inspected. Sonar assessment is useful in locating and mapping debris especially in large diameter pipes with significant base-flow, water filled siphons and pressurized force mains.

1.3 Industry Standard Sewer Inspection Methodology

The National Association of Sewer Service Contractors (NASSCO) has established "de-facto" industry standards for the use of CCTV systems in sewers. The standards include acceptable operating parameters as well as observation and defect coding standards for sewer inspection. NASSCO offers the Pipeline Assessment and Certification Program (PACP) for CCTV operators and those who analyze and interpret CCTV data. The NASSCO PACP system provides for the standardization of the description of defects within the industry.

Inspections performed in compliance with the NASSCO PACP require that CCTV inspections be conducted at a pace of no more than 30 feet per minute for camera transporter travel. PACP compliant inspections also require that the system operator stop and view observed pipe defects and features. Advanced technologies using high-definition (HD) digital scanning and imaging CCTV systems are capable of traveling at a faster pace without the need to stop and view observed pipe defects and features, while maintaining visual clarity and gaining high resolution, enhanced defect, and feature observation. The capture of data from these scanning systems allows for virtual pan, tilt zoom operations and post-inspection coding of defects and features. Use of these scanning systems is acceptable under the NASSCO PACP system if image quality is adequate and meets minimum PACP standards.

Typical average daily CCTV inspection production rates vary from operator-to-operator and from site-to-site. A multitude of factors affect the typical average daily production rates. Such factors include the availability of system access (most commonly manholes) locations, distance between access locations, pipe diameter, pipe materials, flow depth and velocity in the pipes, presence of debris, number of defects, number of features, CCTV system cable length, transporter weight, and other factors. An average daily production rate between 1,000 feet to 4,000 feet can be expected.

CCTV has revolutionized how sewer systems are operated, maintained, and inspected, and made sewer pipe inspection relatively safe when compared to previous methods of inspection. It is an invaluable tool for sewer inspection. Its greatest strength is its ability to visually examine and inspect the entire length of a pipe. This strength imposes CCTV inspection's greatest limitation – the CCTV system must travel the entire length of a pipe to complete an inspection. Significant blockages, defects, or lack of available access denies its ability to inspect the sewer in part or total.

1.4 Innovative Sewer Inspection Methodologies

Multi-sensor robotic transporter platforms have been developed and introduced to the industry that allow for the coupling of laser and sonar profiling technologies onto a remotely operated and controlled CCTV inspection system. These systems provide for significant advancements in the ability to inspect a sewer system. These technologies are typically integrated with the CCTV camera transporter, increasing the overall cost, but providing additional insights into the condition of the sewer.

Innovative inspection approaches are now emerging that take advantage of the advances in newly available observation and detection technologies and deployment strategies, such as acoustic- (sonic, ultrasonic) and light- (laser, infrared) based devices that have not traditionally been applied to sewer system investigation. These technologies are designed for rapid deployment using portable equipment and do not necessarily require a robotic transporter in order to capture data for the entire length of the pipe. The deployment of these non-traditional technologies, supported by emerging digital, modular, and robotics technologies has the potential to greatly expand the “reach” of sewer system inspection techniques, while reducing the overall cost of sewer inspections.

One commercially available line of emerging technology for the rapid assessment of gravity sewer lines is acoustic-based technology for sewer inspection. This technology provides for the acoustic “lamping” of lines rather than using a light source to illuminate the lines. Acoustics has an inherent advantage over light for inspecting the interior of sewer pipes. Light energy tends to disperse within a sewer pipe. If an obstruction is encountered, the light energy is scattered (including back towards the light source). This allows the obstruction to be seen or videoed. Obstructions include water vapor, the pipe wall and pipe curvatures. Acoustic energy naturally follows a pipe’s curvature. Obstructions within the pipe will cause a portion of the acoustic energy to be reflected and absorbed. In addition, unless the obstruction is significantly dense, a portion of the acoustic energy also passes through. These inherent physical properties of acoustics within pipes provide the mechanisms for evaluating a pipe’s condition. Based on these mechanisms, acoustic inspection technology may be capable of quickly evaluating the presence of blockages, features, and defects in the interior of sewer pipes and provide informed decisions relating to the need for cleaning or further inspection using other available technologies.

CCTV sewer inspections, especially in “off road” conditions, generally require special equipment, such as a highly customized vehicle equipped with an on-site generator, remotely operated transporter, tether cable and spool system, operator control hardware, a computer system, specialized software, and various other tools. Acoustic sewer inspections require much less supporting equipment and the inspection equipment is portable, allowing for easier access to remote sites.

Sewer inspections with acoustic-based technology have the potential of being performed in a fraction of the time in which CCTV inspections are performed; increasing the rate of productivity of the inspections and reducing the cost of the inspections.

A portable acoustic inspection system can assist in making a quick diagnostic determination whether a sewer line needs to be cleaned or if it needs to be investigated further using CCTV inspection. These diagnostic determinations will allow the utility to more cost-effectively deploy their limited resources to areas that require cleaning or further investigation. It will optimize the deployment of the special equipment and crews required for CCTV inspection to where they are most needed, thus increasing the cost-effectiveness of their CCTV inspection program.

1.5 Study Objective

The overall objective of this EPA-funded study was to demonstrate innovative sewer line assessment technologies that are designed for rapid deployment using portable equipment. This study focused on demonstration of technologies that are suitable for smaller diameter pipes (less than 12-inch diameter). One recently developed and commercially-available acoustic-based sewer pipe assessment technology is the Sewer Line – Rapid Assessment Tool (SL-RAT™) manufactured by InfoSense, Inc. (InfoSense) of North Carolina. This report summarizes the collaborative demonstration and evaluation of the SL-RAT.

1.6 SL-RAT Equipment Overview

The SL-RAT is a portable, battery-operated, acoustic sewer inspection tool that provides blockage assessment in less than 3 minutes. The SL-RAT system is composed of two basic components: 1) the acoustic signal transmitter (TX) unit and 2) the acoustic signal receiver (RX) unit. Each SL-RAT system is deployed as a uniquely configured "pair" of TX and RX units. The TX unit provides the active acoustic transmission through the pipe and the RX unit provides the microphone and signal processing capabilities to listen for and interpret the received acoustic signal. The TX and RX units are typically deployed atop adjacent manholes on a sewer line. Figure 1-2 shows the SL-RAT's conceptual deployment for blockage assessment.

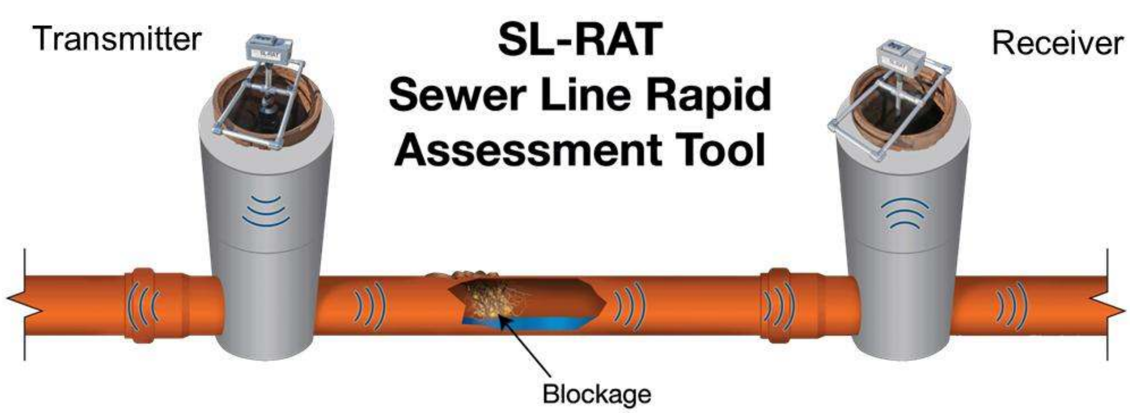

Figure 1-2. SL-RAT Conceptual Deployment.

Deploying the SL-RAT involves transporting the TX and RX units to the sewer access points (manholes). At the manholes, when the units are turned on, the onboard firmware conducts an initialization process and in less than five minutes the units are ready to operate. The TX/RX units should remain turned on when moving from one location to another throughout the work day. This eliminates the initialization time and allows the units to be ready for operation. Figure 1-3(a) shows the SL-RAT units in their transport mode at one of the EPA study sites. To perform an acoustic inspection with the SL-RAT, the manhole covers at both ends of a pipe section are either partially or fully removed. The SL-RAT units are then placed in their operational mode as depicted in Figure 1-3(b) and (c) for the RX and TX units, respectively. For off-road or on-road inspections, the SL-RAT can be easily transported manually with the RX unit weighing 11 pounds and the TX unit weighing 18 pounds. Typical usage involves inspecting multiple pipe segments along a leg of a sewer line. This is facilitated by only moving one unit at a time after each inspection (effectively "leap frogging" the units down the sewer line). Tests are conducted while the pipe is in operation, with no need to restrict or change the flow conditions. The units can be deployed for testing in either the upstream or downstream direction.

Figure 1-3. SL-RAT Deployment at EPA Project Site: (a) TX and RX Units in Transport Mode, (b) RX Unit Operational Mode Deployment, (c) TX Unit Operational Mode Deployment.

Once deployed, the SL-RAT measures the dissipation of sound energy between the TX and RX units through the airspace within the pipe (i.e., the space between the wastewater flow and the pipe wall). Any single defect that completely obstructs the pipe will not allow the transmission of sound energy between the TX and RX units. Additionally, aggregate obstructions within the pipe – such as roots, grease, debris, joint offsets, hammered lateral connections, cross bores, pipe sags, high water levels etc. – will increase the sound energy dissipation. The SL-RAT measures this "energy gap" and then develops a blockage assessment. The assessment uses a proprietary algorithm based on a statistical model of sound behavior in conduits that was developed through several years of empirical research on sewage lines. The only operator input required to perform an inspection is the approximate length, in 50 foot increments, of the pipe segment between the TX and RX units. This estimate may be aided by the RX and TX themselves as they are able to suggest an estimated pipe-length based on Global Positioning System (GPS) and radio frequency communication in the majority of cases. The overall blockage assessment by SL-RAT is provided in the form of a numeric output value on a scale of 0 (completely obstructed) to 10 (completely unobstructed). Table 1-1 summarizes the relative output value provided by SL-RAT in comparison to an expected visual assessment based on CCTV. Charlotte Mecklenburg Utilities (CMU) has tested this technology during the development phase and has developed action plans based on the output results (Fishburne, J. 2011). For example, if the SL-RAT output results are in the 7 to10 range, the pipe is considered to be clear, if the results were 0 to 4, the pipe is in need of cleaning or further investigation to determine the cause of the poor SL-RAT results. Additionally, depending on the available resources, any other score in the mid-range may undergo additional investigation to further determine if cleaning is needed.

Table 1-1. Comparative SL-RAT vs. CCTV Blockage Assessment.

SL-RAT Assessment Range	CCTV Assessment / Interpretation
10	No significant obstructions within the pipe
7-9	Minor impediments within the pipe such as joint offsets, partial sags, protruding laterals, debris, minor grease, and/or minor root fibers.
4-6	Impediments within the pipe such as joint offsets, partial sags, protruding laterals, debris, grease, and/or root fibers. Single or multiple occurrences.
1-3	Significant impediments within the pipe such as multiple joint offsets, near full pipe sag, multiple protruding laterals, significant debris, significant grease, significant root fibers and/or root balls. Single or multiple occurrences.
0	Full pipe sag; single or multiple obstructions within the pipe reaching or nearly reaching the flow.

Since the SL-RAT employs sound energy to detect blockages, it can negotiate bends and obstacles – unlike a pole-mounted zooming camera that relies on straight visual sight lines. InfoSense's prior deployments of SL-RAT have indicated that, with sufficiently low ambient noise levels, users have reliably obtained measurements for up to 800 foot pipe-distances between the TX and RX modules. For the greatest reliability, it is recommended that the SL-RAT inspections be conducted between adjacent manholes. The results of the assessment are immediately displayed to the user at the time of testing. The SL-RAT device is also equipped with a GPS chip for location determination, as well as other electronics that allow the paired TX and RX units to communicate via radio frequencies (RF). Additional data, such as time stamp, user identification, and GPS location, are stored in an encrypted format on the device that can be uploaded for archiving and further analysis to InfoSense's cloud-based Sewer Line Diagnostic OrGanizer (SL-DOG) via a Universal Serial Bus (USB) connection to a personal computer (PC). The SL-DOG provides post-processing, allowing the infield blockage assessment to be verified and assist in location registration of the blockage assessment as well as correcting the acoustic assessment result for operator errors in estimating the pipe length. These features are further discussed in Appendix A – SL-DOG Condition Assessment Data Verification.

1.7 Project Team

This collaborative field demonstration of the SL-RAT was led by EPA's National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. EPA engaged MSDGC as a collaborative research partner to provide access to the study area (see Section 2.0) sewer lines and to perform the related field work. For coordinating and performing this demonstration, EPA issued a work assignment to Pegasus Technical Services, Inc. (PTSI) under EPA Contract No: EP-C-11-006. Shaw Environmental & Infrastructure, Inc. (Shaw - a team subcontractor to PTSI) served as the project lead to assist in the selection of technology vendors, obtain the equipment through lease, coordinate the field efforts with MSDGC, evaluate the data generated, and produce this report with the project team.

To perform these tasks, Shaw subcontracted with Brown and Caldwell (BC) and ALSA Tech LLC (ALSA) to serve as industry experts/consultants in this demonstration. In addition, Shaw contacted selected technology vendors (e.g., InfoSense) to arrange for the lease of the SL-RAT device. The members of this project team included:

- EPA – Dan Murray, Patrick Clark and John Olszewski
- MSDGC – Jerry Weimer, Eric Withers, Eric Schneider, Dustin Prue, and Mike Pittinger
- Shaw – Srinivas Panguluri and Don Schupp
- BC – Gary Skipper and Steve Donovan
- ALSA – Abraham Chen
- InfoSense – Ivan Howitt and Alex Churchill

The EPA and Shaw project team participated in this collaborative field demonstration mainly as neutral observers during the field activity-phase of this study. The project team's main objective was to compile the data collected by MSDGC and perform the evaluation contained in this report. The project team members periodically accompanied MSDGC personnel while they deployed the equipment and assessed the condition of sewers in the Cincinnati area using both a conventional CCTV camera-based inspection system and the SL-RAT. Specifically, the results obtained from the following technologies will be discussed in this report:

- SL-RAT manufactured by InfoSense, Inc.
- Pan-Tilt-Zooming pole-mounted camera (aka “camera on a stick”) manufactured by Envirosight Quickview.
- HD-digital scanning CCTV or the PANORAMO 3D Optical Pipeline Scanner manufactured by RapidView-IBAK.

Section 2—Study Area Description and Evaluation Parameters

MSDGC is responsible for the operation and maintenance of over 3,000 miles of sewer, with approximately 600 miles of those sewers being "off-road." These off-road sewers are typically inspected every 8 – 10 years and are difficult to access, and expensive to inspect. In addition to these "off-road" sewers, MSDGC also inspects and cleans on-road sewers on a proactive basis. For the purposes of this study, the following three Greater Cincinnati-area locations were identified and selected for this demonstration:

- Hunt Road – off-road sewers (see Appendix B for a detailed figure)
- Galia Drive – off-road sewers (see Appendix B for a detailed figure)
- Greenhills – on-road sewers (see Appendix B for a detailed figure)

These locations include a range of pipe sizes and a variety of pipe materials and were scheduled for cleaning and inspection during the study year. Tables 2-1 and 2-2 summarize the total number of pipe segments by size and material type selected for this study.

Table 2-1. Hunt Road, Galia Drive, and Greenhills Pipe Segment Size Summary.

Pipe Size (in)	No. of Segments
6	1
8	97
10	1
12	56
Total	**155**

Table 2-2. Hunt Road, Galia Drive, and Greenhills Pipe Segment Material Summary.

Pipe Material	No. of Segments
Concrete (RCP)	75
Ductile Iron Pipe (DIP)	2
Cast Iron Pipe (CIP)	1
Vitrified Clay Pipe (VCP)	60
Poly-Vinyl Chloride (PVC)	1
Slip-lined	5
Unknown	11

As summarized in Table 2-1, the selected study areas have sewer pipes ranging from 6- to 12-inch diameters. The SL-RAT system deployed in this evaluation is designed to work optimally in this pipe size range. For optimal evaluation of larger diameter pipes (i.e., greater than 18-inch diameter), adjustments to the SL-RAT algorithm implemented in the RX unit's firmware would likely be required.

2.1 Test Conditions

A project-specific EPA required Quality Assurance Project Plan (QAPP) was developed and implemented by the project team (EPA, 2012b). As part of the QAPP, the inspections were to be conducted during times when the water level in the sewer was below 40 percent of pipe diameter and there were no significant changes to the water levels between the technology deployments. Each sewer pipe-segment was to be examined and assessed using selected acoustic methods, pole mounted camera, and CCTV prior to cleaning. If cleaning was considered necessary based on the inspections, the sewer segments were to be cleaned, examined, and assessed again after cleaning. Figure 2-1 depicts the overall test procedure that MSDGC was to follow during this study. Figure 2-2 shows the inspection test procedure, and Figure 2-3 shows the mainline CCTV test procedure. As indicated in Figure 2-1, another acoustic inspection technology - SewerBatt was also evaluated during this demonstration study with results contained in a separate EPA report. Both acoustic inspection technologies were evaluated using the same underlying CCTV-based PACP assessments.

2.2 Condition Assessment/Inspection Strategy

Per the project's QAPP, the following strategy was specified for conducting the inspections. Sewer line branches were to be inspected by starting at the furthest downstream pipe segment, with the inspection regime systematically conducted to the furthest upstream pipe segment. This procedure was specified to ensure that if any material (or debris) was dislodged during testing, the material would flow downstream and not impact subsequent testing in the upstream pipe segments.

For each pipe segment, the following inspection regime was employed for the specified technologies and in the specified sequence:

- SL-RAT
- Pole/Stick Mounted Camera
- CCTV and/or PANORAMO Pipeline Scanner

The inspection sequence for the technologies was selected so that the pipe segment's condition would remain consistent over the inspections by each technology. For example, since the SL-RAT does not come in contact with the flow, performing this inspection first does not impact the condition of the pipe segment for the subsequent camera-based inspections.

In January 2013, at the outset of the field demonstration, the SL-RAT representatives from InfoSense visited Cincinnati to train all project personnel on the appropriate techniques to deploy and use the SL-RAT equipment. After the initial training session, the vendor remained onsite for a day as an observer to verify correct SL-RAT operation by the MSDGC operators and to address any questions. Due to scheduling issues, the SL-DOG software was installed at the MSDGC facility several weeks later, based on communication via telephone conference between MSDGC and InfoSense personnel. Thereafter, InfoSense personnel were available, if required, for further consultation by MSGDC personnel via email, teleconference, or by onsite visit. However, no additional contact with the vendor was required by MSDGC during the remaining course of the project. Per the QAPP, Shaw, BC, and EPA personnel accompanied the MSDGC crew periodically to observe the inspection and the data collection process.

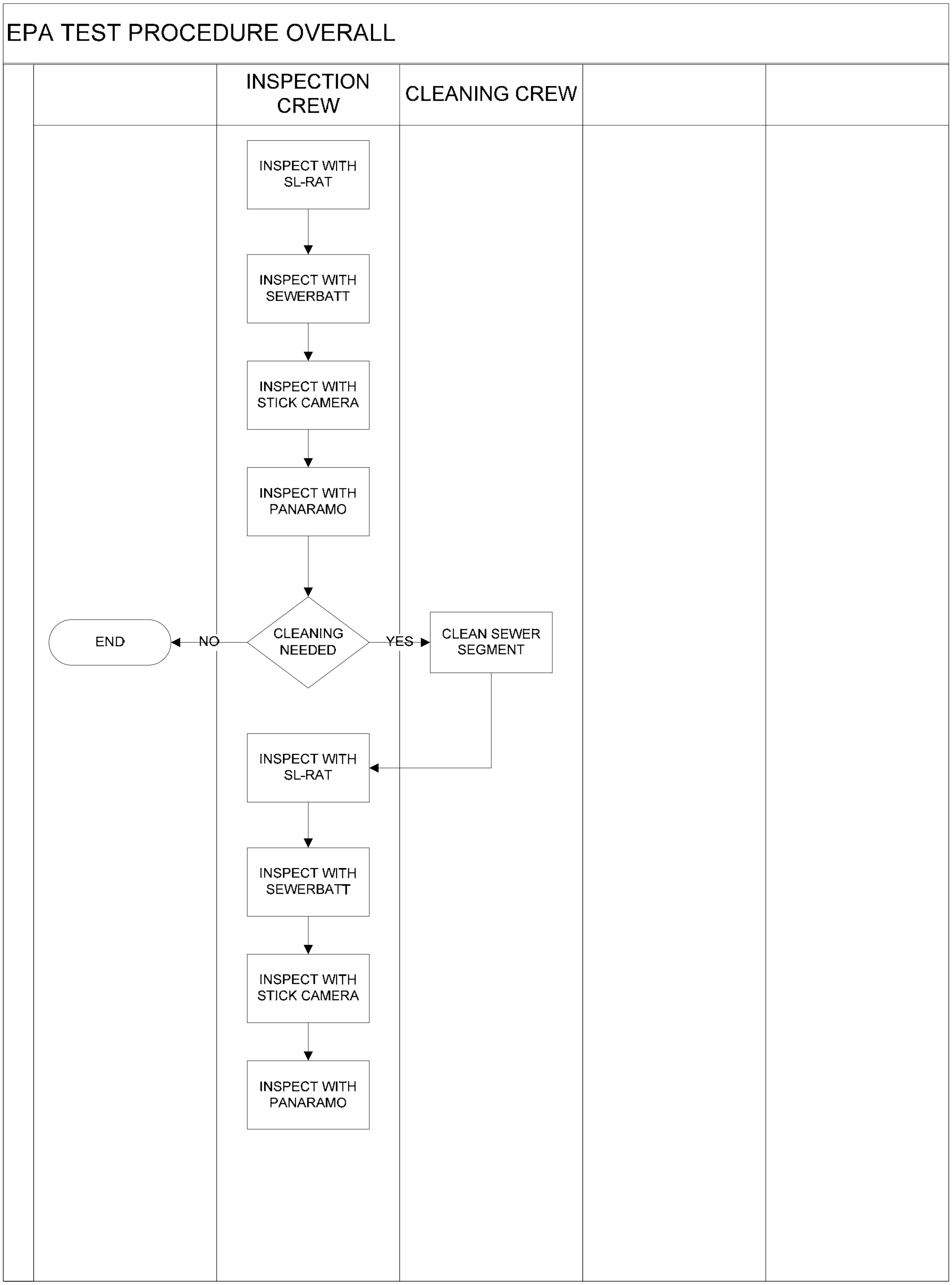

Figure 2-1. Overall Test Procedure.

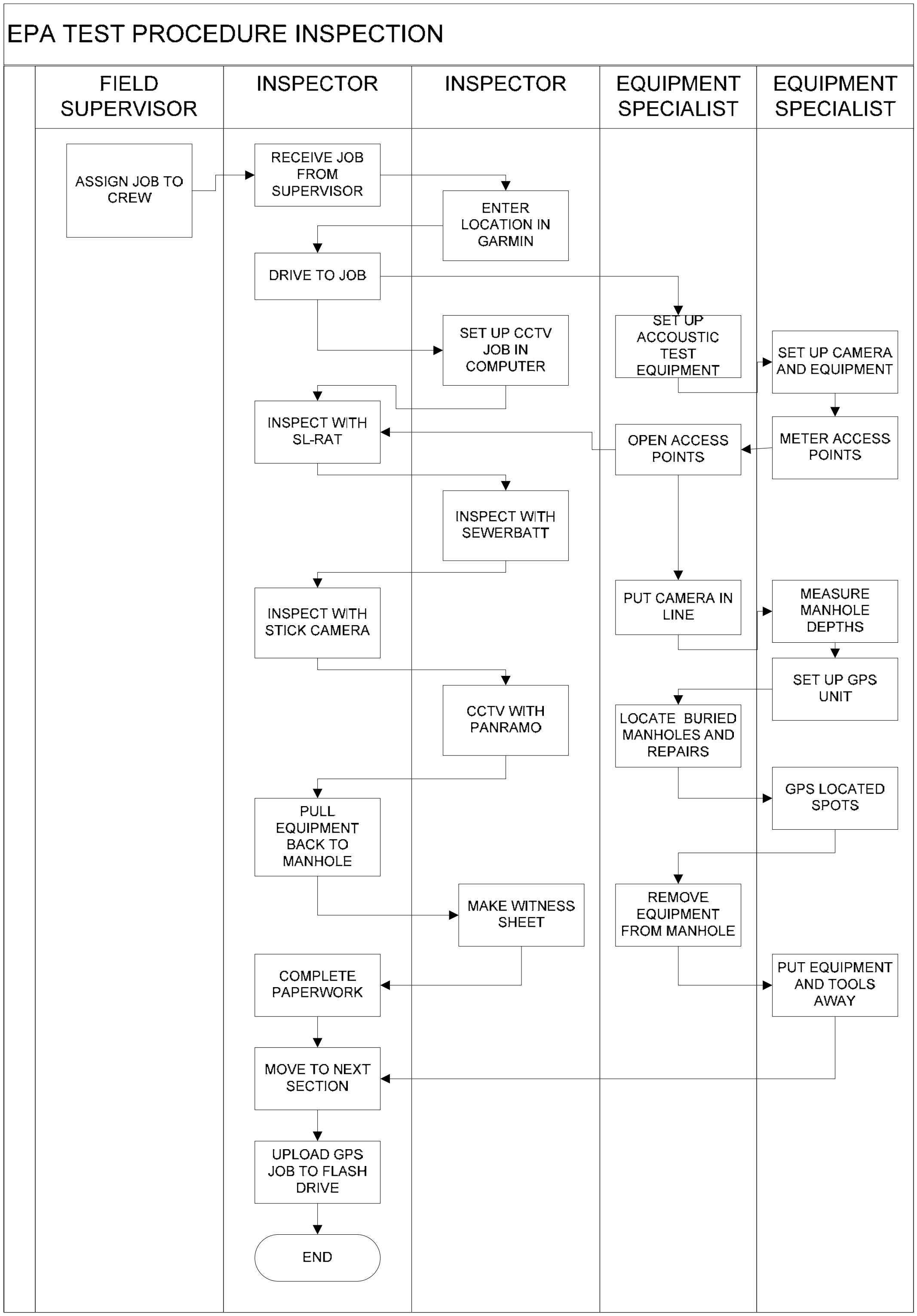

Figure 2-2. Inspection Test Procedure.

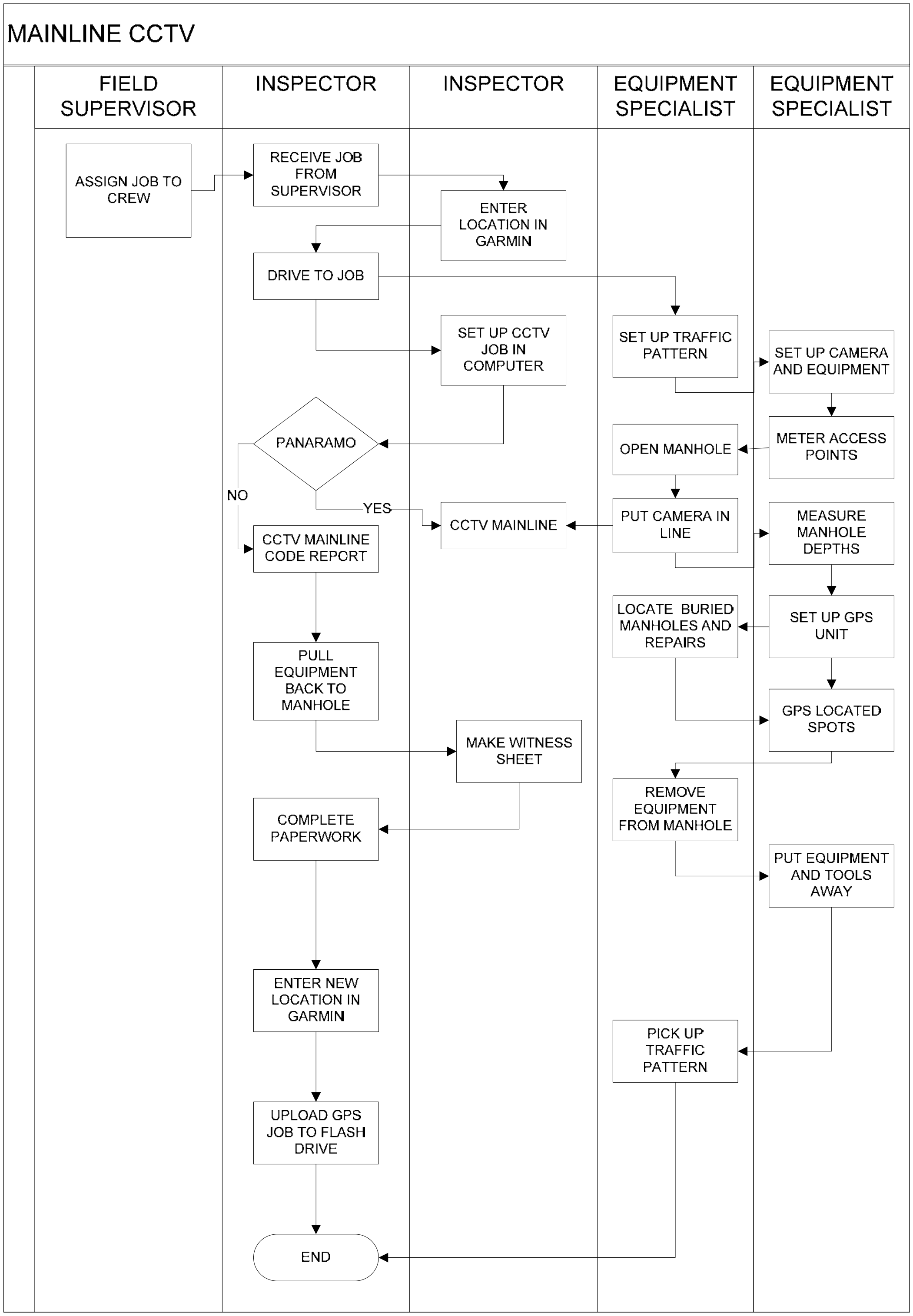

Figure 2-3. CCTV Test Procedure.

2.3 CCTV and Pole Mounted Zooming Camera Data Evaluation Procedure

As indicated in the previous sections, two camera-based technologies where specified in the QAPP to be used as part of the inspection regime for each pipe segment evaluated. The two specific camera technologies used during the project were:

- Envirosight Quickview (Pole/Stick Mounted Camera) –handheld pole mounted zooming camera used to visually inspect and assess the sewer condition.
- PANORAMO – robotic CCTV which utilizes two high-resolution 186° wide-angle camera lenses to capture a complete 360° spherical image of the pipe. The video recording images can be unfolded and assessed in real time or at a later date. The system permits computer-aided measurement of the positions and sizes of objects or pipe defects.

For both camera-based technologies, the condition assessment of the sewer segments was based on the NASSCO PACP methodology. The PACP provides a standard method for coding each defect, based on a visual assessment of the type and extent of the observed defect within a pipe segment. The PACP methodology stipulates a mapping between defect codes to a numeric pipe condition grade. The general assignment of pipe condition grades are:

- Grade 5 – Pipe segment has failed or will likely fail within the next five years. Pipe segment requires immediate attention.
- Grade 4 – Pipe segment has severe defects with the risk of failure within the next five to ten years. Pipe condition is generally poor and will likely become Grade 5 in near future.
- Grade 3 – Pipe segment has moderate defects and the condition is fair to moderate. Deterioration may continue, but not for ten to twenty years.
- Grade 2 – Pipe segment has minor defect, but generally good and has not begun to deteriorate. Pipe is unlikely to fail for at least 20 years.
- Grade 1 – Pipe segment may have minor defects, but otherwise in excellent condition. Failure is unlikely in the foreseeable future.

Using the set of pipe condition grades determined by a pipe segment's defect codes, the pipe segment's condition rating can be evaluated. The condition rating is a single numeric value representing the relative condition assessment for the pipe segment. The NASSCO PACP provides several methods for evaluating the condition rating for a pipe segment. One approach for aggregating the pipe condition grades (as specified by the PACP) is given by a weighted sum of the number of pipe condition grades occurrences where the weighting factor is the Grade number, i.e., $Rating = \sum_{i=1}^{5} i \times N_i$

where N_i is the number of occurrences of the i^{th} Grade. An alternative approach specified by the PACP for aggregation is a weighted average:

$$Index = \frac{Rating}{\sum_{i=1}^{5} N_i}.$$

To illustrate, given a pipe segment's PACP evaluation results in the following condition grading: eleven Grade 1 defects, one Grade 2 defect, three Grade 3 defects and one Grade 5 defect, then

$$\text{Rating} = (1 \text{ x } 11) + (2 \text{ x } 1) + (3 \text{ x } 3) + (5 \text{ x } 1) = 27$$

$$\text{Index} = \frac{27}{(11 + 1 + 3 + 1)} = 1.69$$

The PACP condition Rating and condition Index will be presented along with the blockage assessment score from the SL-RAT as outlined in Section 1.6.

2.4 Rapid Deployment Evaluation Procedure

Besides providing a pipe condition and blockage assessment, the key advantage of implementing technologies such as SL-RAT is the rapid deployment feature using portable equipment that can result in significant cost savings to utilities. As mentioned previously, the Greenhills area within MSDGC was selected to evaluate the time it takes to conduct an acoustic assessment campaign using SL-RAT. As the goal of this study area was to evaluate the time required to perform the acoustic inspections, advanced planning and preparation was conducted to help mitigate issues associated with traffic control and location of manholes. All manholes were pre-marked, and motorized All Terrain Vehicles (ATVs) were used to conduct this campaign. This sub-study involved SL-RAT measurements at 53 pipe-segments covering approximately 9,500 linear feet of pipe in the Greenhills study area with pipe sizes of 8" and 10" diameters. It should be noted that the NASSCO-PACP CCTV assessments were performed only for four of the 53 pipe-segments in the Greenhills study area.

Section 3—Technology Demonstration Results

The inspection test procedure shown previously in Figure 2-2 and the CCTV test procedure depicted in Figure 2-3 were not accomplished for every pipe segment during the course of the project. This was due to a variety of reasons including access limitations, wet-weather rain events that interrupted the schedule, unscheduled CCTV tractor repairs, and the unforeseen periodic need for the MSDGC crew to address issues requiring immediate attention. The change in procedure was not due to the SL-RAT operation or its failure to operate as specified by the vendor. Due to the impact on the test procedure, the data/results presented in the following sections are the field findings based on the time frame during which they were collected. As indicated in Section 2, video data were collected using both the pole/stick mounted camera and the CCTV camera. In assessing the two sets of video data collected, the data obtained from the pole/stick mounted camera provided limited to no additional benefit for achieving the goals outlined in the QAPP (i.e., demonstrating/evaluating the acoustic inspection technology condition assessment performance based on the SL-RAT), and therefore has not been included in this document.

To facilitate the SL-RAT evaluation in the following sections, the SL-RAT assessment was divided into three categories: Upper Range (7-10), Medium-Range (4-6), and Low Range (0-3). This categorization is consistent with the vendor's categories (see Table 1-1): Good (7-10), Fair (4-6), Poor (1-3) and Blocked (0). A similar classification is used by CMU (Fishburne, J. 2011): Maintenance Action Not Required (7-10), Maintenance Action Required (0-4).

3.1 Galia Drive Study Area CCTV/SL-RAT Assessment Summary

The Galia Drive evaluation area consists mainly of off-road sewers, through a wooded area serving several residential subdivisions. The terrain has very high slopes and access to the manholes is provided by an unpaved path cut through the area. The alignment of the sewer along the path is above a steep ravine that leads to an unnamed creek in the Muddy Creek watershed. The initial training on the SL-RAT operation and the inspections began in January 2013. All of the inspections listed in this section were performed between January 2013 and May 2013.

Of the fifty-four (54) sewer pipe-segments originally identified for inclusion in the Galia study area, only a total of thirty-four (34) individual pipe-segments were inspected through either PANORAMO or CCTV, or both. Many pipe-segments were inspected more than once due to several weeks of equipment breakdown and weather-related site access issues. No issues were encountered with the operation of the SL-RAT.

During the same period, a total of sixty-three (63) valid SL-RAT assessment tests were recorded in this study area. These sixty-three (63) SL-RAT assessments represent thirty-seven (37) sewer pipe-segments; again, many segments were assessed more than once due to interruptions and field crew re-deployment in the spring. Nine (9) of the sixty-three (63) SL-RAT assessments did not have any CCTV inspection data for comparison purposes. Therefore, fifty-four (54) SL-RAT assessments are supported by CCTV inspection data. Table 3-1 summarizes the SL-RAT test results and associated CCTV inspection findings for the Galia Drive study area.

Table 3-1. Summary of SL-RAT and CCTV Results Galia Drive.

SL-RAT Record No	Pipe Segment ID	SL-RAT Test Date /Time	Input Pipe Length (feet)	GPS Pipe Length (feet)	SL-RAT Assess-ment	Pipe Status	CCTV Date	CCTV Findings
619	11702001-11702002	1/28/2013 11:17	150	91	9	Good	xxxxxx	xxxxxxx
672	11702001-11702002	4/16/2013 11:16	150	166	9	Good	4/30/2013	Light grease
624	11702003-11702012	1/29/2013 14:24	150	142	8	Good	1/29/2013	No issues
699	11705009-11706007	4/18/2013 9:34	150	234	9	Good	3/18/2013	*No Issues*
700	11705009-11706007	4/18/2013 9:39	150	234	9	Good	5/2/2013	No issues
615	11705010-11705009	1/25/2013 15:29	150	67	9	Good	xxxxxx	xxxxxxx
701	11705010-11705009	4/18/2013 9:45	150	151	10	Good	5/2/2013	Fine roots
609	11705011-11705010	1/24/2013 14:02	350	214	10	Good	xxxxxx	xxxxxxx
702	11705011-11705010	4/18/2013 9:56	350	276	9	Good	5/2/2013	Fine roots
610	11705012-11705011	1/24/2013 14:13	250	231	9	Good	xxxxxx	xxxxxxx
703	11705012-11705011	4/18/2013 10:18	250	290	10	Good	5/2/2013	Slight debris
613	11705013-11705012	1/25/2013 11:52	250	204	9	Good	xxxxxx	xxxxxxx
704	11705013-11705012	4/18/2013 10:24	250	279	8	Good	5/3/2013	Roots Med
614	11705014-11705013	1/25/2013 11:59	150	230	9	Good	xxxxxx	xxxxxxx
705	11705014-11705013	4/18/2013 10:36	150	117	8	Good	5/3/2013	No issues
646	11705015-11705014	3/20/2013 10:26	250	107	9	Good	xxxxxx	xxxxxxx
706	11705015-11705014	4/18/2013 10:42	150	127	9	Good	5/3/2013	Roots fine
622	11706002-11707005	1/28/2013 12:34	250	262	8	Good	xxxxxx	xxxxxxx

SL-RAT Record No	Pipe Segment ID	SL-RAT Test Date /Time	Input Pipe Length (feet)	GPS Pipe Length (feet)	SL-RAT Assess-ment	Pipe Status	CCTV Date	CCTV Findings
674	11706002-11707005	4/16/2013 11:28	250	155	9	Good	4/30/2013	Roots Med
710	11706002-11707005	5/3/2013 17:05	250	368	9	Good	5/2/2013	Fine roots
626	11706003-11706002	1/31/2013 11:41	350	218	5	Fair	xxxxxx	xxxxxxx (see Text)
675	11706003-11706002	4/16/2013 11:33	350	275	8	Good	4/30/2013	Root Ball (see Text)
708	11706003-11706002	5/3/2013 16:58	350	350	9	Good	5/2/2013	Roots fine (see Text)
627	11706004-11706003	1/31/2013 11:53	350	375	7	Good	xxxxxx	xxxxxxx
676	11706004-11706003	4/16/2013 11:39	350	356	8	Good	xxxxxx	xxxxxxx
677	11706004-11706003	4/16/2013 11:43	250	233	9	Good	4/30/2013	Roots fine
628	11706005-11706004	1/31/2013 12:02	150	188	10	Good	3/5/2013	Roots Med
629	11706006-11706005	1/31/2013 12:11	150	239	7	Good	3/5/2013	Slight structural
678	11706006-11706005	4/16/2013 11:48	150	105	8	Good	4/30/2013	Slight structural
620	11707005-11702001	1/28/2013 11:43	250	236	0	Block	xxxxxx	xxxxxxx (see Text)
621	11707005-11702001	1/28/2013 11:46	250	236	0	Block	2/1/2013	Roots Lt / Med (see Text)
673	11707005-11702001	4/16/2013 11:22	250	191	7	Good	4/30/2013	Root Ball (see Text)
630	11711001-11706006	1/31/2013 12:23	150	210	8	Good	2/28/2013	Roots Med
679	11711001-11706006	4/16/2013 11:54	250	220	9	Good	3/4/2013	Roots Med
680	11711001-11706006	4/16/2013 12:03	250	306	9	Good	4/30/2013	*No Issues*
631	11712001-11711001	1/31/2013 12:30	150	257	9	Good	4/30/13	Light O&M
632	11712002-11712001	1/31/2013 12:50	250	172	9	Good	2/28/13	Surface damage
681	11712002-11712001	4/16/2013 12:09	150	202	9	Good	4/30/13	Roots fine
633	11712003-11712002	1/31/2013 12:57	250	191	9	Good	2/1/13	No issues

SL-RAT Record No	Pipe Segment ID	SL-RAT Test Date /Time	Input Pipe Length (feet)	GPS Pipe Length (feet)	SL-RAT Assess-ment	Pipe Status	CCTV Date	CCTV Findings
682	11712003-11712002	4/16/2013 12:15	250	188	9	Good	4/30/13	Roots fine
683	11712004-11712003	4/16/2013 12:21	250	205	10	Good	5/1/13	Light deposits
637	11712005-11712004	3/7/2013 11:51	250	93	9	Good	2/28/13	Light deposits
684	11712005-11712004	4/16/2013 12:27	150	112	9	Good	5/1/13	Light deposits
685	11712006-11712005	4/16/2013 12:32	150	122	9	Good	2/28/13	No issues
692	11712006-11712005	4/17/2013 12:57	50	110	8	Good	5/1/13	No issues
639	11713003-11713002	3/7/2013 13:00	350	257	7	Good	3/1/13	Sideline splash at Rx
687	11713003-11713002	4/16/2013 12:49	350	413	5	Fair	5/1/13	Gusher / Light deposits
688	11713004-11713003	4/16/2013 12:58	250	103	10	Good	3/1/13	Light deposits
689	11713004-11713003	4/16/2013 13:07	250	90	9	Good	5/1/13	Sideline splash at Tx – no effect
691	11713006-11712006	4/17/2013 12:53	50	132	8	Good	5/3/13	No issues
640	11713018-11713003	3/7/2013 13:13	250	68	9	Good	5/3/13	No issues
695	11713018-11713003	4/17/2013 14:42	50	246	7	Good	xxxxxx	xxxxxxx
641	15016001-11713004	3/7/2013 13:37	250	143	5	Fair	3/1/13	Sideline (not splashing) may affect Rx
642	15016002-15016001	3/7/2013 13:45	250	117	9	Good	3/15/13	No issues
618	11702002-11702003	1/28/2013 10:52	250	322	8	Good	Not done	NA
644	11706007-11705010	3/20/2013 9:59	350	209	10	Good	Not done	NA
645	11706007-11705010	3/20/2013 10:06	350	209	8	Good	Not done	NA
635	11712004-11712012	3/7/2013 11:12	150	165	10	Good	Not done	NA

SL-RAT Record No	Pipe Segment ID	SL-RAT Test Date /Time	Input Pipe Length (feet)	GPS Pipe Length (feet)	SL-RAT Assess-ment	Pipe Status	CCTV Date	CCTV Findings
636	11712005-11712012	3/7/2013 11:43	150	273	9	Good	Not done	NA
693	11712006-11713005	4/17/2013 14:09	350	352	8	Good	Not done	NA
694	11713003-11713014	4/17/2013 14:38	150	347	9	Good	Not done	NA
696	11713004-15016002	4/17/2013 14:55	250	381	10	Good	Not done	NA
697	11713006-11713001	4/17/2013 15:25	250	74	10	Good	Not done	NA

Of the fifty-four (54) SL-RAT assessments supported by CCTV, forty-nine (49) assessments were in the upper range (7 to 10), three (3) in the medium range (4 to 6), and two (2) in the low range (0 to 3). No major structural defects were found during the CCTV inspections (no PACP Structural Grades of 4 or 5 defects). However, numerous minor PACP O&M defects were identified.

3.1.1 Upper-Range Score Discussion

Of the forty-nine (49) upper range scores, forty-two(42) assessments were found to correlate with the CCTV inspection results. For the remaining seven (7) of the forty-nine (49) upper range SL-RAT assessments, the CCTV inspection identified roots in the pipe perhaps warranting a lower assessment score. These seven (7) readings represent only four (4) individual pipe-segments. The root intrusion on three (3) of the four aforementioned pipe-segments was estimated to be less than 50%. In all cases the CCTV robot transporter was able to pass through or around the roots, indicating the root density was limited. The remaining pipe-segment (11706003-11706002), which registered an 8 reading, had previously registered a five (5) reading due to roots. Subsequently, this segment was root cut and a follow up CCTV inspection showed an 80% root ball (new) about three feet from the manhole.

3.1.2 Medium-Range Score Discussion

Of the three (3) medium range scores, the segment discussed above registered a score of five (5) due to roots. In addition, two other sections also registered a five (5), but no significant issues were identified with these pipe segments. At one location, based on the inspection video, a sideline pipe was seen splashing into the manhole where the RX unit was deployed. This location had previously registered a reading of seven (7). At the other location, a sideline was also observed coming out of the manhole. These sidelines may have interfered with the results.

3.1.3 Low-Range Score Discussion

The two (2) low range assessments were on the same pipe-segment (11707005-11702001) and were conducted within minutes of each other. In both cases, the SL-RAT assessment was a zero (0) indicating that essentially no acoustic energy was being received at the RX from the TX transmission. The pipe segment was root cut prior to CCTV inspection. A subsequent CCTV inspection conducted a few days after the root cut operation indicated only light and medium roots in the pipe. A follow up SL-RAT assessment conducted two and half months later registered a seven (7). A CCTV inspection was conducted two weeks later that identified a root-ball in the pipe. During this CCTV inspection, the robot transporter was able to pass through or around the roots, indicating that the root density was limited.

3.2 Hunt Road Area CCTV/SL-RAT Assessment Summary

The Hunt Road Evaluation area consists mainly of off-road sewers, through a wooded area serving several residential subdivisions. The terrain on the periphery has very steep slopes and access to the manholes is provided by an unpaved path cut through the area from the downstream location. The alignment of the sewer is along the path which is adjacent to an unnamed creek in the East Branch of the Mill Creek watershed.

In this study area, the SL-RAT operation and inspections were performed between May 2013 and June 2013. Originally, 40 sewer segments were defined for inclusion in the evaluation area. Only twenty-six (26) sections were inspected using CCTV. Based on the CCTV inspections, no sewer segments were found in need of cleaning and two (2) segments were found with structural issues, neither of which resulted in obstruction of the pipe. Only nineteen (19) of the sewer segments were assessed with the SL-RAT and these assessments are used for the evaluation. The seven (7) pipe-segments that were inspected by CCTV, but not inspected using the SL-RAT are not reported in this dataset.

Table 3-2 presents the SL-RAT test results and the correlating CCTV inspection findings of the nineteen (19) segments at the Hunt Road site.

Table 3-2. Summary of SL-RAT and CCTV Results Hunt Road.

SL-RAT Record No.	Pipe Segment ID	SL-RAT Test Date/Time	Input Pipe Length (feet)	GPS Pipe Length (feet)	SL-RAT Assessment	Pipe Status	CCTV Date	CCTV Findings
771	44705004-44706017	5/13/2013 11:43	150	126	7	Good	5/28/13	No Log - Minor O&M
772	44705004-44706017	5/13/2013 13:02	150	194	8	Good	xxxxxx	xxxxxx
773	44705005-44705004	5/13/2013 13:06	50	29	9	Good	5/28/13	Minor deposits throughout
830	44706004-44707026	6/3/2013 15:02	150	253	8	Good	6/12/13	Deposits - Water Level 25%
834	44706009-44706010	6/3/2013 16:29	150	27	8	Good	6/12/13	No issues
831	44706010-44706004	6/3/2013 15:14	150	183	8	Good	6/12/13	Minor deposits throughout
832	44706011-44706010	6/3/2013 15:21	50	36	8	Close	6/13/13	No issues
833	44706012-44706011	6/3/2013 15:43	250	351	9	Good	6/12/13	No issues
835	44706013-44706010	6/3/2013 16:39	350	232	9	Good	6/12/13	No issues
836	44706014-44706013	6/3/2013 17:02	350	314	10	Good	5/28/13	Minor structural issues
837	44706015-44706014	6/3/2013 17:25	150	60	8	Good	5/28/13	Minor grease
770	44706017-44706015	5/13/2013 11:36	250	133	7	Good	5/28/13	Deposits - Water Level 45%
774	44712001-44705005	5/13/2013 13:13	350	201	9	Good	5/28/13	No Log - Minor O&M
822	44712002-44712001	6/3/2013 11:26	350	819	9	Good	5/28/13	Minor grease & deposits
823	44712007-44712002	6/3/2013 11:37	150	219	9	Good	5/28/13	Minor structural issues
824	44712008-44712007	6/3/2013 11:47	150	151	9	Good	5/28/13	Minor deposits
825	48209013-44712008	6/3/2013 11:55	350	24	8	Good	5/28/13	Minor deposits
826	48209014-48209013	6/3/2013 12:07	350	593	10	Good	6/10/13	No log- minor O&M
827	48209015-48209014	6/3/2013 12:17	250	164	10	Good	6/10/13	No issues
828	48209016-48209015	6/3/2013 12:25	250	206	9	Good	6/10/13	No issues-Water Level 50% at DS manhole

Several sewer segments were documented to have high PACP O&M ratings; however, those scores were due to continuous minor grease or encrustations/deposits in the pipe.

All SL-RAT assessments in the upper range (7 to10) were consistent with the CCTV inspection findings. Two segments were assessed at the low end of the upper range, i.e., an assessment of seven (7). One of the two segments that registered a SL-RAT score of seven (7) had a follow up assessment (less than two hours later) and returned a score of eight (8). The other segment with an SL-RAT assessment of seven (7) had grease deposits throughout the length of pipe, as did some of the other segments that returned higher scores. Based on the CCTV inspection for this pipe-segment, a water level at 45% was reported due to a sag in the 12-inch diameter pipe. As indicated by the vendor, Table 1-1, sags can result in lower assessment scores.

3.3 Greenhills Area - Rapid Deployment Evaluation Summary

As mentioned previously in Section 2.4, the Greenhills study area involved SL-RAT measurements at 53 pipe-segments representing approximately 9,500 linear feet of pipe with pipe sizes of 8” and 10” diameters. A goal of this study area was to evaluate the time required to perform the acoustic inspections with the SL-RAT. The SL-RAT inspections were performed on May 8, 2013 (between 9:59 AM and 1:29 PM) and May 10, 2013 (between 9:12 AM and 10:37 AM) which computes to a total assessment time of 6 hours, or effectively one day (including time for travel to field and equipment setup). For 51 of the 53 measurements, the time to conduct the SL-RAT inspections was either 79 or 80 seconds. The other two inspections required 111 seconds to complete. These two inspections resulted in low range assessment scores. Longer inspection times are typically required for obstructed pipe segments. The time interval between inspections was also evaluated by using the time/date stamp recorded by the SL-RAT at the start of each inspection. The time interval evaluation includes

- Travel time between segment locations within the study area
- Inspection setup time, i.e., removing the manhole cover and inserting the SL-RAT unit
- Measurement time.

The time intervals between inspections are summarized in Table 3-3, with an average time interval of 5 minutes and 33 seconds. Since the inspections were conducted over a two day interval, there are a total of 51 time intervals to conduct the 53 inspections.

Table 3-3. Summary of Time Interval between Inspections for Greenhills.

Time Interval (min.)	<3	3 to 6	6 to 9	9 to 12	>12
Occurrences	0	37	7	4	3
% of Total	0	73	14	8	6

The assessment scores for the SL-RAT inspection are summarized in Table 3-4. Based on the inspection results, there are forty-seven (47) segments in the high range (7-10), 4 in the medium range (4-6) and 3 in the low range (0-3), corresponding to 88.7%, 7.5% and 3.8% of the total number of segments, respectively. Based on the CMU SL-RAT action plan (Fishburne, J. 2011) this implies that 88.7% of the pipes are considered clear with no additional maintenance action taken. The assessments between 0 to 4 or 5.7% of the pipes would be cleaned and the assessments with 5 or 6, another 5.7%, would either be conservatively cleaned, CCTV inspected or placed on a watch list depending on the availability of maintenance resources. The three pipe segments with scores less than 5 represent approximately 650 feet of linear pipe, i.e., 6.9% of the total pipe length. The six pipe segments with scores less than 7 represent approximately 1,400 feet of linear pipe, i.e., 14.7% of the total pipe length. Four pipe segments were assessed using CCTV. Table 3-5 presents a summary of these results.

Table 3-4. Summary of SL-RAT Assessment Scores for Greenhills.

SL-RAT Assessment	10	9	8	7	6	5	4	3	2	1	0
Number of Occurrences	0	16	22	9	2	1	1	1			1

Table 3-5. Summary of SL-RAT and CCTV Results Greenhills.

SL-RAT Record No.	Pipe Segment ID	SL-RAT Test Date /Time	Input Pipe Length (feet)	GPS Pipe Length (feet)	SL-RAT Assessment	Pipe Status	CCTV Date	CCTV Findings
713	31602004-31601005	5/8/2013 10:05	250	110	9	Good	5/10/13	90% root at one of the seven taps
734	31602007-31602008	5/8/2013 12:09	150	103	6	Fair	6/17/13	Offset joint, heavy roots at one tap, grease and deposits needs cleaning
717	31601005-31601001	5/8/2013 10:42	250	199	9	Good	5/10/13	Encrustation, intruding seal material, roots on tap
743	31602008-31602009	5/8/2013 12:51	350	304	9	Good	6/17/13	Deposits, roots medium at joint

3.4 Miscellaneous Pipe Evaluation Summary

Except for the one pipe segment in the Galia Drive study area, there were no other pipes found during the study that were significantly blocked. In order to assess improvements in SL-RAT reported scores in areas where blocked pipes were expected or reported, thirty (30) pipe-segments were randomly evaluated during the month of August 2013. Based on the SL-RAT inspection, one pipe segment (ID - 54815003-54815004) was found that scored a zero on August 1, 2013. The pipe was subsequently cleaned and re-evaluated on August 30, 2013.The SL-RAT re-evaluation indicated the pipe segment was clean based on an assessment score of 9. The remaining 29 pipe-segments were found to be not completely blocked, i.e., had SL-RAT assessments greater than zero.

3.5 PACP and SL-RAT Score Correlation

As noted previously in Section 1.3, the de-facto industry standard for observation and defect coding for sewer pipe CCTV inspection is the NASSCO PACP methodology. During the evaluation phase of the SL-RAT results, an attempt was made to correlate the SL-RAT output values to the defect coding recorded during the CCTV inspection and subsequent PACP condition grading. It was believed that the output results on both the low and high-ends of the range for the SL-RAT could potentially correlate to the PACP ratings. However, it was unknown if the intermediate SL-RAT results would correlate with the PACP defect scores.

To perform a correlation, the PACP Segment Grade and Overall Pipe Rating (Rating), the Quick Rating, and the Pipe Ratings Index (Index) calculations of pipe condition were collectively evaluated in an attempt to construct a method of comparison to the SL-RAT's numerical scaled-output value. Both the Rating and Index provide a single numerical assessment for a pipe segment as discussed in detail in Section 2.3. Examples of the PACP O&M scores obtained from the data gathered during this field study are presented in Table 3-6.

Table 3-6. Example of PACP Assessment O&M Score - Galia Drive Data.

	PACP O&M Score from CCTV Reports								
Segment	**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**	**Rating**	**Quick**	**Index**	**SL-RAT**
11702001-11702002	0	30	0	0	0	30	2B00	2.0	9
11707005-11702001	11	2	9	0	5	27	5133	1.6875	0

The first pipe-segment number 11702001-11702002 has a higher rating (O&M Rating - 30 and Index - 2.0) compared to the second pipe segment number 11707005-11702001 (O&M Rating – 27 and Index

1.68) due to a high number on Grade 2 defects. In comparison, the SL-RAT scores are at the opposite ends of its computed scale. This result is not surprising to an operator who understands the PACP score nuances because the second pipe-segment has one Grade 5 defect due to a root ball that would block the transmission of the SL-RAT acoustic signal as well as obstruct the flow. Whereas the minor grease encrustation along the first pipe segment resulted in PACP Grade 2 defect score of 30, this would have minimal impact on acoustic transmission as well as the flow.

Another example of numerically incompatible results is the case of a PACP code matrix for a deposit of grease greater than 30% in a pipe, which would be given an O&M grade of 5. Following the PACP scoring methodology, a completely obstructed pipe due to a grease blockage would also be given a PACP score of 5. In the first instance, the SL-RAT is likely to return a score in the mid- range of the output scale (between 4 and 6); however, the second instance would likely return a low SL-RAT output of (between 0 and1), meaning almost no sound would be received at the SL-RAT's RX unit.

In summary, to perform a correlation between PACP and SL-RAT scores, each discrete defect recorded on the PACP inspection log must be individually compared to see how it would impact the SL-RAT results. Therefore, a simple algorithmic approach for comparing PACP and SL-RAT score was not possible.

3.6 SL-RAT Data Visualization and Post-Processing Tools

In addition to the on-screen SL-RAT reported scores in the field, InfoSense also provides additional data visualization and post processing tools. The visualization tool provided by InfoSense is a Google Earth based data viewing option where the SL-RAT measurements can be visualized. Figure 3-1 presents a summary visual of the Galia Drive results using Google Earth and the Keyhole Markup Language (KML) file generated by InfoSense. To utilize this tool, the SL-RAT data needs to be uploaded using their proprietary Sewer Line Diagnostic OrGanizer (SL-DOG) software-as-a-service (SaaS) application to a secure online environment from a properly configured web-enabled computer.

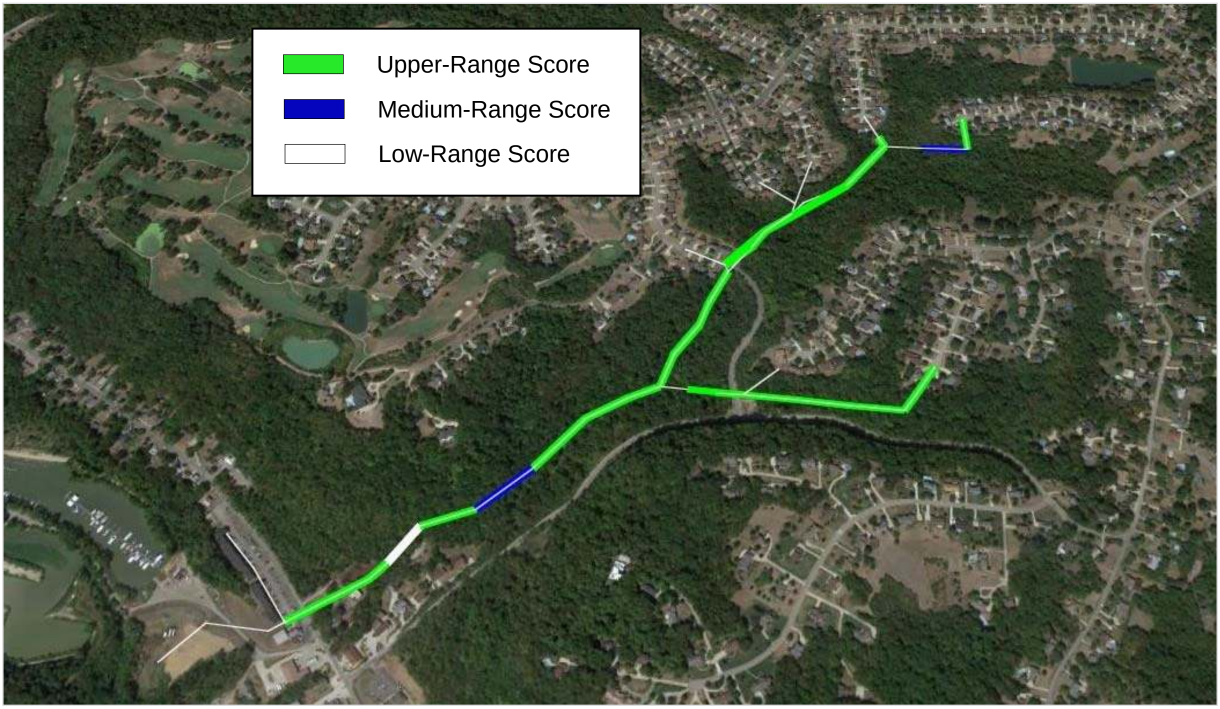

Figure 3-1. Summary visual of SL-RAT Results Galia Drive.

In addition to the visualization, post-processing and verification can also be performed. Varying stages of verification are available based on customer requirements. The verification process has two objectives:

1. Verify the pipe segment length used in evaluating the SL-RAT condition assessment. The SL-DOG uses the reassessed pipe length to reevaluate the condition assessment.
2. Verify the utility's pipe segment ID associated with the SL-RAT condition assessment.

The length of pipe impacts the amount of acoustic energy that is expected to pass through a pipe-segment. The larger the pipe length, less of the transmitted energy from the TX unit is expected to travel through and be received by the RX unit in the field. At the time of assessment, the SL-RAT algorithm requires an estimate of the segment length to conduct the assessment. During the in-field measurement, the operator enters the pipe length ($\pm$ 50 feet) used in the initial on-site evaluation. The SL-DOG post-processing allows the reevaluation of the assessment based on an updated pipe length. As an example, if an operator inadvertently enters 50' for a 250' pipe segment, the recalculated acoustic assessment score may be higher than the field reported value on the SL-RAT device because less sound energy is expected to pass through a longer pipe. The SL-DOG can adjust the field-reported assessment score based on the corrected length. A more detailed discussion of this option from InfoSense is presented in Appendix A.

It should be also noted that the GPS-based positioning is prone to errors especially in off-road areas where significant vegetation (i.e., canopy) and topographic features (e.g., steep slopes) are present (Rumble and Lindzey, 1997). Therefore, the pipe lengths must not be corrected simply based on the GPS data collected during the assessment. The GPS mapping errors of one pipe-segment assessed in Galia road is also depicted in Appendix A (Figure 2).

3.7 SL-RAT Operator Feedback

As a part of this evaluation, MSDGC field personnel were asked to provide input on the SL-RAT performance from an operator perspective. The following is a categorized summary of their observations:

3.7.1 Usability

SL-RAT is a wireless device that is easy to operate, is very rugged, batteries last awhile, and only two pieces of equipment have to be carried. Every manhole needs to be accessed in order to perform a test. The device is loud when standing at the manhole with the TX unit that contains the speaker. When using acoustic devices, understanding the exposure to excessive noise levels is important for the operator's safety. The vendor, InfoSense, has evaluated the sound level experienced by the SL-RAT TX operator under normal operation. Multiple sound pressure level (SPL) measurements were made within a two foot radius and at a height of four feet above a manhole while the TX unit was operating. The averaged results for each of the 16 tones used to conduct an SL-RAT inspection are depicted in the graph in Figure 3-2. Based on Occupational Safety & Health Administration (OSHA) requirement (OSHA, 1910) for noise exposure, the permissible exposure for 85dBA is 16 hours per day and for 88 dBA is 10.6 hours per day. Using the data from the graph in Figure 3-2, the operator is exposed to an SPL between 85 to 88dBA for 3 seconds during each tone sequence. There are typically 5 tone sequences per pipe segment inspection. As a conservative estimate, assuming 12 inspections per hour over an eight hour work day, the total exposure time for SPL levels between 85 to 88 dBA is 24 minutes, significantly less than the 10.6 hours permissible by OSHA at the 88dBA level. For comparison, a vacuum truck's average acoustic noise emission level at 50 feet is 85dBA with a usage factor of 40% (USDOT, 2006).

3.7.2 Data Quality

The results are very easy to interpret. The operator should be aware that the results sometimes will depend upon the environment. For example, in the case of data received when testing sewers/manholes that have other inlets tied into the manhole, the result may come back as bad. The operator must be aware of these types of site-specific nuances while interpreting results.

3.7.3 Software

Downloading the information is quick. The operators did have issues with using the software, but were always able to resolve these issues without having to contact the vendor. As indicated in Section 1.6, the initial onsite training by the vendor was hampered primarily by weather. This limited the onsite SL-DOG software training and did not allow the vendor to provide hands-on training of the correct steps for downloading the measurement data from the device. Even though the software is straight-forward to use, there are key steps required for its correct operation, such as ensuring measurement data stored on the SL-RAT TX unit is transferred to the RX unit via the unit's RF interface.

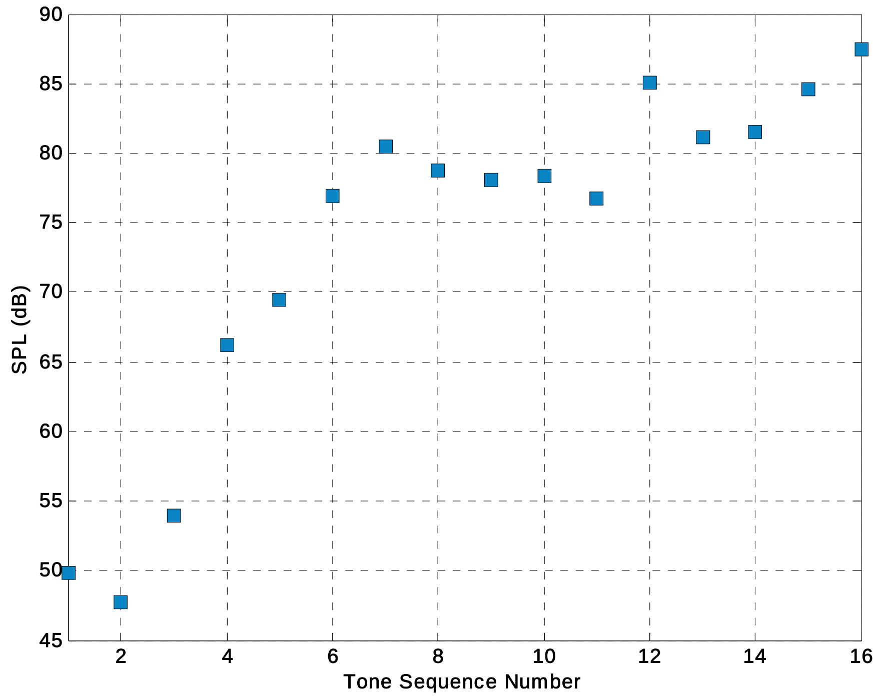

Figure 3-2. Typical Sound Pressure Level (SPL) Experienced by the SL-RAT Transmitter Operator for Each One Second Tone.

Section 4—Summary and Conclusions

For the purposes of this report, three ranges of SL-RAT output scores have been used to determine if the pipe is open (high), there is a blockage (low), or if additional investigation is needed (medium). The actual output numbers that make up these ranges can be flexible based on the user's experience and the policies established by individual organizations. As reported previously in Section 3.0, for the purposes of this report, the SL-RAT score ranges are mapped as follows: 0-3 (low), 4-6 (medium), and 7-10 (high). A zero reading is reliable in identifying a blocked pipe and a 10 indicates the pipe is open and no further cleaning or investigation is needed. The two detailed study areas (Galia Drive and Hunt Road) did not have a substantial number of pipe segments with a range of defects that could be used to statistically define these ranges. However, the data indicates that the extreme scores are reliably assessed in the vast majority of the cases. In general, outputs of 7 to 10 reliably indicated that the pipe was open and free of significant obstructions.

Overall, the use of SL-RAT as a pipe-condition assessment tool needs to be evaluated in context with the existing tools available to wastewater utilities. Figure 4-1 presents a graphic summary of where the SL-RAT as a sewer pipe inspection tool is likely to fit into a wastewater utility's "tool-box."

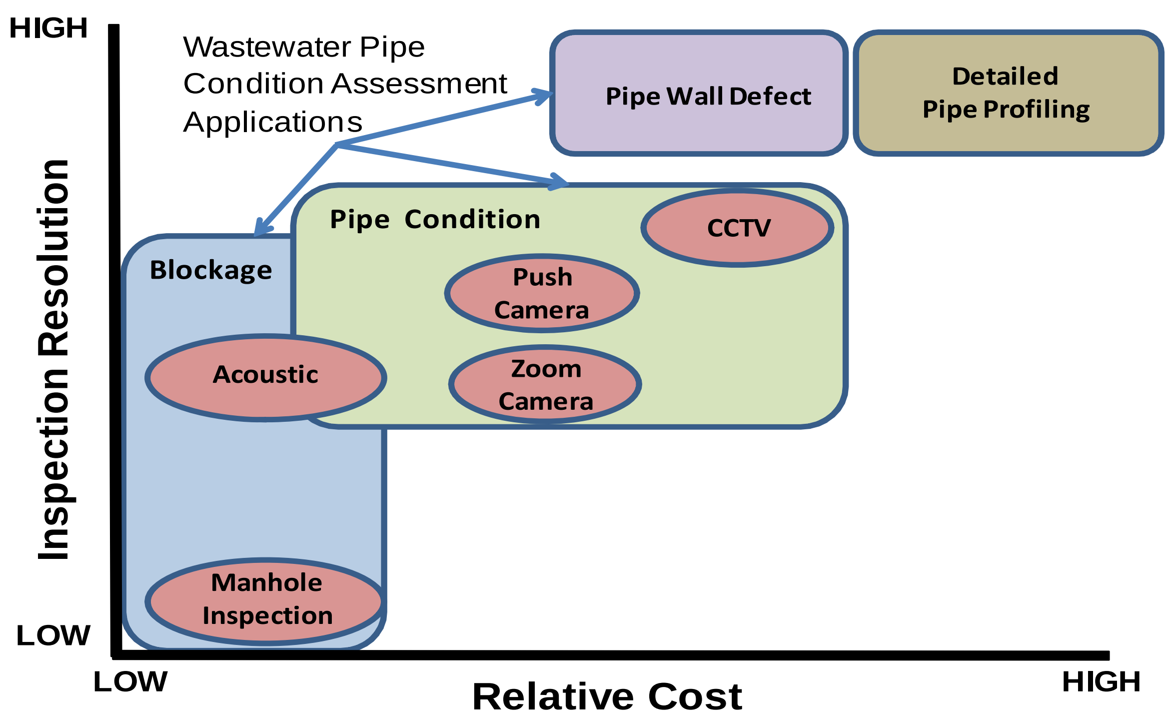

Figure 4-1. Sewer Pipe-Condition Assessment Tools (Adapted from: InfoSense, 2013)**.**

4.1 Inspection Cost per Foot Analysis

The costs for CCTV inspection and cleaning of small diameter pipelines can vary widely from pipe to pipe and from utility to utility. There are many variables that affect the cost of pipe inspection for any given utility. For MSDGC, cost variables for CCTV inspection of small diameter pipes include factors such as personnel costs, travel costs, setup, planning and data management costs. Certain locations, that are not in the public right-of-way, in easements or difficult to access due to off-road locations, often require special arrangements or specially equipped off-road vehicles. Tables 4-1 and 4-2 summarize the average cost of on-road and off-road CCTV inspections, respectively, for MSDGC.

Table 4-1. MSDGC On-Road CCTV Inspection Costs.

S. No.	Labor/Equipment	Unit Cost/Hour	Quantity	Annual Cost	Assumptions
1	Crew	$38.46	2,000	$76,923	Assume 2 persons and annual burdened salary of $80,000 per person, dedicated ~1/2 time (1,000 hours/year each)
2	CCTV Truck	$25.00	1,000	$25,000	Assuming 1,000 hours of average operation per year
3	Polaris ATV	$80.00	200	$16,000	Assuming 200 hours of operation per year needed for special access at select locations
4	Setup, Planning and Data Management	$100.00	1,000	$100,000	Includes Multiple Personnel, Work Order management, GIS software and Data Management Costs, QA/QC of CCTV data
			Total	$217,923	$ per year (computed from above)
			Average Daily CCTV Production	1000	feet/day (MSDGC estimate)
			Average Annual CCTV Production	130,000	feet/per year (1/2 time 130 workdays - 26 weeks, 5 days/week)
			CCTV Inspection Cost	$1.68	$/foot of on-road pipe inspected

Table 4-2. MSDGC Off-Road CCTV Inspection Costs.

S. No.	Labor/Equipment	Unit Cost/Hour	Quantity	Annual Cost	Assumptions
1	Crew	$38.46	2,000	$76,923	Assume 2 persons and annual burdened salary of $80,000 per person, dedicated ~1/2 time (1,000 hours/year each)
2	CCTV Off-Road Tractor	$71.50	1,000	$71,500	Assuming 1,000 hours of average operation per year
3	Polaris ATV	$80.00	200	$16,000	Assuming 200 hours of operation per year needed for special access at select locations
4	Setup, Planning and Data Management	$100.00	1,000	$100,000	Includes Multiple Personnel, Work Order management, GIS software and Data Management Costs, QA/QC of CCTV data
				Total	$264,423	$ per year (computed from above)
			Average Daily CCTV Production		1000	feet/day (MSDGC estimate)
			Average Annual CCTV Production		130,000	feet/per year (1/2 time 130 workdays - 26 weeks, 5 days/week)
			CCTV Inspection Cost		$2.03	$/foot of off-road pipe inspected

The Water Environment Research Foundation (WERF) and EPA (WERF, 1997, EPA, 1999), have reported an average nationwide CCTV inspection cost of $4,600 per mile or $0.87 per foot. In the above referenced EPA report, ADS Environmental Services (ADS, 1998) reports CCTV inspection cost range of $1,000 to $11,450 per mile, which at the high end computes to $2.17 per linear foot. The most recent WERF report (WERF, 2013) reviewed the trends and cost drivers of CCTV inspection as a function of pipeline diameter, project length, and regional location. WERF reported that the majority of the CCTV projects for inspecting pipelines fell under $3.00 per foot regardless of pipe size. Furthermore, the WERF report indicated that the majority of the projects reported a unit cost of less than $2.00 per foot, once the overall inspected pipe length surpassed 5,000 feet. The report concluded that 5,000 linear feet of pipe is the threshold for attaining savings from economies of scale. Comparatively, Table 4-3 summarizes the expected cost of both on-road and off-road SL-RAT inspections for MSDGC.

Table 4-3. SL-RAT On/Off-Road Inspection Costs.

S. No.	Labor/Equipment	Unit Cost/Hour	Quantity	Annual Cost	Assumptions
1	Crew	$38.46	2,000	$76,923	Assume 2 persons and annual burdened salary of $80,000 per person, dedicated ~1/2 time (1,000 hours/year each)
2	SL-RAT Purchase Price	$20.00	1,000	$20,000	$20,000 purchase price cost of SL-RAT spread over 1000 hours of use. Not amortized for 3-years expected life
3	Regular Truck	$6.00	1,000	$6,000	A regular truck will be needed to carry personnel to site
3	Polaris ATV	$80.00	200	$16,000	Assuming 200 hours of operation per year needed for special access at select locations
4	Setup, Planning and Data Management	$100.00	500	$50,000	Assumes these costs will be halved compared to CCTV inspection. Includes Multiple Personnel, Work Order management, GIS software and Data Management Costs, QA/QC of SL-RAT data
			Total	$168,923	$ per year (computed from above)
		Average Daily SL-RAT Production		9,500	feet/day (based on Greenhills data)
		Average Annual SL-RAT Production		1,235,000	feet/per year (1/2 time 130 workdays - 26 weeks, 5 days/week)
		SL-RAT Inspection Cost		$0.14	$/foot of on-road and off-road pipe inspected

Although the inspection output or detail provided by SL-RAT is not equivalent to a CCTV report, the order of magnitude cost-per-foot savings makes a good case for using the SL-RAT as a tool to perform screening type assessments (prior to the deployment of the more expensive condition assessment equipment or cleaning).

4.2 Rapid Deployment Capability

The majority of the pipes selected for CCTV inspection, acoustic inspection and cleaning for this demonstration project were off-road difficult to access, inspect, and assess. The objective of the project was to demonstrate the performance of the acoustic inspection technologies rather than evaluate the cost of performance. It can be reported that one of the key advantages of SL-RAT is the rapid deployment feature using portable equipment that can result in significant cost-savings to the utilities in comparison with traditional inspection methods such as CCTV inspection, especially when “screening-type” assessments, such as those to determine cleaning needs, are the goal of the inspections.

The majority of the SL-RAT test durations for this project were 79 or 80 seconds. Two test durations were greater than 80 seconds; in both cases, the pipe was substantially blocked with roots. When compared to CCTV inspection rates of 30 feet/minute, the rapid assessment capabilities of the acoustic-based SL-RAT system is apparent. While this tool does not eliminate the need for using CCTVs in assessing pipes, it can limit the deployment of the more expensive CCTV resources to focus on critical pipe-segments.

4.3 Opportunity to Refocus Critical Resources Deployed for Pipe Cleaning

As reported previously in Section 1.1, cleaning and inspecting sewer pipes is essential for utilities to operate and maintain a properly functioning collection system and avoid SSOs. For many utilities, sewer cleaning and inspection programs are generally part of a larger CMOM program. The routine maintenance of a sewer system often includes sewer system cleaning, root removal/treatment, and cleaning/clearing of sewer mainline stoppages. However, understanding where and when to perform cleaning activities is not necessarily a straight-forward task. The three common approaches adopted by utilities are as follows:

4.3.1 Routine Cleaning

Some wastewater utilities clean their sewer system as a matter of course without knowing in advance whether the system or portions of the system require cleaning. Pipes with blockages receive the same attention and resources as those with potentially no cleaning needs. In this approach, the use of staff and equipment is not optimized consuming staff time and resources that could be directed to other more productive maintenance activities.

4.3.2 Directed Cleaning

In an attempt to direct maintenance staff and cleaning equipment to just those pipes in a sewer system that require attention, some agencies attempt to identify cleaning needs by conducting inspection of the sewers prior to cleaning. These pre-cleaning inspections are conducted using various approaches and equipment to varying degrees of success, efficiency and speed.

4.3.3 Reactive Cleaning

For many wastewater utilities, staff-time is directed solely towards reactive cleaning where staff and equipment are deployed to address blockages, spills or other emergencies.

4.4 Conclusion

The emergence of acoustic sewer inspection technologies, like SL-RAT, as rapid deployment, low-cost, reliable, pre-cleaning assessment tools is focusing growing attention on the potential for more cost-effective sewer cleaning programs. Through the ease of deployment, reduction of cost, increases in reliability of these inspection approaches, combined with the potential for reducing the "cleaning of clean pipes," significant cost savings are attainable. As utilities apply these new inspection technologies, they can move towards implementing sewer cleaning programs that consist of planned directed and quick response, reactive cleaning. Also, these cost savings can be realized while improving collection system performance and the protection of public health and water quality.

The results of this demonstration project reveal the potential for more cost-effective sewer cleaning programs. The site specific pre-cleaning assessment inspection costs resulting from this project and MSDGC's historic practices for CCTV (on-road), CCTV (off-road), and SL-RAT (on- and off-road) are $1.68/ft., $2.03/ft., and $0.14/ft., respectively. So, for pre-cleaning assessment, the application of the SL-RAT can reduce MSDGC's costs by $1.54/ft. for on-road sewers and $1.89/ft. for off-road sewers. In addition, by moving to a sewer cleaning program predominated by planned directed cleaning, MSDGC can save $2.00/ft. by reducing its "cleaning of clean pipe." In total, when costs of conventional CCTV inspection and cleaning are combined, for each pipe segment that is deemed "clean" using the SL-RAT, MSDGC can save $3.54/ft. for on-road sewers and $3.89/ft. for off-road sewers.

The results of this demonstration of the SL-RAT show promise for its application as a tool for cost-effective, pre-cleaning assessment and post-cleaning quality assurance. The application of the SL-RAT in an overall collection system O&M program should enable wastewater utilities to optimize their sewer cleaning efforts and free up valuable resources to more effectively implement critical CMOM and asset management programs.

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APPENDIX A–SL-DOG CONDITION ASSESSMENT DATA VERIFICATION

During the in-field condition assessment of a pipe segment, the SL-RAT collects data to assist in verification. The verification is performed as an automated post process through the SL-DOG. Varying stages of verification are available based on the requirements of the utility. This verification process has two objectives:

1. Verify the pipe segment length used in evaluating the SL-RAT condition assessment. The SL-DOG uses the reassessed pipe length to reevaluate the condition assessment.

2. Verify the utility's pipe segment ID associated with the SL-RAT condition assessment.

The SL-RAT algorithm requires an estimate of the segment length to conduct its condition assessment. During the in-field measurement, the operator estimates and enters the pipe length (+/- 50 feet) used in the initial on-site evaluation. The SL-DOG post-processing allows the reevaluation of the condition assessment based on an updated pipe length. As an example, if an operator inadvertently enters 50' for a 250' pipe segment, the actual acoustic condition assessment may be higher than the value reported in the field on the SL-RAT device. The SL-DOG can correct the condition assessment based on the 250' length.

Depending on the preventive maintenance policy used by the utility for integrating the SL-RAT condition assessment, registering the SL-RAT measurement can be an essential element. The SL-RAT measurement registration requires associating the utility's pipe segment ID (or equivalent ID) to the SL-RAT's measurement record number. Registration enables the following

1. Identifying the SL-RAT condition assessment within the utility's GIS system
2. SL-RAT condition assessment reevaluated based on the utility's GIS pipe segment length
3. Historical comparative analysis of the SL-RAT condition assessment for the pipe segment.

The SL-DOG verification process is illustrated using the SL-RAT measurements conducted at five pipe segments during the EPA project study. The five segments are from Galia road as depicted in Figure A-1. The corresponding SL-RAT in-field measurement data augmented with the SL-DOG evaluation are given in Table A-1 for the five pipe segments. In Table A-1, the measurements are grouped based on the verified segment ID (column 13) with multiple measurements for each pipe segment. The seven columns under the "SL-RAT In-Field Measurement Data" heading are data obtained directly from the SL-RAT. The "Pipe Length" in column 3 is the operator specified pipe length in feet and is used in evaluating the pipe segment condition assessment given in column 4. This is the SL-RAT condition assessment reported to the operator in the field based on their estimate of the pipe length.

The first verification stage is based on the SL-DOG automatically reassessing the SL-RAT condition assessment when the SL-RAT measurement data is uploaded. The reassessment is based on evaluating the pipe segment length using the GPS location estimates for the SL-RAT transmitter and receiver (columns 5 through 8). The GPS based pipe length estimate and the corresponding SL-RAT condition assessment are given under the heading “GPS Based Evaluation” in Table A-1.

The second verification stage is based on associating the SL-RAT measurement with the utility’s segment ID. This association requires additional information from the utility which identifies the utility’s segment ID based on the upstream and downstream manhole locations for each segment. This can typically be obtained from the utility’s GIS data base as summarized in Table A-2 for the five Galia road pipe segments. The SL-DOG uses both the SL-RAT measurement data and the utility’s GIS data to associate each segment ID to the recorded measurement. The current SL-DOG mapping algorithm is in beta development. The segment ID association provided by the SL-DOG mapping for the five Galia road pipe segments is given under the heading “Mapping Based on GPS & Utility GIS” in Table A-1.

To illustrate the segment ID association, in Figure A-2 the three measurements conducted for pipe segment 11706002-11707005 are depicted based on the GPS location estimates for the SL-RAT transmitter and receiver. As with any GPS device, the location estimates are influenced by variations in relative satellite locations, foliage, weather, and other obstructions affecting signal reception from the satellites. These variations in signal reception impact the error associated with the location estimate as illustrated in Figure A-2. For the three measurements, the SL-DOG mapping algorithm correctly associated the GPS location with the segment ID from the utility’s GIS data.

When the SL-RAT GPS location estimates are sufficiently large, an error in segment ID association can occur. As an example, for the measurement with record number 677, the SL-DOG mapping algorithm incorrectly associated the measurement to the adjacent pipe segment. To assist in identifying incorrect segment ID associations, a confidence measure is provided for the SL-DOG mapping (column 11, Table A-1). A low confidence measure indicates a potential error in segment ID association and/or indicates a potential error in the manhole locations in the utility’s GIS data base.

The third verification stage is based on the recommended use of the SL-DOG mapping algorithm as a verification tool for the operator’s measurement registration. The operator measurement registration is the operator’s association between the utility’s segment ID and the SL-RAT measurement record number recorded at the time of the measurement. During the SL-DOG automated post-processing, discrepancies between the operator measurement registration and the SL-DOG’s mapping can be flagged and corrected based on visual inspection. For the five Galia road pipe segments, the last three columns in Table A-1 contain the verified segment ID association (column 13) for each measurement. Based on this association, the GIS pipe segment length (column 14) was used to reevaluate the SL-RAT condition assessment for the pipe segment (column 15).

Figure A-1. Five Galia road pipe segments used to illustrate the SL-RAT condition assessment verification. Call out box for pipe segment 11706002-11707005 indicates the measurement ID and the condition assessment score for the three SL-RAT measurements conducted for the pipe segment during the EPA project.

Table A-1. SL-RAT in-field measurement data augmented with the SL-DOG evaluation for the five Galia road pipe segments.

SL-RAT Field Measurements & Data								GPS Based Evaluation		Mapping Based on GPS & Utility GIS		Verified Data Registration		
Rec Num	Measurement Date Time	Pipe Length	Assess-ment	Rx Lat	Rx Long	Tx Lat	Tx Long	Pipe Length	Assess-ment	Confi-dence	Segment ID	Segment ID	Pipe Length	Assess-ment
620	1/28/2013 11:43	250	0	39.133	-84.698	39.132	-84.698	236	0	100	11707005-11702001	11707005-11702001	251	0
621	1/28/2013 11:46	250	0	39.133	-84.698	39.132	-84.698	236	0	100	11707005-11702001	11707005-11702001	251	0
673	4/16/2013 11:22	250	7	39.133	-84.698	39.132	-84.698	191	7	100	11707005-11702001	11707005-11702001	251	7
628	1/31/2013 12:02	150	10	39.135	-84.694	39.134	-84.695	188	10	100	11706005-11706004	11706005-11706004	257	10
677	4/16/2013 11:43	250	9	39.135	-84.695	39.134	-84.695	233	9	1	11706004-11706003	11706005-11706004	257	9
627	1/31/2013 11:53	350	7	39.134	-84.695	39.134	-84.696	375	7	97	11706004-11706003	11706004-11706003	401	7
676	4/16/2013 11:39	350	8	39.134	-84.696	39.133	-84.696	356	8	5	11706004-11706003	11706004-11706003	401	8
626	1/31/2013 11:41	350	5	39.134	-84.696	39.133	-84.697	218	4	52	11706003-11706002	11706003-11706002	361	5
675	4/16/2013 11:33	350	8	39.133	-84.696	39.133	-84.697	275	8	7	11706003-11706002	11706003-11706002	361	8
708	5/3/2013 16:58	350	9	39.133	-84.697	39.134	-84.696	350	9	93	11706003-11706002	11706003-11706002	361	9
622	1/28/2013 12:34	250	8	39.133	-84.697	39.133	-84.698	262	8	100	11706002-11707005	11706002-11707005	295	8
674	4/16/2013 11:28	250	9	39.133	-84.697	39.133	-84.698	155	9	50	11706002-11707005	11706002-11707005	295	9
710	5/3/2013 17:05	250	9	39.133	-84.697	39.133	-84.698	368	10	95	11706002-11707005	11706002-11707005	295	9
619	1/28/2013 11:17	150	9	39.132	-84.698	39.132	-84.699	91	9	100	11702001-11702002	11702001-11702002	121	9
672	4/16/2013 11:16	150	9	39.132	-84.699	39.132	-84.698	166	9	100	11702001-11702002	11702001-11702002	121	9

Table A-2. The utility GIS data required by the SL-DOG to associate the pipe segment ID (Name) with the SL-RAT in-field GPS location estimated by the SL-RAT receiver and transmitter units. GIS data is for the five Galia road pipe segments used to illustrate the SL-DOG verification process.

Segment Name	Man Hole 1 ID	Man Hole 2 ID	Length (feet)	MH 1 Latitude	MH 1 Longitude	MH 2 Latitude	MH 2 Longitude
11707005-11702001	11707005	11702001	251	39.1328	-84.6979	39.1322	-84.6984
11706005-11706004	11706005	11706004	257	39.1348	84.6941	39.1344	84.6949
11706004-11706003	11706004	11706003	401	39.1344	-84.6949	39.1336	-84.6959
11706003-11706002	11706003	11706002	361	39.1336 -	84.6959	39.1330 -	84.6969
11706002-11707005	11706002	11707005	295	39.1330	-84.6969	39.1328	-84.6979
11702001-11702002	11702001	11702002	121	39.1322 -	84.6984	39.1320 -	84.6987

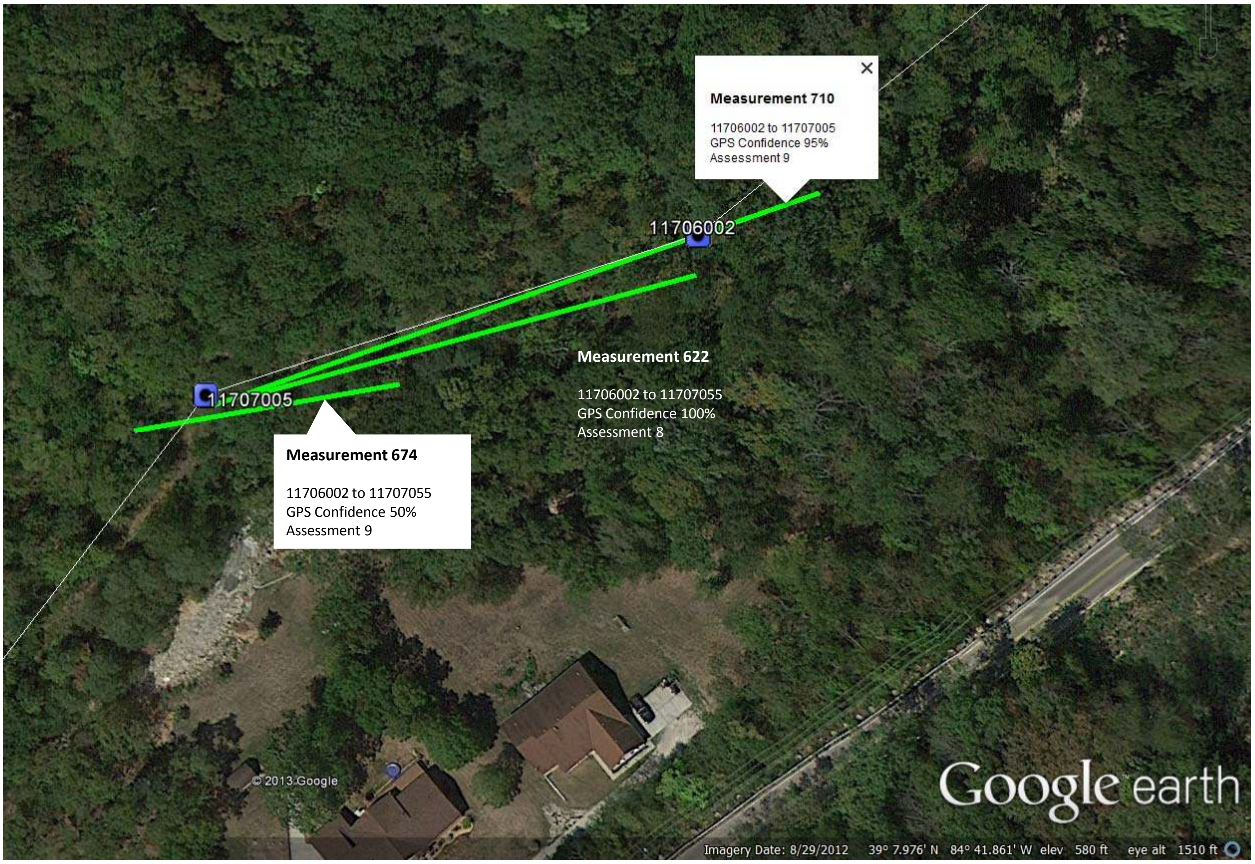

Figure A-2. GPS mapping for the three SL-RAT condition assessments conducted at Galia road pipe segment 11706002-11707005.

APPENDIX B–STUDY AREA FIGURES

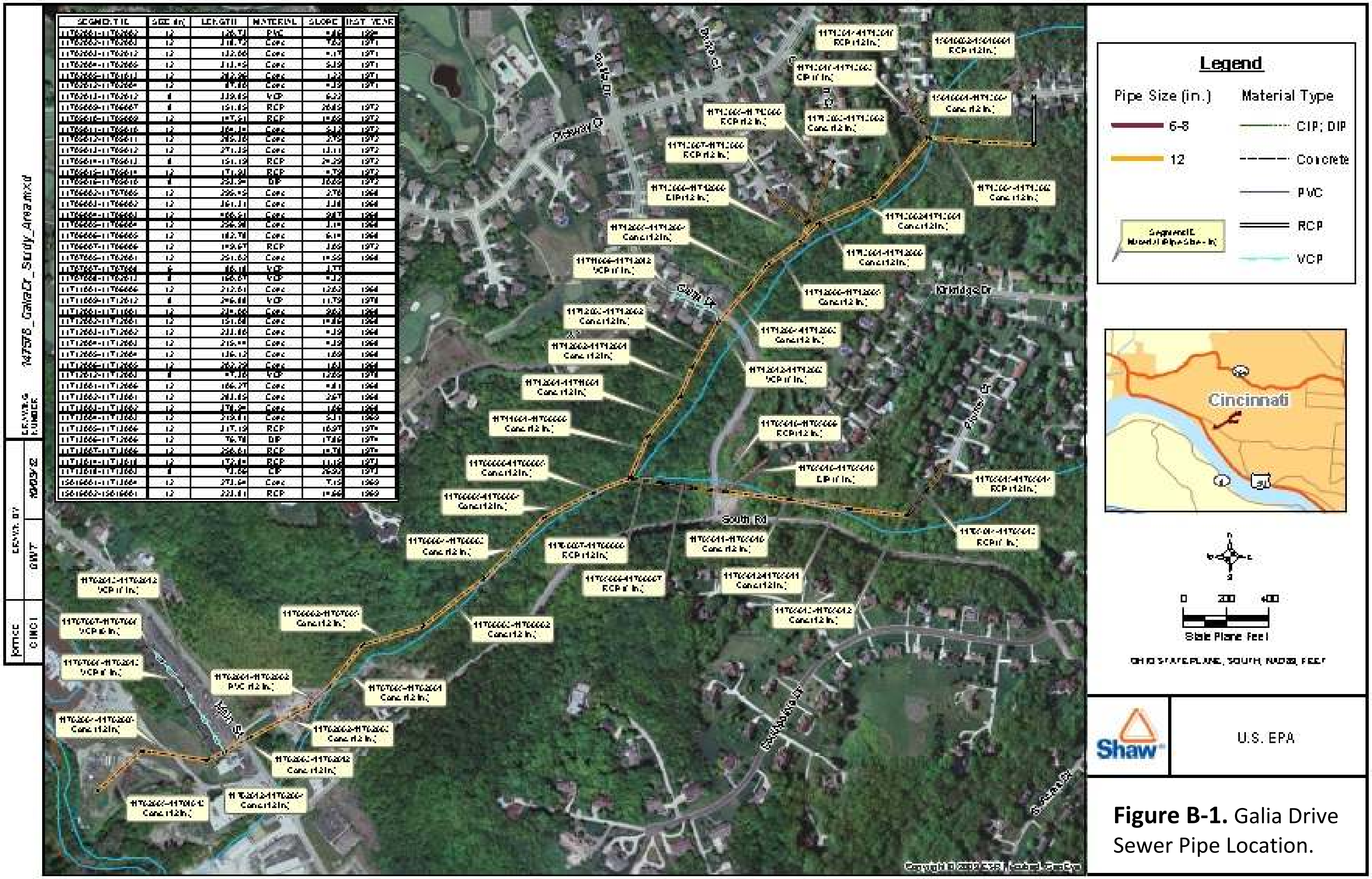

Figure B-1. Galia Drive Sewer Pipe Location.

SEGMENT ID	SIZE (in)	LENGTH	MATERIAL	SLOPE	INST. YEAR
44705004-44708017	12	159.99	RCP	1.87	1979
44705005-44705004	12	85.19	Conc	3.55	1979
44708004-44710058	12	131.23	Conc	1.99	1983
44708007-44708009	8	109.17	Conc	0.73	1979
44708008-44708009	8	275.99	Conc	14.59	1979
44708009-44708010	8	102.82	Conc	1.90	1979
44708010-44708004	12	191.59	Conc	1.42	1983
44708011-44708010	8	21.53	Conc	91.03	1979
44708012-44708011	8	278.73	Conc	22.19	1979
44708013-44708010	12	342.22	Conc	2.44	1983
44708014-44708013	12	315.58	Conc	2.43	1983
44708015-44708014	12	198.37	Conc	2.34	1983
44708017-44708015	12	200.11	RCP	1.49	1979
44710027-44708012	8	203.15	Conc	5.19	1979
44712001-44705005	12	230.54	RCP	4.45	1983
44712002-44712001	12	345.97	Conc	4.05	1983
44712003-44712004	8	78.75	Unk	0.58	1984
44712004-44712005	8	44.58	Unk	34.78	1984
44712004-44712010	8	34.32	Unk	0.83	1984
44712005-44712007	8	39.89	Unk	21.89	1984
44712007-44712002	12	175.10	Conc	9.38	1983
44712008-44712007	12	178.92	Conc	4.18	1983
44712010-44712005	8	88.34	Unk	14.79	1984
45202013-44712008	12	359.21	Conc	2.27	1983
45202014-45202013	12	307.29	Conc	2.94	1983
45202015-45202014	12	249.22	Conc	2.94	1983
45202016-45202015	12	228.05	Conc	9.06	1983
45202017-45202016	12	247.27	Conc	2.72	1983
45202018-45202017	12	214.73	RCP	2.12	1983
45202019-45202018	12	294.59	RCP	1.59	1983
45202020-45202019	12	38.28	RCP	1.41	1983
45202021-45202020	12	159.99	Conc	5.19	NA
45202022-45202020	8	111.00	Conc	-2.95	1983

Figure B-2. Hunt Road Sewer Pipe Location.

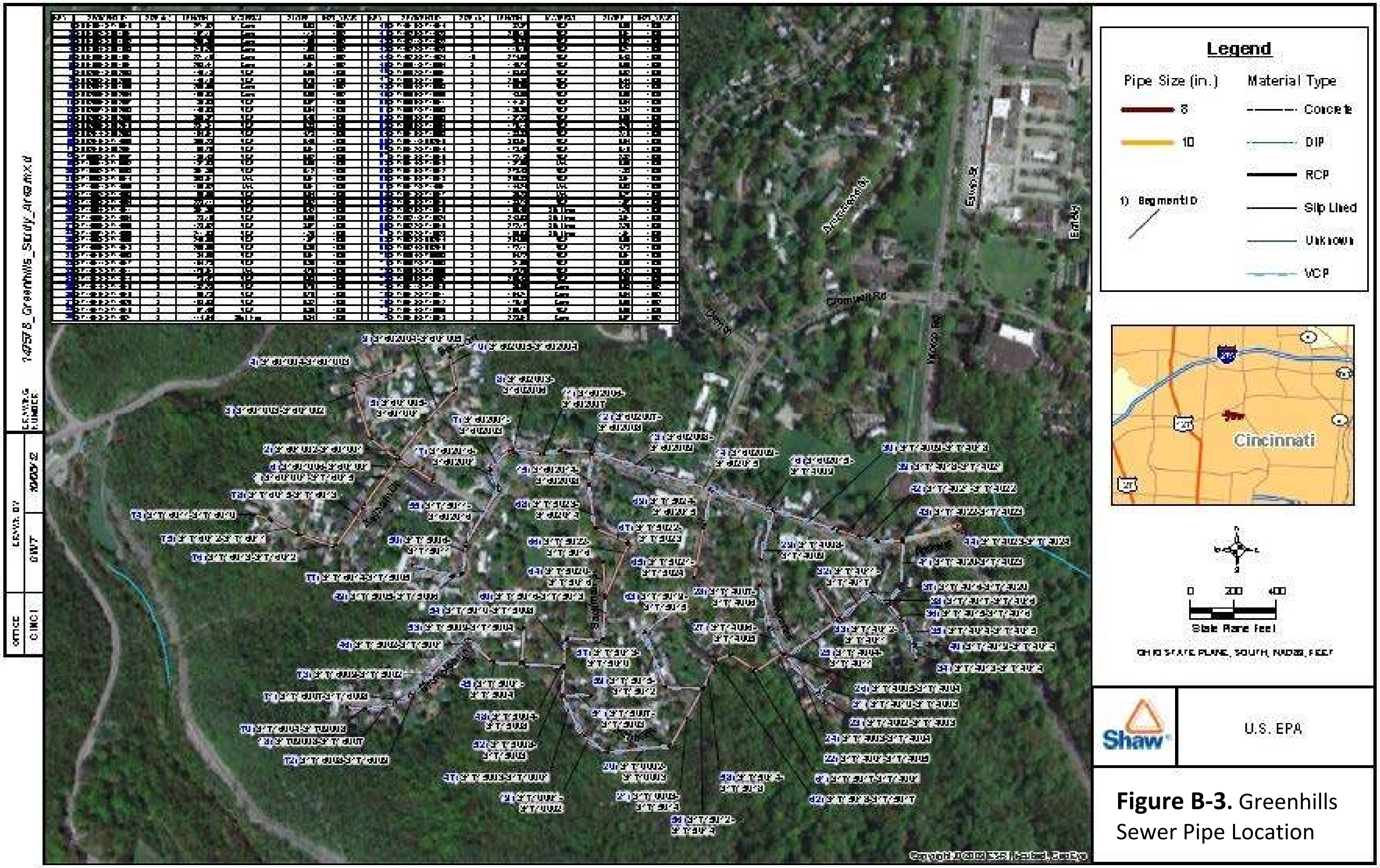

Figure B-3. Greenhills Sewer Pipe Location