Locating Sources of Pressure Transients in Water Distribution Systems

by

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A thesis submitted to the University of Sheffield in partial fulfilment of the requirements for the degree of Doctor of Philosophy

April 2014

Abstract

Transient pressures occur regularly in potable water distribution systems as they are a fundamental mechanism by which changes of state occur. The occurrence of significant transient events is cause for concern because of their potential to adversely affect distribution systems, by causing structural and water quality failures. The source location of problematic transient pressure events is sometimes undisclosed and difficult to identify, highlighting a requirement to develop robust methodology to find the location of transient pressures.

This thesis develops novel methodology for identifying the location of transient pressure sources in water networks. The method uses graph theory to determine primary wave front transit paths and the shortest transit times between multiple locations in a system. Theoretical wave front arrival time differences are then compared to measured arrival time differences, which are observed in temporally synchronised pressure data, from multiple, optimally placed pressure data loggers. The results provide a Likeliness for the existence of a source at each location in a system.

Conceptual, laboratory and field experiments were performed to verify and validate the transient source localisation procedure. This involved; evaluating the effectiveness of the localisation procedure by analysing novel data from a modular laboratory test pipe system, comparison and novel application of wave arrival time estimation methods and the development of bespoke solutions to optimally place pressure data loggers.

Finally, all the procedures developed were validated through full scale field experimentation, proving a robust method for locating transient pressure sources in water distribution systems. Problematic transient events can therefore be localised so that mitigation strategies can be employed, hence reducing the risk of structural and water quality failures.

Keywords:

Pressure transients, Water networks, source location, graph theory, shortest path, high frequency data logging,

Acknowledgements

I would like to thank my supervisors Joby Boxall and Stephen Beck for valuable support and guidance throughout the undertaking of this work. Also to Richard Collins for his helpful advice.

Thankyou to Yorkshire Water for partially funding the work and to the staff who have been crucial in facilitating field experiments, particularly to Julian Longbottom, David Hayes and the late Mark Dicker.

Thankyou to anyone at the University of Sheffield who has helped me along my way including the transient inhabitants of D106 and D105.

Thanks to my family and family in law for help and Jonah care.

Last but definitely not least, many many thanks to Bryony for the endless support, understanding and patience and to Jonah for just being great.

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Notation

A	*adjacency matrix*
a	*wave speed*
D	*internal diameter of the pipe*
E	*elastic modulus of the pipe material or Young's modulus*
e	*pipe wall thickness*
G	*graph definition*
ΔH	*change in pressure head*
K	*bulk modulus of the fluid*
L	*source Location Likeliness*
l	*pipe length*
N	*vertices matrix*
n_i	*single vertex*
Ω_0	*optimal placement vector*
P	*Pipes definition matrix*
r	*influence vector for sensor placement*
ρ	*density of fluid*
s_i	*sensor location*
t_0	*wave arrival time*
T	*shortest path matrix*
τ	*wave arrival time difference*
ΔV	*change in fluid flow velocity*

1 Introduction

In the U.K. and for the majority of the developed world the provision of potable water to most domestic, commercial and public buildings is accepted as the norm and it now seems inconceivable not to have this facility. Since the industrial revolution extensive networks of water supply systems have been developed such that is a vast and essential part of our societal infrastructure. In the U.K. the length of operational buried pipe in the ground is vast at approximately 330000 km, for which the care and management is a huge logistical task involving thousands of employees. Water companies have an obligation to maintain water supply networks so that they are suitable for use for our current circumstances but they are also required to future proofing supply networks and systems to ensure security of supply to future generations.

The inherited legacy of water distribution systems means that large portions of our water supply infrastructure is aging and in various states of degradation. There is an increasing need to identify innovative and cost effective solutions, to improve management and maintenance strategies associated with distribution assets. Increasing understanding of the physical condition and performance of supply infrastructure is a key contributor to ensuring effective and reliable operation of our water supply systems both now and in the future.

Erratic weather patterns and the implications of climate change mean the surety of water supply is difficult to predict and as a result the reduction of pipe bursts and leakage are one problem that is of concern to water companies. Water is becoming scarcer due to rapidly increasing populations and the risk of water shortages is an ever increasing problem. Current economic levels of leakage may not be sustainable and a shift towards more sustainable level of leakage and reducing the potential for pipe failures is of upmost importance.

One crucial area of research receiving increased levels consideration over recent years concerns the role that transient pressures (also referred to as pressure surge or water hammer) have in contributing to a multitude adverse effects on water distribution systems and the supply of potable water. Historically, the potential for structural pipe failures as a result of transient events has been accepted to some extent and while in recent times surge modelling software has improved our ability to develop and adopt surge mitigation strategies in new and existing pipe systems; vast areas of our supply system were installed when design processes and understanding did not fully account for transient pressures. A large number of questions arise when we consider the impact that transient pressures are currently having on our distribution systems. Besides major and minor structural failures transients have the potential to cause water quality failures through facilitating the intrusion of contaminants from surrounding ground water and through apertures in pipe wall, they may also have the potential to remove adhesions from the pipe walls introducing biological and mineral deposits into the fluid.

In general transients are the cause for a multitude of concerns pertaining to the secure supply of potable water suitable for human consumption. When we then consider that a transient pressure wave can propagate for a number of kilometres at speeds up to 1500 ms^{-1}, it becomes apparent that problems may not just arise in the near vicinity of the source of a transient pressure but may occur at numerous distant locations from the initial source.

State of the art pressure monitoring devices now have the ability to independently observe and record dynamic pressure fluctuations in live water distribution systems at high sample frequencies, giving us the ability to identify the occurrence of transient pressures. Transient pressures are the fundamental process by which changes of state occur as a result of flow variations, therefore the multitude of potential causes of transient events particularly in complex networks with multiple flow control devices can make it difficult to identify the location of problematic transient events.

Having the facility to identify the location of transient sources will help in understanding the actual causes of problematic transients and the subsequent adoption of surge mitigation strategies.

Water company operatives have a wealth of anecdotal evidence to suggest that pressure transients are having adverse effects on distribution systems and it is in part due to these that has lead to the desire to develop methodology for localising the source of transient in complex pipe networks. A broader hypothesis is that, having the ability to identify transient sources of various magnitudes in water networks may help to provide greater understanding in the future, to the impact that transient pressures have on water supply systems.

Failures and supply issues do result of transient events and it is, not always, but sometimes, prohibitive and or time consuming to find the location of the problem.

2 Literature Review

A common theme introducing vast amounts of the literature discussed here refers to the aging and deterioration of our water distribution networks. Much of these networks were laid over 100 years ago using cast iron pipes Boxall et al., (2007). These early pipes are susceptible to degradation due to a multitude of factors to be discussed later. Combining this with inconsistent material properties, variable construction techniques and limited understanding of the physical operating conditions, a large variety of potential failure modes exist, compromising the integrity of our distribution networks. These underlying problems have implications on various factors concerning the condition and operation of distribution systems and their ability to meet current and future demands imposed upon them. Due to their age water pipe networks are susceptible to failure

2.1 Pipe Failure

2.1.1 Structural Failure

Leakage in water distribution networks can be attributed to a number of factors, the physical mechanisms leading to pipeline failure and leakage are complex, including, aging pipes, degradation, traffic loading, ground movement, soil type Boxall et al., (2007) Kleiner and Rajani, (2001) identified three main areas when considering contributing factors to pipeline leakage.

> *"Pipe structural properties, material type, pipe soil interaction, and quality of installation"*
>
> *"Internal loads due to operational pressure, and external loads due to soil overburden, traffic loads, frost loads and third party interference"*
>
> *"Material deterioration due largely to the external and internal chemical, bio-chemical and electro-chemical environment."*

Various models have been developed to help predict future pipe breakages. Physically based models predict pipe loadings and assess pipeline physical characteristics to estimate the potential for failure Kleiner and Rajani, (2001); Rajani and Makar, (2001); Tesfamariam and Rajani, (2007). Physical models can be prohibitive, as a very large number of possible outcomes need to be assessed to develop accurate models, combined with a good understanding of current pipe condition. Also, every pipe in a distribution system may have different characteristics and operating conditions, with inconsistencies in installation methods and ground condition.

Statistical burst prediction methods look at previous burst histories and use statistical analysis to assess the Mean Time to Failure MTTF and establish annual burst rates Boxall et al., (2007); Kleiner and Rajani, (2001); Meoli et al., (2009). Statistically based models often combine the physical pipe and environmental attributes increasing the robustness and usefulness of model predictions.

With all burst prediction models, they are only as good as the data provided, while some data could be accurate and high quality some may not be. Different water utilities have different data storage procedures. Therefore a model developed using data from one water utility may not be as successful when using data from an alternative utility.

The extent to which hydraulic transients impact on leakage rates is not fully understood. References are made to catastrophic failures associated with hydraulic transients Karney and McInnis, (1990). Often overlooked is the concept that smaller regularly occurring transient events could still initiate significant failures.

2.1.2 Asset Deterioration

Deterioration of internal and external pipe material can potentially lead to leaks, bursts, water quality failures, increased frictional losses, which are all of concern to water utilities who have contractual and ethical responsibilities to provide clean safe drinking water to their customers. Pipe degradation can be classed in two categories. The first being structural deterioration of the pipe material, reducing the pipe’s ability to withstand various stresses imposed upon it. The second being surface deterioration which can reduce hydraulic capacity and degrade water quality and also reduce structural integrity Kleiner and Rajani, (2001). For further clarification of the two categories it could be said that structural deterioration is caused by internal and external forces acting on a pipe either through long term fatigue loading or short and long term shock loadings. Surface deterioration, for metallic pipes, is more likely to be caused by the effects of corrosive processes, internally and externally, either chemical or electro-chemical reactions acting on the pipe material Kleiner and

Rajani, (2001). Reduced hydraulic capacity can also be caused by adhesions and sedimentary build up occurring inside a pipe.

Seica and Packer, (2004) Evaluated the strength of exhumed cast iron water pipes, confirming that corrosion and air pocket in the pipe material exist, and contribute to reducing a pipes structural integrity by acting as stress concentrators and crack instigators. Manufacturing defects were more prevalent in older pipes due to manufacturing processes of the time. The research confirms findings of previous studies showing large variations in the tensile strength of pipe material, large proportions of the samples had excessive strength based on the provisions of modern standards, while some samples were considerably weaker. The large variations in pipe strength made it difficult to predict failure rates based on pipe material.

In the discussions of failure mechanisms, internal dynamic pressures are identified as one of many causal factors, but the literature is generally concerned with the impact of significant events. The total stress in a pipe is a combination of axial stress and hoop stress which are in turn a combination of external loads, internal pressure, temperature differential and longitudinal bending Tesfamariam and Rajani, (2007). The implications of this being that the identification and mitigation of any these contributing stresses could cause a reduction in failure rates. While internal dynamic pressures are recognised as a contributor to failure stresses their magnitude and rate of occurrence in live distribution systems has not been conclusively quantified. Longitudinal failures are realised to be predominantly a result of internal pressures Kleiner and Rajani, (2001) and transient are attributed to be one causal factor. This begs the question; to what extent do longitudinal failures occur as a result of transient pressure? And how would this be evaluated?

One solution to rectifying problems associated with the legacy of an aging distribution system would be to renew the entire distribution network. While this could be a physical possibility, the high capital investment required is prohibitive; therefore rehabilitation and improved operational practices are the preferred approach.

While the continued utilisation of aging distribution assets poses a considerable challenge, problems also exist in pipelines constructed from relatively modern materials. Current materials such as Medium Density Polyethylene (MDPE) have considerably higher strength ratings than historically used materials, but structural problems have been encountered with PVC pipes. Failure mechanisms need to be fully understood so mitigation measures can be developed.

2.2 Dynamic Pressures

The existence of transient pressure waves in water distribution networks is inevitable; they are the mechanism by which changes of state occur within the system. Any change in flow, hence pressure, at one point in the system, must be transmitted through the system to establish a new state of equilibrium. These changes in pressure are transmitted as pressure waves, through changes in strain energy in the fluid and pipe walls and can involve pressures well outside steady state operating pressure.

Catastrophic component failures, made utilities and researchers aware of the consequences of large transients, researchers and engineers have developed methods to mitigate their occurrence but application of these methods can be complex, expensive and require regular maintenance. More recently, modern technology and computational modelling has enabled us to gain a far greater understanding of the behaviour of pressure transients. The long standing misnomer that as a rule, within complex pipe networks, transients are rapidly attenuated has increasingly been debunked and the need for further research in to the role of pressure transients has become more apparent. While greater understanding of transient activity enables us to understand and mitigate adverse effects, analysing the propagation of transient waves throughout distribution networks can potentially reveal a large amount of information attaining to the operation and condition of pipe networks.

Many causes of Transient pressures have been documented. Fundamentally, an operation that rapidly changes the fluid flow velocity in a pipeline can initiate a transient wave. Common causes of pressure transients in distribution systems noted in Kirmeyer et al., (2001) are:

> "*Opening and closing a fire hydrant*
> *Pump trip due to a power failure*
> *Losing an overhead storage tank*
> *Flushing operations*
> *Altitude valve closure*

Valve operation – opening and closing

Break in a pipeline

Malfunctioning air release/vacuum valves

Controlled pump startup and shut down

Air valve slam

Surge tank draining

Feed tank draining

Malfunctioning pressure relief valves

Booster pump startup and shut down

Check valve slam

Resonance

Sudden change in demand"

This list highlights the extensive range of possible causes of pressure transients in distribution networks and emphasises a need to understand their effects further. It also highlights the difficulties which could be encountered when trying to identify the location of a transient source. The list is not exhaustive, and other situations could exist leading to transient pressure waves originating at potentially undisclosed locations.

2.2.1 Characteristics of Transient Pressures

Properties of the fluid and pipe material govern the behaviour of transients in pipelines, the accepted equations to show maximum pressure change and wave speed are below Chaudhry, (1987); Massey, (1989); Wylie and Streeter, (1978).

The Joukowski equation gives the approximate change in pressure head according to instantaneous changes in mean pipe velocity. The equation represents an idealised situation, achieving an instantaneous change in velocity is not physically possible but the equation provides an approximation the maximum possible head change:

$$\Delta H = \pm \frac{a\Delta V}{g} \tag{2.1}$$

Where a =wave speed, ΔH =change in pressure head ΔV = change in velocity.

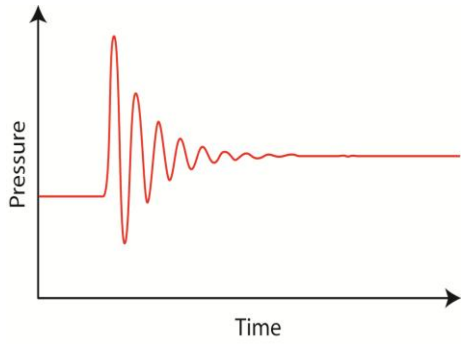


Figure 2-1 - Upsurge pressure transient

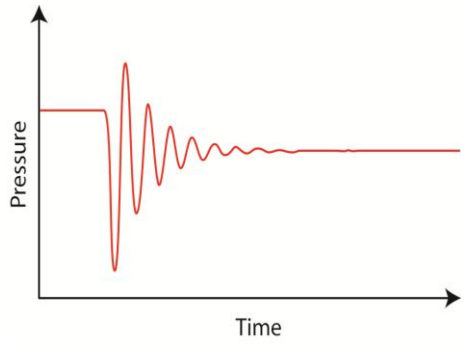


Figure 2-2 – Downsurge pressure transient

Characteristic Transient pressure signals close to the source of origin are represented in Figure 2-1 and Figure 2-2 The initial pressure increase in occurs as a result of the kinetic energy changing to stored pressure energy in the fluid, following a sudden change in flow velocity. The subsequent pressure oscillations occur as strain and kinetic energy are successively transferred within the fluid and pipe wall material. The amplitude of the oscillations decreases as energy is dissipated, mainly through frictional losses Massey, (1989). Examples of an operation creating an upsurge as in Figure 2-1 would be upstream of a valve closure, downstream of a valve opening, or downstream of a pump start-up. Conversely a downsurge as in Figure 2-2 would coincide with being downstream of a valve closure, upstream of a valve opening or upstream of a pump start-up.

More comprehensive calculations are also available with the use of computational models, this will be discussed later Wylie and Streeter, (1985). Jung et al., (2007) Suggests engineering guidelines relating to the design of water pipe systems are inadequate and that comprehensive analysis techniques are more robust. Computer modelling is used to show insufficiencies in the American Water Works Association (AWWA) guidelines which could lead to poor design. Computers and increased accuracy of transient models make the use of computational design more appealing and more relevant. The paper implies a need to review current guidelines on design for water hammer.

2.2.2 Impact of Transient Pressures

2.2.3 Structural Failure

Ghidaoui et al., (2005) states that advent of hydro electric power generation highlighted extreme pressure regimes associated with pressure transients and their potential to cause catastrophic structural failures leading to an increased desire to understand the development and propagation of dynamic/transient pressures. Pressure transients have the ability to create considerably high dynamic pressures in a pipe system, well above that of steady state operating pressures; hence it is clear that if they are not fully considered in the pipeline design process then maximum design pipe loadings may not be sufficient, leading to inadequate strength and increased risk of structural failure. Historically, the significance that pressure transients play in the structural deterioration of water distribution networks has often been overlooked. A number of general misconceptions and assumptions are made when regarding transient pressures, such as assuming lower flow rates produce smaller transient pressures and that rapid attenuation of pressure waves make their impact of little significance.

The advances made in computational modelling have lead to renewed interest and understanding of the structural threats posed by transient pressures, Along with an increased understanding of potential causes. Research has shown that problematic events may not always be intuitively apparent, and the complex nature of wave propagation in pipe networks could lead to higher than expected dynamic pressures in certain locations. This points to the need for comprehensive analysis for fuller understanding Jung et al., (2007). Much of the work undertaken assessing likelihood of failure has been through modelling and while water utilities may undertake transient analysis there is very little published research looking in to the frequency of occurrence and significance of structurally damaging transient events.

This section has not yet discussed the effect that asset deterioration could have on failures associated with transients. A pipeline may deteriorate and still retain adequate integrity to withstand steady state pressures but not excessive dynamic pressures. With better understanding and mitigation of dynamic pressures we may be able to extend the serviceable life of existing infrastructure. As mentioned in section

2.1.2 it is difficult to know the strength of the existing infrastructure and therefore establish its ability to withstand pressure changes associated with dynamic events

Boulos et al., (2005).identifies the significant damage to infrastructure that can be caused by uncheck dynamic pressure whether associates with resonance phenomenon or regular transient pressure events

2.2.4 Quality and Ingress

In recent years there has been growing concern over the potential risks associated contaminant ingress as a result of low and negative pressures caused by transient pressure events. This has spurred new research to understand the significance of the threat to water quality and consumer health. When a down-surge event occurs in a distribution system, transient pressures can drop considerably lower than steady state pressures. In some circumstances pressures can drop below atmospheric pressure, this is often termed a negative pressure transient. It is generally assumed that if pressure inside a pipeline is higher than the pressure external to the pipeline and should a hole exist in pipe wall, then clean water will be extruded with little risk of external material entering the pipe and contaminating the treated water supply. Conversely, if the internal pressure becomes lower than the external pressure, water and contaminants external to the pipe could potentially be drawn into the system causing contamination and a potential health risk. Boyd et al., (2004a), (2004b) showed that in experimental laboratory test rig, that intrusion occurs as a consequence of negative pressure transients and also, that contaminants stay in the system and are not subsequently extruded through the same orifice. The research is limiting in that the laboratory simulation were far removed from actual in situ conditions experienced by a real network. The work did not consider material external to the pipe or investigate the intrusion associated with different pipes and failure modes.

Work by Walski and Lutes, (1994) showed that low and negative pressures can occur as a consequence of pump stoppage. LeChevallier et al., (2003) evaluated the risk to distribution systems from contaminant ingress based on available research, drawing heavily on Karim et al., (2000); Kirmeyer et al., (2001). The paper concluded that negative pressures do exist in live distribution systems and they have the potential to cause water quality failures. Karim et al., (2003) collected water and soil samples, from 8 different North American water utilities. Samples were taken from trenches where pipe repairs were being undertaken and then tested for various viral and bacteriological content. The significant findings were that 58% of samples contained faecal coliforms, showing that potentially harmful contaminants were present in soils adjacent to distribution pipelines. If low or negative pressure transients occurred in the presence of a leaking pipe and intrusion were to occur, these contaminants could potentially be introduced into domestic water supplies. Water samples were not consistent with normal operating conditions as the material external to the pipe had been removed. The findings are therefore not conclusive as to the level of contaminants in extruded water immediately adjacent to in situ pipelines. Based on the body of evidence that negative transients exist and contaminants are present adjacent to distribution piping, the paper called for more industry funded research in part to investigate the merits of surge modelling and high speed loggers.

If contaminant ingress is to be of concern, then the coupling of economics and leakage should become of reduced significance and the bias should maybe move more towards a risk based evaluation of leakage. With aging distribution infrastructure, identifying and reducing further causes of leakage will in turn mitigate the associated risks from ingress.

2.2.5 Attenuation/mitigation

Our limited understanding of the potential consequences associated with pressure transients in distribution networks informs us of the need to reduce the significance of their occurrence. Stopping transient waves altogether is not feasible as they are an inextricable constituent of the operation of fluid pipe systems. A number of options remain, reducing the frequency of their occurrence, reducing the maximum pressures observed and attenuating waves so that energy is dissipated more effectively. The Joukowski equation assumes a rapid change of velocity less than $2l/a$ Massey, (1989) where l is the pipe length and a is the wave speed. If the rate of change in velocity can be reduced then the magnitude of the associated transient wave can also be reduce. Some surge protection methods employing this theory have been developed to help mitigate the impact of transient pressures.

At a basic level slow operation of valves and hydrants can reduce the magnitude of transients Walski, (2009). For more specific case some of the mitigation techniques below can be incorporated. The vast majority of mitigation techniques aim to reduce the rate at which the change in kinetic energy is dissipated through the system by providing an alternative route for fluid to enter or leave the system. With regards to pumps, reducing the rate of change in rpm with variable speed control systems and fly wheels can help to reduce the magnitude of transients. Surge tanks provide a reservoir where energy can either be supplied to or relieved from a system reducing the strain energy in the fluid. Jung et al., (2007) emphasises the need for rigorous and comprehensive design to ensure appropriate surge protection devices are used.

Leaks in a distribution network can provide points where energy can enter or leave a system, hence can aid in the attenuation transient events. One concern as efforts are made to reduce leakage is that the reduced levels of attenuation associated with leakage could lead to increased burst rates. Colombo and Karney, (2003). To fully evaluate the level of attenuation in our water networks extensive field work needs to be undertaken to measure the real impact of transient pressures.

2.2.6 Section Summary

The role of dynamic pressures in water networks have been investigated for a long time, but only relatively recently, have we begun to develop a fuller understanding of their significance and the impact they have on water quality and structural integrity in our distribution networks. It is clear that transient pressures cause problems but the full extent of these problems is not yet known. Emerging technologies increase our ability to learn about the existence of transients in real water networks; to date this has not been comprehensively undertaken. The majority of recent research measuring transient events has been concerned with the occurrence of low and negative pressures. There is a clear need for further research looking at the frequencies and magnitudes of more general transient events. While a large number of potential causes of transients are known, extensive field measurements recording the system pressures associated with these causes have not been published. The level of deterioration occurring in distribution systems due to the presence of transients is not known. Were this to be known, effective mitigation techniques could be employed to potentially reduce failure rates. There is still a large hole in understanding regarding the frequency and magnitude of events in systems with a great deal of scope for further research.

A vast array of potential transient sources exist, as do the potentially adverse effects on the integrity of distribution systems. Many situations could arise were dynamic pressure events could go unchecked and cause structural and water quality failures. A robust and effective means for identifying the source of transient events could help in reducing the potential for adverse effects associated by identifying the source and adopting mitigation strategies.

2.3 Transient Modelling

With the development of the digital computer in the 1960s, researchers started to develop computational solutions to fluid flows in pipe networks. Since then, continuous improvements in computational power and increased availability, have enabled successive implementation of more complex pipe network solutions and the inclusion of comprehensively modelled operating regimes. These advances have enable researches and practicing engineers, to increase our level of understanding of fluid flows in complex pipe networks, and facilitated greater diligence in the design and operation of new and existing infrastructure.

Better understanding can ensure appropriate sizing of pipe network components for optimised operation while also reducing costs associated with overdesign. Modelling can be useful for analysing the condition of existing networks through comparing field measurements with those predicted by modelling packages, disagreements between the predicted and measured results can be indicative of problems in a network and can point to the location and nature of a problem.

2.3.1 Transient Analysis

The development of digital computation enabled the first models capable of solving complex equations associated with transient problems. Two main approaches have been adopted for computational pressure transient modelling, the Eulerian based, Method of Characteristic (MOC) Chaudhry, (1987); Wylie and Streeter, (1978) and the Lagrangian based, Wave Characteristic Method (WCM) Wood et al., (1966), originally termed the wave plan method Jung et al., (2009). Most software on the market available today incorporates one of these methods. Early models were still hampered by the limited availability of computational power and as such models were simplified to facilitate computational transient solvers. With increased understanding and computational power, we now have a situation where we are able to perform sophisticated transient modelling, numerical models have been developed to incorporate numerous physical factors affecting transient wave propagation Bergant et al., (2008). While modelling software has become increasingly robust, the number of variables in a real distribution system, still means there are shortcomings in models accurate prediction of real transient events. The major advances have helped achieve realistic design loadings and very good approximations, but for more detailed studies, the reliability of physical experimentation is still required.

Ghidaoui et al., (2005) Offers a comprehensive review of the development and understanding of fluid transients and the equations developed to model such phenomenon.

2.3.2 Eulerian – Method of Characteristics

Increased accessibility to personal computers lead to the first models considering the occurrence of pressure transient in water distribution systems. Karney and McInnis, (1990) modelled a simple distribution pipeline using MOC, emphasising the need for comprehensive analysis to fully understand the role of transients in more complex distribution networks. As the precursor to much future work on transient analysis in water systems Karney and McInnis, (1990) modelled transient events in a simple pipe network with improved code for higher efficiency and reduced computational time. These early models showed the potential for computer models to improve design practice and shed light on the effectiveness of mitigation techniques. Validation of the appropriateness of computer models was undertaken by McInnis, (1995). Still employing the MOC approach models were compared to field observation. While the models were able to provide encouraging representations of the magnitude and approximate initial profile of transient waves, beyond the first wave cycle models were lacking.

Further developments in computer modelling using the MOC approach have been concerned with increasing the model complexity to match that of real distribution networks. Improvements have been made by incorporating various physical properties into modelling procedures such as accurate valve and pump operations Filion and Karney, (2002), surge suppression mechanisms, column separation, entrained gas, air pockets, improved turbulence estimation, pipe visco-elasticity Covas et al., (2005), leakage. Bergant et al., (2008), (2003) Address many shortcomings in MOC models to increase robustness and achieve a more comprehensive analysis.

Even by improving model complexity, inaccuracies in steady state models such as lumping multiple demands and ignoring dead ends, considerably influence the outcome of transient models, reducing their ability to provide accurate results. Afshar and Rohani, (2008) Implicit (MOC) model as opposed to conventionally use explicit (MOC) Proposed method allows for any arbitrary combination of devices in the pipeline system.

MOC Modelling has more recently been used for intrusion analysis. With increased concerns over recent years among researchers and water industry professionals about the risks associated with pathogen intrusion from low and negative pressure conditions. Modelling has proved useful in showing areas of networks susceptible to low and negative pressures. Karim et al., (2003).

2.3.3 Lagrangian Method

The Wave Characteristic Method (WCM) initially proposed Wood et al., (1966)was initially termed the Wave Plan Method and provides an intuitive approach to the understanding and modelling of transient wave propagation in pipe systems. The WCM has been shown to be more computationally efficient than MOC due to the fewer number of steps associated with each calculation cycle Wood et al., (2005). The method also generally requires lesser subdivision of pipes thus further reducing the time required to find a solution. Wood, (2005) shows that the accuracy obtained using WCM is highly comparable to that using MOC even though it uses considerably fewer calculations. These comparisons do not compare the two methods in the context of other physical parameters that affect the profile of a transient pressure wave such as those indicated by Bergant et al., (2008).

A comprehensive comparison between the efficiency and accuracy of MOC and WCM was conducted by Ramalingam et al., (2009b). Clarifying previous comparisons and assumptions, the findings showed that the relative efficiency of the WCM is greater than that of the MOC as the MOC requires a far larger number of segments to achieve the same level of accuracy as the WCM. If the same number of segments were used then WCM would be 6 times more accurate than first-order MOC and 3 times more accurate than the second-order MOC. The implications of these findings are reaching, as large numbers of commercial software currently use MOC as the basis of their transient analysis tools.

(Jung, et al., 2007) investigates simplified methods for the design of water distribution networks compared to more rigorous numerical techniques. The aim is to show that simplified design methods could lead to wrongly sized pipes. Simplified pipelines and networks are used to analyse maximum pressures in pipes using water hammer analysis software, these are then compared to the design pressures given by simplified design methods. The results from pipes of different size and wave speed are compared. The research is useful in showing that even newly built real systems could be either under or over engineered regarding the occurrence of pressure transients. The results aren't significantly backed by empirical evidence; hence better understanding of transient occurrence in real systems would further verify the findings.

The major benefit of WCM is that performing numerous computation cycles to optimise design and analysis procedure becomes more viable and adaptive learning algorithms can be used to better design and characterise distribution systems. (Jung, *et al.*, 2009) uses Genetic Algorithm optimisation to establish worst case transient loadings allowing for variation in numerous operational parameters.

A lagrangian model is also adopted by Ferrante et al., (2009) and applied to the problem of leak localisation.

2.3.4 Section Summary

Modelling is a valuable design and analysis tool which can be used to evaluate potentially catastrophic failures without harming distribution networks. Considerable advances have been made in modelling techniques that are advantageous for design development. Modelling still has a number of shortcomings and it is still difficult to accurately model complex networks. In live systems the complexity of modelling is increased due to the large amount of unknown variables.

While a number of software packages still incorporate the MOC method, the higher efficiency of the WCM make it seem a more desirable and versatile approach when considering further developments of transient modelling. If self learning systems are to be implemented the increased speed available through the WCM makes it a more viable approach.

This section has only shown an overview of modelling techniques and neither approach is adopted to develop a procedure for identifying sources of transient events. For complex pipe systems with many uncertainties model development and calibration would possibly be too prohibitive in cost and time for a routine re-deployable source localisation procedure. A more direct, robust solution could possibly be achieved through data acquisition and signal analysis.

2.4 Transient Data Acquisition

Historically, before the advent of the digital computer, the most common method for recording pressures in fluid pipelines over extended periods was with pen and charts. It is now common practice to used digital storage processes. Advances in sensor technology, battery technology, processing power and memory capacity have enabled various parameters to be stored at increasing levels of accuracy. (Friedman, *et al.*, 2005) Compared the use of traditional pen charts and digital data loggers for measuring dynamic pressure data in live distribution networks, in particular low and negative pressure events. The two methods were show to be comparable for recording the same dynamic events although the pen charts were show to record higher values in the case of pressure reductions.

2.4.1 Lab Based

High sample rate pressure data logging has been available for use in the laboratory for some time and various laboratory based studies have explored the mechanisms associated with dynamic pressures in water pipelines Beck et al., (2005); Covas et al., (2004). Stoianov used high frequency data up to 600hz. Using high sample rates for data acquisition increases the information available for signal analysis. Very high sample rates are useful for wavelet analysis where each successive decomposition level halves the number of data points. A number of lab studies have explored burst detection and system characterisation using transients; this is discussed further in the next chapter. (Creasey and Sanderson, 1977) explored pipeline measuring and modelling with simple model.

2.4.2 Field Based

Water Utilities have the ability to record some pressures in distribution systems through supervisory control and data acquisition (SCADA) systems albeit at relatively low frequencies e.g. one sample every 5 minutes Friedman et al., (2005). Due to the short duration of some dynamic events, logging at such low sample frequencies, transient events could easily be missed. A number of studies have used "high speed" data loggers 20 Hz Fleming et al., (2007); Friedman et al., (2005); LeChevallier et al., (2003) (Fleming, *et al.*, 2007, Friedman, et al., 2005, LeChevallier, et al., 2003) for improved observation of transient events in live distribution networks, by current standards a 20 Hz sample rate would not necessarily be considered high. It would seem that a 20 Hz sample frequency is sufficient for visual identification of transient events providing a reasonable representation for the profile of a transient wave. The rate of pressure change associated with a pressure transients can be very high, therefore temporal resolution at 20 Hz may not be adequate to gain sufficient date for effective later analysis.

Recent studies state the ability to record field data at high rates of 500 Hz Misiunas et al., (2005); Stoianov et al., (2007) and 2 KHz Srirangarajan et al., (2010). These abilities to record high speed data are achieved by either logging for short durations or only recording specific events which are relayed to a central server through mobile phone networks. The highest rates of data sampling are generally associated with the development of burst detection methods where localisation of bursts is the primary role. Analysis processes are concerned with identifying transients resulting from burst events and as such smaller transient events are ignored, thus large quantities of data from the sample period are not collected.

A high proportion of recent studies incorporating long term data collection in live distribution systems have been primarily concerned with observing low and negative pressures Friedman et al., (2005); Gullick et al., (2004); Karim et al., (2003), (2000); LeChevallier et al., (2003). The major findings are that low and negative pressures do occur and that the major contributors to these are associated with pumping operations. Gullick et al., (2004) undertook extensively monitored of distribution networks and assessed different operations. 15 low and negative pressure events were detected, 12 as a result of pump start/up shut down and 2 due to the use of high pressure water cannons. 1 more event was detected, the cause of which was unknown. This raises the question; what may have been the trigger for the unknown event, and would it be possible through subsequent analysis of logged data to establish the source of the initial trigger. No specific research is evident in the literature that looked at identifying the source and type of generic transient instigator base on the analysis of logged field data. There is also little research material, if any, employing high speed data logging to make a general assessment of transients of all magnitudes and frequencies, to assess their rates of occurrence and global impact on water distribution networks. This fits with the widely held view that small to medium transient pressures are rapidly attenuated in distribution networks and have little significance. There is no conclusive evidence in the literature to either confirm or disregard these views.

2.4.3 Section Summary

Various Laboratory studies have been performed, primarily using simple pipe loops; very little physical lab data has been measure observing networked system. Current uses of pressure monitoring in distribution systems are primarily concerned with identification of leakage and pipe breaks and there is no reference to identifying potential causes of transients. It is known that other valve operations can cause transient events but there is no current research specifically trying to localise transient sources. It is generally accepted that transients occur in distribution networks but current technology not used for source localisation.

Current field work is generally concerned with the occurrence of negative events and burst localisation. Limited comprehensive field trials have been conducted due to the large data storage requirements and difficulties associated with deploying instrumentation. Srirangarajan et al., (2010) uses wireless systems but reduces data storage by implementing a threshold and only collecting small portions of data. In general data has been sampled at low sample rates and for higher sample rates data is sacrificed. There is no current research recording high sample rate data that has collected all data, and no research looks to locate sources of generic transient triggers.

Only recently has the technology become available to sample data at high rates, relatively recent studies consider 20 Hz as high but Srirangarajan et al., (2010) suggests using higher rates of up to 2Khz based on trials of 600 Hz sampling in lab conditions. There is little or no reference to the use of sample rates in the range 20-500 Hz for acquiring pressure data in live distribution systems.

2.5 Applications of Transient Monitoring

There are a number of past and ongoing studies looking at the use of pressure transients as a means of identifying the location and also size of leaks in single pipelines and in distribution networks. An extremely useful overview of the various methods employed can be found in Colombo et al., (2009). Most methods for leak detection normally fall within one of two main categories, either inverse transient analysis or a signal processing approach.

2.5.1 Inverse transient Analysis

Inverse transient analysis (ITA) is based on an ability to accurately model transient waves, it relies on the predictability of wave propagation in a system, based on known physical properties of that particular system. The underlying principle of ITA being, a model of the network in question is developed which is, within reason, to the highest level of accuracy possible. A transient is initiated at some point in the system and data loggers observe that transient as it propagates through the network. Knowing the input transient source and location, optimisation algorithms are applied to modify parameters in the modelled network such that the outputs compare to those observed at logger locations in the live network. Ferrante et al., (2007).

Colombo et al., (2009). To do this either Nash and Karney, (1999) is used or a genetic algorithm approach is taken. Various methods have been developed where either or both of these approaches have been modified to better suit the specific requirements for leak detection purposes

A large proportion of work on ITA has been largely based on deriving methodologies at a theoretical level. Advances in computational power have enabled a move towards Genetic Algorithm (GA) solvers as opposed to more generic optimisation techniques but even these can still be time consuming. More recent improvements in data capture technologies have increased the viability for performing field experiments but a more recent study Covas and Ramos, (2010) still uses controlled large scale laboratory conditions to simulate a live system. With nearly 20 years development since the instigation of the inverse transient solution Pudar and Liggett, (1992), the limited ability to carry out full scale field experiments highlights the complexity and magnitude of challenges involved. Even now, successful application of the ITA techniques is only achieved on relatively simple and well understood networks. It is suggested that a large number of unknowns within real systems can contribute to providing misleading results as to actual leak locations. The implied solution is to ensure that the system in question has been well characterised by inducing transients in the system and measuring the actual wave speeds from the wave arrival time at different locations in the system. Only large leaks can be detected using ITA over 12l/s and 35l/s in the two systems used for the study Covas and Ramos, (2010). When singularities are identified they can be difficult to differentiate from other physical components in the system.

2.5.2 Signal processing

Analysis of pressure signals in fluid pipelines could be seen as a more direct approach than ITA to the location of leaks in either single pipes or distribution networks. As with the ITA methods signal analysis also has the ability to identify features other than leaks and it can therefore be employed as a method for characterising systems and locating unknown features. Signal processing techniques generally rely on similar fundamental principles; the wave speed in pipes can be ascertained by knowing the physical properties of the pipe and fluid, waves are reflected when they encounter features in a network such as bends, valves, dead ends, leaks. By triggering a transient from a known location and recording the response at some point in that system, it is possible to gain a large amount of information about the system by analysis of the recorded pressure signal. On the other hand, measuring and analysing the pressures at various locations in a system should make it possible to establish the location of transients triggered in the system. The signal processing approach can therefore be considered in two main categories, continuous online monitoring, and a trigger response methodology.

2.5.3 Continuous Monitoring

Continuous monitoring constantly observes the pressure in a system looking for the occurrence of significant events. Although often termed as a leak detection methods, these methods actually look for burst incidents in the system and would be better described as burst location methods/techniques. Misiunas et al., (2005) considers a single pipe line, the basis for the method is that an instigated transient wave will travel in both directions down a pipe. Analysis of the transient signal from a single sensor can establish the moment at which the initial wave front arrives at the sensor and also the reflected wave of the wave which initially travelled in the opposite direction. Knowing the length of the pipe and the wave speed the difference in arrival times between the two signals can be used to establish the location of the initial trigger.

Stoianov et al., (2007) Proposes a wireless sensor network for real time burst detection and location although a simple pipe is analysed in this paper. This work is progressed to trials in a live distribution system in Singapore by Srirangarajan et al., (2010).

2.5.4 Trigger Response

Beck et al., (2005) Shows that cross correlation techniques can be used to determine the location of network features and leaks. A transient source is triggered at the same location as the sensor. The second derivative of the cross correlated filtered signal indicates the location of network features. Signal processing techniques are explored further by Ghazali et al., (2010)

Ferrante et al., (2007) and Stoianov et al., (2001) applied wavelet analysis to signals of transient pressures. A useful overview of various leak detection methods can be found in Colombo et al., (2009).

2.5.5 Section Summary

Much of the research leading to the analysis of field and laboratory data of transient waves is concerned with one of two issues, either characterisation of distribution systems or burst location. No literature discusses the use of data analysis techniques as a means of identifying generic transient sources in a distribution network. A large quantity of work undertaken only considers the analysis of data associated with single pipeline and localised sensor placement. There is large scope for further research into global network sensor placement and subsequent data analysis.

2.6 Graph Theory for Transient analysis

Graph theoretical approaches are not widely adopted for transient pressure problems For example in Oliveira et al., (2011) Graph Theory but it was not adopted for transient analysis but to evaluate burst clusters. Slow valve closures are modelled using a graph theoretical approach Axworthy and Karney, (2000) and Shimada,

(1989) and further application is suggested by Srirangarajan et al., (2010) for considering burst detection. Graph theory could be directly applicable to water distribution networks for numerous applications and particularly for transient analysis situation. This is discussed in further detail in section 4.3.

2.7 Pipe Wave Speeds

The accepted approach for calculating pipe wave speeds is to use the wave speed equation (2.2) Wylie and Streeter, (1985):

$$a = \sqrt{\frac{K / \rho}{1 + (K / E)(D / E)}} \quad (2.2)$$

Where:

K =bulk modulus of the fluid, ρ =density of fluid, E =elastic modulus or Young's modulus of the pipe material, D =internal diameter of the pipe and e =pipe wall thickness

This is the generally use approach and its use is rarely disputed but anomalies occur when viscoelastic pipe materials are considered. Covas et al., (2004) measures wave speed retardation associated with pipe wall viscoelaticity in a HDPE pipe and shows that a dynamic elastic modulus associated with shock loading the pipe material is higher than specified values. The wave speed is also shown to reduce as it propagates along the pipe. Similar observations were made in PVC pipes Alexandre Kepler Soares et al., (2008) although wave speed retardation was found to be less significant. Other empirical measurements are shown in Meniconi et al., (2012).

Other factors change the wave speed in a pipe from those estimated using equation (2.2), such as entrained air Streeter and Wylie, (1973). Other factors including unrestrained pipes and column separation are mentioned Bergant et al., (2008). The assessment the findings is that wave speed can only generally be estimated in real distribution system unless empirical observations of the wave speed are made as in Stephens et al., (2011)

2.8 Wave Arrival Detection

2.8.1 Multi-scale Discrete Wavelet Transform (MSDWT)

The need to establish the arrival times of pressure waves is used frequently in leak detection procedure Ferrante et al., (2008) uses multi-scale and continuous wavelet transform methods. Srirangarajan et al., (2010) Whittle et al., (2011) also uses multi scale Discrete Wavelet Transform (DWT) for identifying the arrival times of pressure waves in live distribution systems. It is suggested that decomposition levels 5, 6 and 7 can be used to detect wave arrival times but temporal resolution available for accurate arrival time detection is reduced so that:

$$D_s^N = \frac{F_s}{2^N} \tag{2.3}$$

Where N is the decomposition level, D_s^N is the effective temporal data frequency at level N and F_s is the sample frequency. The effective frequency D_s^6 and D_s^7 with a F_s of 2 KHz as stipulated in Srirangarajan et al., (2010) is only 31.25Hz and 15.65Hz respectively. This is a considerable reduction in the potential for accurate onset detection as significant portions of temporal information are ignored. A disadvantage of using the DWT as described is the need for high data acquisition sample rates to accommodate the loss of temporal resolution, An advantage of using the Continuous Wavelet Transform CWT over MSDWT approaches is that temporal resolution is preserved across all scales.

The application of many wave arrival estimation methods uses high frequency data acquisition upwards of 500 Hz Whittle et al., (2011) Srirangarajan et al., (2010) the use of high frequency data is often required because the temporal resolution is significantly reduced if for instance MSDWT decomposition is used . Numerous state of the art solutions may therefore sacrifice temporal resolution to adopt specific signal processing techniques. This would generally not be an issue were short term data capture is used and very high sample frequencies can be employed but to if data acquisition is required over extended periods without selectivity then it may be a significant factor.

Another field where temporal detection of signal features is important is in musical signal processing and these could potentially be adapted and used to determine wave arrival times in pressure signals.

2.8.2 Spectral Flux from Short Time Fourier Transform

The Spectral flux detection function Dixon, (2006) and Abdallah and Plumbley, (2003) looks at the change in magnitude between consecutive bins in the n th dimension of the time-frequency representation matrix $X(n,k)$ from a Short Time Fourier Transform (STFT). Where n represents the time index and k is the frequency bin.

$$SF(n) = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} H\left(\left|X\left(n,k\right)\right| - \left|X\left(n-1,k\right)\right|\right) \tag{2.4}$$

Where $(x) = \frac{x+|x|}{2}$, which is the half-wave rectifier function. In many pressure signals the half-wave rectifier function may not be necessary but as some of the acquired data could be negative it was retained. Signals may also be given a zero mean before analysis.

2.8.3 Negative Log Likelihood

Various research studies utilise negative log-likelihood methods for onset detection. Abdallah and Plumbley, (2003) adopts a statistical approach to onset detection based on Independent Component Analysis (ICA). Bello et al., (2005) indentifies various developments of the negative log-likelihood onset detection methods. The NLL method effectively compares the data in two statistical models and the output for the NLL is higher when the two models are less similar. The NLL function is:

$$NLL = l(\mu,\sigma^2,x_1,\ldots,x_n) = -\frac{n}{2}\ln(2\pi) - \frac{n}{2}\ln(\sigma^2) - \frac{1}{2\sigma^2}\sum_{k=1}^{n}(x_k-\mu)^2 \tag{2.5}$$

2.8.4 Section Summary

A wealth of methods exist for wave arrival / onset detection in discrete signal data and a selection are identified here. Many methods are generally applied to high sample frequency data, for example, musical signal processing but a novel application of some of these methods could consider applying them to lower frequency data, for pressure wave front arrival time detection of water pressure signals. A number of advantages can be gained from using wave arrival time detection functions on transient pressure signals. They facilitate the automation of signal analysis procedures and they have the potential to successfully establish the arrival time of a wave front in the noisy data, that could be expected a water distribution system. Work is needed to evaluate and compare the numerous available onset detection methods and also to consider new or alternative methods, which could be applied to water pressure signals.

3 Aims & Objectives

3.1 Aims

The aim was to develop methodology for identifying the source location of significant, problematic transient pressures in water distribution systems, based on the acquisition of high frequency pressure data at multiple locations in the system. A concept was devised based on graph theory, utilising a shortest path algorithm and the estimated transit time of pressure waves in pipe networks.

3.2 Objectives

- Verify the graph theory, source localisation methodology through theoretical evaluation and consider the following.
    - Theoretically assess the localisation procedure for various network configurations with increasing levels of complexity.
    - Assess the effects of uncertainties in the system and in data analysis on successfully identifying the source location.
    - Establish methods for determining placement locations and quantities of pressure data loggers required.
- Develop a physical laboratory test pipe to verify the source localisation methodology and the procedures involved. Achievable through the following:
    - Generate transient pressures in different test pipe configurations and synchronously acquire data at multiple locations in the system.
    - Characterise the wave speeds in the experimental pipe system.
    - Exploring wave arrival time estimation procedures on data acquired at different sample frequencies.
    - Apply and verify the source localisation procedure on data acquired from the test pipe using the developed wave arrival time estimation methods.

- Validate the source localisation procedure and all the concepts involved using physically acquired data from a real distribution system by undertaking the following:
    - Identify a suitable experimental test site in part of a real water distribution system
    - Deploy multiple synchronised data loggers at optimal locations in the experimental test system and once deployed generate transient pressure at different locations in the system
    - Analyse the pressure data from field experiments by using the procedures developed and verified at earlier stages, by conceptually and physical modelling.

4 Conceptual Design and Methodology

4.1 Concept Definition

The literature confirms the existence of transient pressures in potable water distribution systems and presents significant concerns regarding the integrity and safety of such systems as a result of transient pressure events. Many possible causes of transients have been identified and while the true scale and impact of transients in water distribution systems has not been fully understood a wealth of evidence suggests that they do pose considerable cause for concern. In some distribution systems once a problematic transient has been identified the source of the event may be obvious for instance by linking transients with pump operating schedules. However, for many systems, a situation can arise where problematic transients do occur without an immediately apparent source location. For example, a system could contain multiple control devices and/or multiple varying large (industrial) demands, all having the potential to generate a significant transient event.

A generic, robust procedure for identifying the source of a transient has not previously been established. Such a procedure could aid in the efficient management of potable water distributions systems. By identifying the source of problematic transients, mitigation strategies can be employed to reduce their adverse affects. This could lead to reduced burst and leakage rates, reducing the potential for contaminant intrusion LeChevallier et al., (2003) and providing greater understanding of the nature and frequency and occurrence of transients in these systems.

This chapter primarily describes the conceptual development of a novel transient source localisation procedure based on the understanding that transient pressure wave fronts travel independently along fluid filled pipelines and arrive at various locations in a network at different times dependant on varying propagation paths and pipe wave speeds. A graph theoretical approach is adopted as the basis of a method of identifying the most likely area in a network for a transient source. Processes and practicalities associated with the source localisation procedure such as data analysis and the placement of data acquisition hardware are also addressed.

The first part of the chapter considers a transient source localisation framework, evaluating the needs for source localisation and establishing potential signs that problematic transients are present.

4.1.1 Source localisation Framework

The ultimate goal was to identify the location of a transient source in a real water distribution network and to do this a suitable methodology needed to be established, prior to this step a number of other considerations needed to be taken into account. Primarily, the requirement to deploy a source localisation procedure needed to be ascertained. Assessing the need for source localisation could be achieved either proactively or reactively, which in broad terms could be achieve respectively by intentionally looking for transient events or responding to the potential consequences of a transient event Hampson et al., (2011). Table 4-2 identifies some proactive and reactive approaches.

Table 4-1 Proactive Transient Identification

Indicator	Justification
Routine monitoring	An effective proactive approach could be routine monitoring of high frequency pressure data to observe transients occurring in the system. While it is technologically feasible to permanently monitor pressures at specific locations throughout a whole distribution system, economic constraints and data handling requirements could make it prohibitive to monitor entire distribution systems. Selective monitoring at optimal locations of what are deemed to be high risk systems could be adopted to make this approach more feasible. A routine monitoring program could be adopted where a single or small number of high frequency data loggers are systematically deployed at every District Metered Area (DMA) for one or two weeks at a time. Once again high risk areas could be given priority.
Asset Assessment	Many control devices, particularly if operating ineffectively or having deteriorated over time, have the potential to cause transients. Routine monitoring of high risk devices could be implemented to ensure they are operating correctly and not causing transients.

Table 4-2 Reactive Transient Identification

Indicator	Justification
Pipe Burst	Pipe Failure Mode: The occurrence of longitudinal cracks in pipes are generally attributed to excess hoop stress caused by internal pressure. Not ruling out excessive pipe degradation which in itself could also be attributed to excess or frequent dynamic loading, if a system is only subjected to small changes in steady state pressures other than expected diurnal fluctuations then a longitudinal crack could signify excess pressures associated with a transient event. Failure Frequency: Pipe bursts and leakage is accepted as part of the routine operation of aging water distribution systems and increased failure rates in areas of some networks are common for many reasons such as high ground loadings, seasonal ground movement, pipe degradation. If sudden changes occur in pipe failure rates specifically if seemingly unrelated to other causal factors this could be an indicator or a persistent transient.
Water Quality	Water quality failures are a potential indicator of transient events. With evidence suggesting that transients have the potential to cause contaminant ingress then bacteriological failures could signify a transient. As water companies reduce system pressures to reduce leakage this could exacerbate the problem. Areas of a system with lowest pressures should be more susceptible to this problem. Although not fully substantiated transients could potentially remove materials accumulated at the pipe walls leading to discoloration events.
Customer Complaints	Customer complaints are a potential means of realising pipe burst and water quality failures and hence could be an indicator of transient events. They may also be able to directly identify physical characteristics of a significant transient such as fluctuation pressures, and movement or noise coming from pipes.

Whatever the means of disclosing the occurrence of a significant transient, the conventional practice for confirming the existence of transients is to monitor system pressures for a given period of time using suitable data acquisition hardware. Suitable implies that the hardware:

- Is robust and able to withstand the environmental conditions that it will be subjected to while in operation,
- has a high enough sample frequency as to be able to observe a transient event,
- has adequate memory to capture all the required data.

The monitoring time period could vary depending on the system and the particular problem but as a rule of thumb, one to two full weeks observation period should be sufficient. This length of observation period specified as this should generally be sufficient to observe routine operations which may occur hourly, daily or weekly. This period also allows for a manageable dataset to be acquired. If longer observation periods are deemed necessary then redeployment of loggers at routine interval could be adopted. Data acquisition hardware is discussed further in chapter 7. At this stage it could be feasible to deploy a single pressure logger, although the deployment of multiple loggers could improve the ability to confirm the existence of a transient event.

Once a problematic transient has been identified in a system an assessment of known potential sources should be made to try and establish the source location and discern whether a source localisation approach needs to be implemented. As already stated the operating schedule of system assets may correspond to the times of transient pressure events, therefore determining the source. If no obvious cause can be ascertained then a source localisation procedure should be applied.

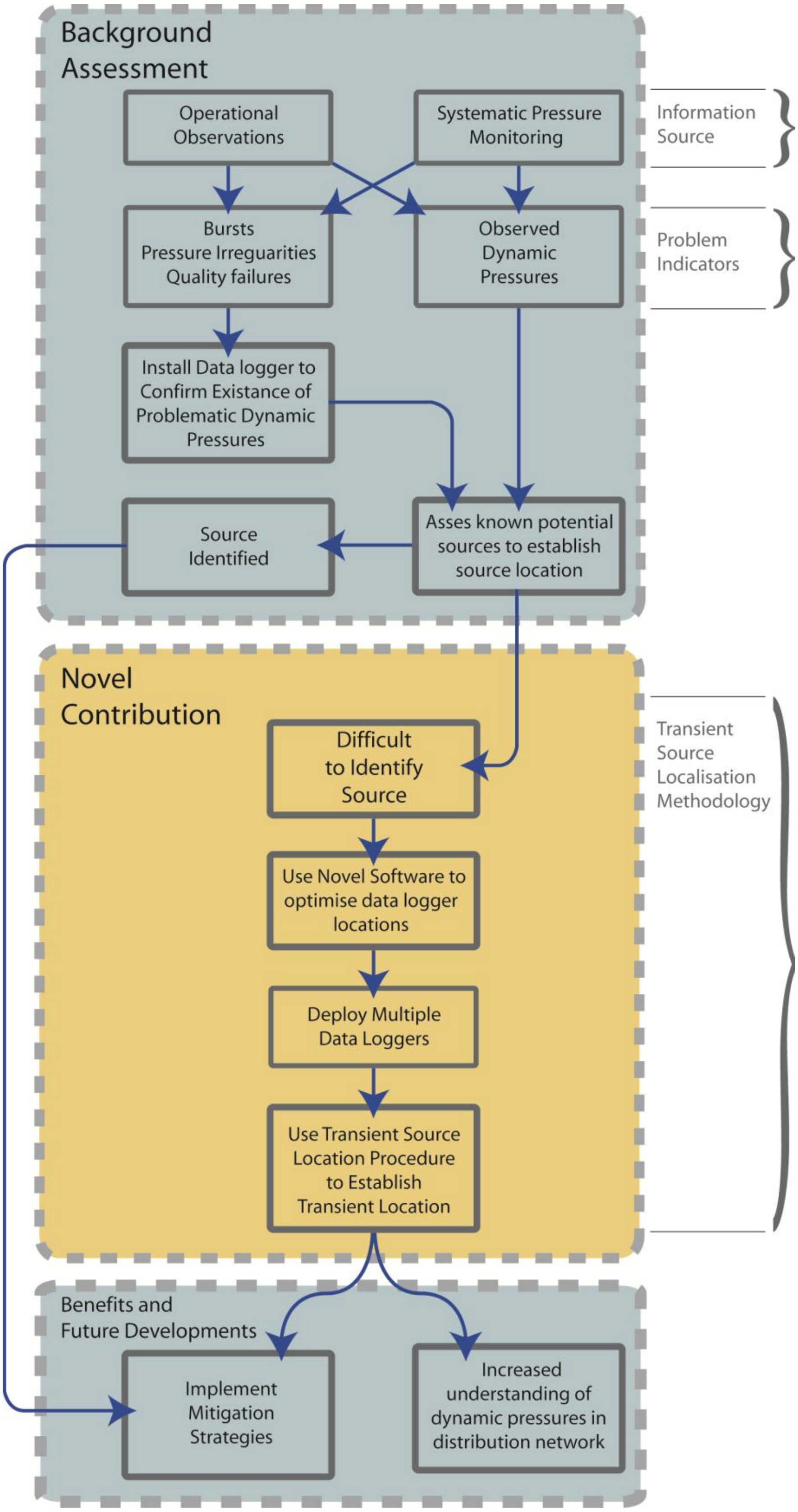


Figure 4-1 Source Localisation Framework Schematic

A schematic of the framework for generic transient source localisation is shown in Figure 4-1. Three main areas of the procedure are identified.

1. Look for probable signs of transient events and confirm the existence of transient events.
2. Deploy transient source localisation methodology and perform analysis to identify the source.
3. Adopt transient mitigation strategies if required.

Developing, verifying and validating the methodology for item 2 forms the basis for much of the work in this thesis. The drivers are to develop a novel, practicable and robust approach to locating undisclosed transient sources by developing and applying state of the art technologies.

4.2 Source localisation Fundamentals

This section outlines some fundamentals for locating the source of a pressure wave in water pipe networks using know pipe parameters and temporally synchronised pressure data. Locating a wave source in a single pipe is initially considered; this understanding is then extended to incorporate a full network and then developed to show how graph theory can be used to provide a practicable solution.

4.2.1 Single pipeline

By estimating the wave speed in a pipe and knowing or estimating the pipe length, then placing two pressure sensors either side of a transient source the source location can be determined for a situation as shown in Figure 4-2 from the difference in arrival times at the two locations.

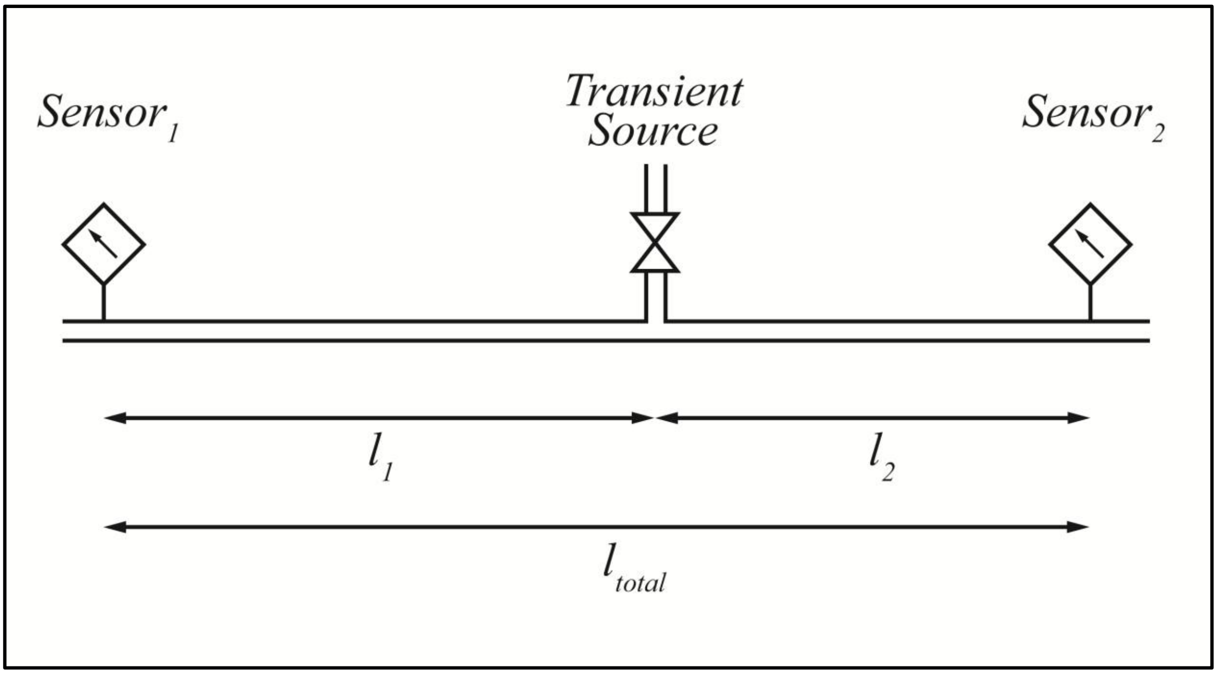


Figure 4-2 Single pipe source location schematic

Figure 4-2 shows a simple pipeline with a transient source situated between two sensors where l_{total} is known but the specific location of the transient source along the pipe, hence l_1 and l_2 are not known. If the wave propagation speed in the pipe is a and a transient is triggered at time t_0 the primary wave front will be observed at *sensor₁ and sensor₂* respectively, at times:

$$t_{s1} = t_0 + \frac{l_1}{c} \tag{4.1}$$

And

$$t_{s2} = t_0 + \frac{l_2}{c} \tag{4.2}$$

The difference in arrival times between sensor 1, s_1 and sensor 2 s_2 is denoted by $\tau_{s1,s2}$ which is given by:

$$\tau_{s1,s2} = t_1 - t_2 \tag{4.3}$$

Therefore

$$\tau_{s1,s2} = \left(t_0 + \frac{l_1}{a}\right) - \left(t_0 + \frac{l_2}{a}\right) \tag{4.4}$$

$$\Rightarrow \tau_{s1,s2} = \frac{1}{a}\left(l_1 - l_2\right) \tag{4.5}$$

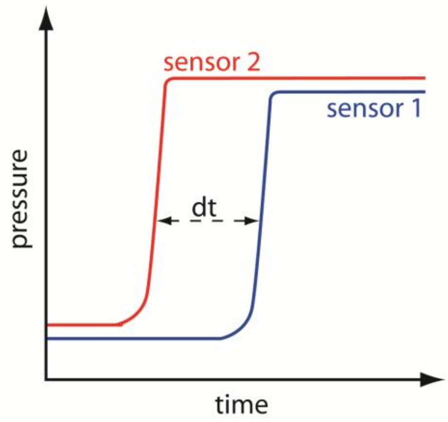


Figure 4-3 Schematic of wave front arrival time difference

By comparing recorded system pressures at the two sensors, a difference in arrival time of the primary wave front maybe apparent as described in Figure 4-3. $\tau_{s1,s2}$ can be measured from this difference in the primary wave front arrival times at each sensor and l_1 is given by:

$$l_2 = l_{total} - l_1 \tag{4.6}$$

Combining (4.5) and (4.6) and rearranging gives:

$$l_1 = \left(a.\tau_{s1,s2} - l_{total}\right)/2 \tag{4.7}$$

Similarly:

$$l_2 = \left(l_{total} - a.\tau_{s1,s2}\right)/2 \tag{4.8}$$

Therefore with the ability to accurately determine the arrival time of a transient pressure primary wave at a pair of time-synchronised pressure sensors it is possible to establish the location of a transient source along the pipe.

If the pipe connecting the transit source to the main pipe is extended, this will not change the localisation result. The source will still only be localised to the junction where the pipe joins the main pipe because this is the location where the primary wave front diverges.

If the transient source is not located between the two sensors but to either side of one of the sensors then in and ideal case where wave speeds and arrival times are known exactly, $l_{total} = a.\tau_{s1,s2}$ and the localisation result will indicate that the source is at or beyond the sensor with the first arrival time. This result provides an early indication as to the optimal placement of sensors. Suggesting that provided the sensors are place at the extremities of the pipe so that the source is between the two sensors then the localisation result will be valid.

4.2.2 Network Source Localisation

Locating transients on a single pipeline may be suitable for transmission pipes, where limited, know system assets may readily lead to an obvious solution without the need for a specific source localisation procedure. More complex situation arises in distribution systems where multiple branch/loop configurations exist with multiple potential transient sources, providing the requirement for a network based generic transient source localisation procedure.

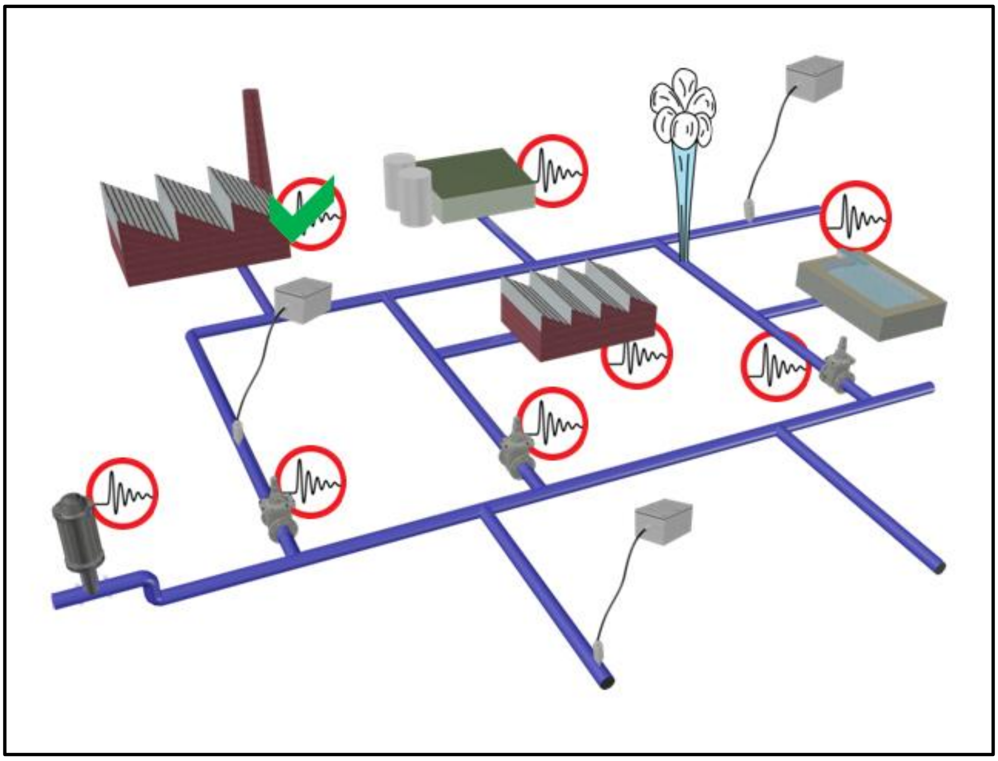


Figure 4-4 Schematic of network with multiple potential transient sources

The above problem is represented by the schematic in Figure 4-4, which shows multiple demands and system assets which are all potential transient sources. The tick represents the location of a single problematic source, although there is no reason why multiple problematic sources at different locations could not exist.

It is a priori that the primary wave front from a transient source will arrive at all connected locations in a water network having travelled there by the shortest temporal path. Therefore, if the source localisation procedure described for a single pipeline can be adapted to a network situation it should be possible to identify a source location in a network. It is possible to locate the origin of a wave/signal in a two-dimensional plane by analysing the difference in wave arrival times at multiple locations and adopting a procedure known as multilateration. Based on this understanding, although differences apply, it was logical to conclude that by applying similar principles it could be possible to locate the source of a pressure signal within the constraints of a one dimensional pipe network.

For the network case the fundamental difference lies in that the propagation of the wave fronts are restricted to the pipe network so the geographical location of the sensors and the source have limited significance and wave propagation need only be considered within the restraints of the pipe network. Wave propagation speeds can vary depending on pipe and fluid parameters, fortunately, as long as the relevant pipe properties are known, wave speeds can be estimated by using equation (2.2).

4.3 Graph Theory - Water Pipe Network Representation

4.3.1 Justification for graph theoretical approach

Considering a network of pipes as a series of nodes which represent pipe intersections and terminations, and the pipes as connections between these nodes, provides an intuitive and efficient means for the computational representation of the water distribution network configuration and pipeline parameters. This method of representation is directly compatible with a graph theory approach. Although previous research has used graph theory for water distribution problems the use has been limited for transient related problems Axworthy and Karney, (2000b) and Shimada, (1989), which both considered slow transient activity.

Graph theory is a suitable approach for transient source localisation problems because the requirement is to only consider the transit times of the primary wave fronts. Just considering the primary wave front helps to simplify the problem and has distinct advantages. If branches and service connections are omitted from a model, provided they do not alter the transit times of the primary front then it should not considerably alter the solution. This means models can be simplified by intentionally omitting connections which would not change the result. A wealth of tools exist for determining travel times of single entities in graphs and these are directly applicable to this problem. While considering secondary fronts and reflections may have advantages the increased uncertainties (which would be likely), would increase the need for a greater understanding of the system and would tend to lead more towards a deterministic solution.

At junctions and intersections wave fronts are transmitted, reflected and absorbed according to the intersection characteristics. Subsidiary wave fronts generated at these intersections may also be considered to travel independently along their respective paths. This view of transient pressure wave propagation is consistent with the Wave Characteristic Method Ramalingam et al., (2009a) one of a number of methods developed to solve transient pressure wave propagation problems in complex pipe networks. It is also this view that makes graph theoretical representation suitable for certain transient pressure wave front propagation problems. A graph theoretical approach is considered because as expressed in Ramalingam et al., (2009a) there are still many shortcomings in conventional transient analysis procedures in complex pipe networks.

Graph Theory has developed a wealth of algorithmic tools to efficiently search through graphs and to calculate the propagation of entities from vertex to vertex in a graph. For some situations water distribution systems are ideally suited for graph theory representation with pipes and junctions being directly represented as vertices and edges respectively. For example in Oliveira et al., (2011) Graph Theory is used to statistically identify clusters of pipe failures in a water distribution system and Axworthy and Karney, (2000) uses a graph theoretical approach to model transients associated with slow valve closures in a relatively simple network. It is the high efficiency and direct applicability of some graph theoretical tools that make them suited to transient wave propagation problems. Use of graph theory for wave propagation problems requires an understanding of the pipe wave speed.

4.3.2 Network Representation

A graph is conventionally described by the doublet $G = (N, A)$ where N defines a set of vertices, $N = (n_1, n_2, n_3, ...n_n)$ and A is an *adjacency* matrix defining how the vertices in N are connected Christofides, (1975). For this application we considered the vertices to be situated on a two dimensional plane and will generally refer to them as nodes, the location of each node is specified by Cartesian coordinates (x_n, y_n) this information is stored in N. The connections between nodes defined by A are generally referred to as arcs but for this application arcs represent water pipes. It is possible to weight the adjacency matrix so that each arc holds a certain value, this is useful as the wave transit time and hence celerity a needs to be known for each pipe. To populate A a pipe properties matrix P was provisionally defined which stored all adjacent nodes and also the characteristics of the connecting pipes required to calculate a, these being, internal pipe diameter, wall thickness and Young's modulus (material). Using the data in the pipe array the celerity c could be calculated for each pipe and also stored in the pipe array. The wave transit time along each pipe was calculated based on the pipe length and pipe celerity. An example of P is shown in Table 4-3.

Table 4-3 Example of the pipe properties matrix

node 1	node 2	Diameter (D)	Wall thickness (e)	Young's Modulus (E)	Wave Speed (a)	Transit Time ($t_{n1,n2}$)
-	-	-	-	-		

The pipe length was simply calculated using Pythagoras' Theorem using the adjacent node co-ordinates in N .

$$l_{n1,n2} = \sqrt{(x_{ni} - x_{nj})^2 + (y_{ni} - y_{nj})^2} \tag{4.9}$$

Pipe curvature was therefore not directly accounted for but curved pipes could be approximated by using a number of straight pipe sections. This approximation should not generally prove to be detrimental for real pipe systems where stored geo data is generally only an approximation to the actual pipe locations.

For the purpose of this application the graph representation needs to be non-directional indicating that a transient wave can travel in either direction along a pipe. This could be achieved by ensuring that the adjacency matrix A was symmetrical about the diagonal and that all values of t_{n_i,n_j} are positive. This means that for every pair of adjacent nodes $\left(n_i, n_j\right)$ a path exists $n_i \rightarrow n_j$ and $n_j \rightarrow n_i$.

4.3.2.1 Simple Network Example

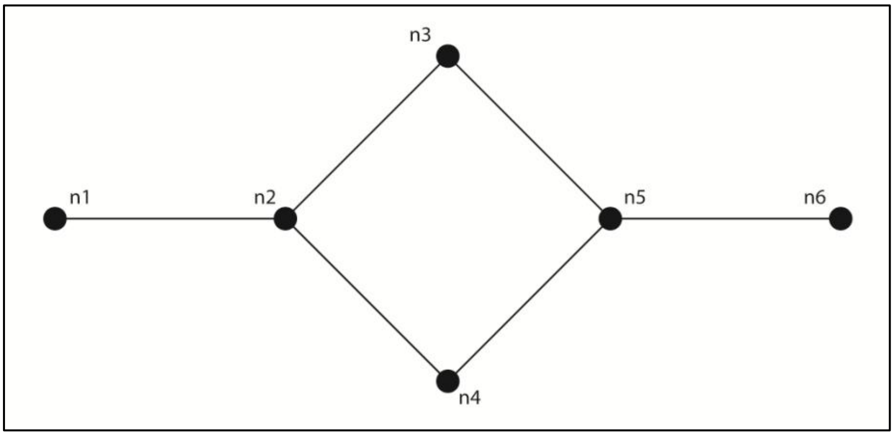


Figure 4-5 Simple Network Graph

The nodes matrix N defining the location of the nodes in Figure 4-5 is:

$$N = \begin{matrix} & x_n & y_n \\ n_1 & x_1 & y_1 \\ n_2 & x_2 & y_2 \\ n_3 & x_3 & y_3 \\ n_4 & x_4 & y_4 \\ n_5 & x_5 & y_5 \\ n_6 & x_6 & y_6 \end{matrix} \qquad (4.10)$$

The pipes matrix P defining the adjacent nodes to each pipe in Figure 4-5 is:

$$P = \begin{matrix} & n_i & n_j & D & e & E & a & t_{n_i,n_j} \\ p_1 & n_1 & n_2 & \ldots & \ldots & \ldots & \ldots & \ldots \\ p_2 & n_2 & n_3 & \ldots & \ldots & \ldots & \ldots & \ldots \\ p_3 & n_2 & n_4 & \ldots & \ldots & \ldots & \ldots & \ldots \\ p_4 & n_3 & n_5 & \ldots & \ldots & \ldots & \ldots & \ldots \\ p_5 & n_4 & n_5 & \ldots & \ldots & \ldots & \ldots & \ldots \\ p_6 & n_5 & n_6 & \ldots & \ldots & \ldots & \ldots & \ldots \end{matrix} \qquad (4.11)$$

The Adjacency Matrix A for the Graph shown in Figure 4-5 is:

$$A = \begin{matrix} & n_1 & n_2 & n_3 & n_4 & n_5 & n_6 \\ n_1 & 0 & t_{n2,n1} & 0 & 0 & 0 & 0 \\ n_2 & t_{n1,n2} & 0 & t_{n3,n2} & t_{n4,n2} & 0 & 0 \\ n_3 & 0 & t_{n2,n3} & 0 & 0 & t_{n5,n3} & 0 \\ n_4 & 0 & t_{n2n4} & 0 & 0 & 0 & 0 \\ n_5 & 0 & 0 & t_{n3,n5} & 0 & 0 & t_{n6,n5} \\ n_6 & 0 & 0 & 0 & 0 & t_{n5,n6} & 0 \end{matrix} \qquad (4.12)$$

4.3.2.2 Discretisation Granularity

Referring to the above example it is clear that a location in a network could only be defined as a node location or a pipe. There is no facility to specify a location part way along a pipe which limits the possibilities for specifying source locations to pipe ends or nodes. This problem was overcome by interpolating between adjacent nodes and spacing extra nodes along each pipe. Pipes were then subdivided by connecting the adjacent extra nodes along the pipe length. The length of the subdivided pipe sections represents the granularity or grains size of the model, with smaller pipe lengths providing a smaller grain size. The length of the subdivisions was specified globally to provide a consistent grains size throughout the model. Performing this task had a number of advantages; the model implementation could use a large grains size with relatively sparsely located node locations. This meant, for long pipes every possible service connection did not need to be accounted for, as reasonable approximations could be gained by increasing the grain size.

Increasing the granularity of the model does have its disadvantages such as; increased physical memory storage requirements and increased calculation times for processes performed on the model. Grain size could therefore be increased incrementally for successive calculations until the required level of accuracy was gained.

4.3.3 Shortest path between nodes

It has been previously stated that a transient will be first observed at any location in a network having travelled there by the shortest temporal path (which is an obvious conclusion). The term temporal path is emphasised here because a network could be constructed from pipes of different size and/or material type meaning the shortest path by distance may not necessarily have the fastest transit time between two locations. To clarify, it is accepted that components of the initial wave may arrive at locations in the network having travelled via alternative paths but the initial observation can only be by the shortest temporal path.

Fortunately as wealth of graph theoretical tools exist for determining the shortest path between two points in a graph and these are directly applicable to the source localisation methodology being discussed. A commonly used approach to determine shortest paths between a source and all other vertices 'single source shortest path' is the Dijkstra's algorithm Dijkstra, (1959). For this application an 'all pairs shortest path' approach is required. A suitable all pairs shortest path method is Johnson's algorithm Johnson, (1977) although this particular approach accounts for negative edge weights which is not necessarily required for this particular application. By using Dijkstra's algorithm and applying this to all nodes then an all pairs solution can be achieved. Although not a necessary step the inclusion of a priority queue may help to reduce processing time and improve the efficiency of the algorithm.

The output of the 'all pairs shortest path' algorithm is an n by s matrix T where the value stored in the cell (n_i, s_j) is the travel time between n_i and s_j. The node nomenclature for the row header has been changed from an n to an s for the clarity of the next section where s defines sensor locations. Applying Dijkstra's algorithm does not directly provide an undirected solution but adding the transpose of the shortest path solution does provide an undirected solution. A generic example of the shortest path solution is shown below in equation (4.13):

$$T = sensors \begin{array}{cccccc} & & & sources & & \\ & n_1 & n_2 & n_3 & \ldots & n_n \\ s_1 & 0 & t_{n_2 s_1} & t_{n_3 s_1} & \ldots & t_{n_n s_1} \\ s_2 & t_{n_1 s_2} & 0 & t_{n_2 s_2} & \ldots & t_{n_n s_2} \\ s_3 & t_{n_1 s_3} & t_{n_2 s_3} & 0 & \ldots & t_{n_n s_3} \\ \ldots & \ldots & \ldots & \ldots & 0 & \ldots \\ s_n & t_{n_1 s_n} & t_{n_2 s_n} & t_{n_3 s_n} & \ldots & 0 \end{array} \quad (4.13)$$

For the shortest path solution, provided there is a viable path between all nodes in a graph then every cell in a shortest path matrix will be populated apart from the diagonal which is populated with zeros.

It should be noted that for the purpose of the method the transit times in the shortest path matrix represent the travel time between all possible sources denoted by the column header and each possible sensor location denoted by the row header.

4.3.4 Source Location from Wave Arrival Time Difference

The method outlined here relies on the comparison of the data from two models, a theoretical model developed as above, (using graph theory and the estimated wave transit times between all nodes in the network) and a second model, which can be either from the 'real' distribution system, a laboratory based physical model or for the purpose of design verification, another theoretical model.

The difference in the initial wave arrival time at different sensor locations between the two models provides information pertaining to the location of a transient source within a distribution network. If a reasonable approximation to wave transit times in the real network is obtained in the theoretical model then the arrival time differences at the specified sensor locations between the modelled data and the acquired data should be the same for the true source location. A caveat exists in that situations could occur where the values are the same or similar for a false or incorrect source location providing an incorrect or ambiguous result, this will be discussed in section 4.3.4.2.

4.3.4.1 Single Sensor Pair and Likeliness Vector

If a pair of sensors is considered s_i and s_j, the theoretical arrival time difference at the sensor from every node in the network and hence every possible source location can be calculated by subtracting row s_i from row s_j from the shortest path matrix T creating the vector T_{s_i,s_j} so that:

$$\mathrm{T}_{s_i,s_j} = T_{s_i 1}^{\;n} - T_{s_j 1}^{\;n} \tag{4.14}$$

An example of T is:

$$\mathrm{T}_{s_i s_j} = \begin{array}{cccccc} & n_1 & n_2 & n_3 & \dots & n_n \\ \tau_{s_i s_j} & \tau_{s_i s_j n_1} & \tau_{s_i s_j n_2} & \tau_{s_i s_j n_3} & \dots & \tau_{s_i s_j n_n} \end{array} \tag{4.15}$$

The arrival time difference at the same pair of sensors in the real system can simply be found by subtracting the arrival time at one from the other to give the time difference τ :

$$\tau_{s_i,s_j\,observed} = t_{s_i\,observed} - t_{s_j\,observed} \tag{4.16}$$

In an ideal situation where T_{s_i,s_j} can be accurately and confidently calculated the source S is given by finding the value of T_{s_i,s_j} which is closest to or equal to the value of τ_{s_i,s_j}. A vector, which will be called the Likeliness vector (L) can be defined as:

$$L = \mathrm{T}_{s_i,s_j} - \tau_{s_i,s_j} \tag{4.17}$$

The likeliness that a source is situated at a particular location is provided where $L_i \rightarrow 0$, hence the closer a value in L is to zero the more likely it is the transient source location.

4.3.4.2 Multiple Sensor Pairs

If increasingly complex networks were to be considered then it would not be feasible to obtain a satisfactory localisation result by only using the outcome from a single pair of sensors. Particularly where loops existed in a network the increased numbers of possible paths could potentially provide incorrect or ambiguous results. It was therefore necessary to establish a means by which the results from multiple sensors could be considered. Directly comparing the arrival times at more than two sensors was not feasible or desirable but obtaining the results from multiple sensor pairs and combing these to create a localisation result was achievable.

If more than two sensors are used then we can use all possible sensor pairs for source localisation. Where s_n is the number of sensors the number of possible pairings s_{pairs} is given by:

$$s_{pairs} = \sum_{i=1}^{s_n - 1} (s_n - i) \tag{4.18}$$

For example if four sensors are used then there are six possible pairings.

T now becomes a matrix where the columns still represent the potential source location and the rows provide $\tau_{s_i s_j}$ for each sensor pair for example:

$$\begin{array}{cccccccc} & & & n_1 & n_2 & n_3 & \dots & n_n \\ & & \tau_{s_1 s_2} & \tau_{s_1 s_2 n_1} & \tau_{s_1 s_2 n_2} & \tau_{s_1 s_2 n_3} & \dots & \tau_{s_1 s_2 n_n} \\ \mathrm{T}_{s_n} & = & \tau_{s_1 s_3} & \tau_{s_1 s_3 n_1} & \tau_{s_1 s_3 n_2} & \tau_{s_1 s_3 n_3} & \dots & \tau_{s_1 s_3 n_n} \\ & & \dots & \dots & \dots & \dots & \dots & \dots \\ & & \tau_{s_{n-1} s_n} & \tau_{s_{n-1} s_n n_1} & \tau_{s_{n-1} s_n n_2} & \tau_{s_{n-1} s_n n_3} & \dots & \tau_{s_{n-1} s_n n_n} \end{array} \tag{4.19}$$

For every possible source location there are s_{pairs} localisation results where ideally at the true source location all the values in the column vector n_{source} should be close to zero.

4.3.5 Source Location Likeliness from Multiple Sensor Pairs

Given that s_{pairs} results are given in each column in T_{s_n} it was desirable to combine the values in each column to provide a single value to generate a single Likeliness vector. In a real system it is unlikely that all the results corresponding to the source location will be exactly zero so a method needed to be establishing to show which nodes had the most results closest to zero. Three methods were identified and evaluated for achieving this.

4.3.5.1 Absolute of the mean

Taking the mean of the results was one method for establishing how close the data in the column n_i were to zero. The absolute value of the mean was used so that the result could be minimised.

$$L = \frac{1}{n}\left|\sum_{k=1}^{n} \tau_{s_i s_j n_k}\right| \tag{4.20}$$

4.3.5.2 Root Mean Squared

Because results T_{s_n} were positive and negative the RMS value was useful for determining a magnitude of the values in column n_i.

$$L = \sqrt{\frac{1}{n}\sum_{k=1}^{n} (\tau_{s_i s_j n_k}{}^2)} \tag{4.21}$$

4.3.5.3 Negative log likelihood

The negative log-likelihood of a dataset is a means of comparing the fit of the data to the mean (μ) and the variance (σ^2) of a particular statistical model or Probability Density Function (PDF). On its own, the negative log likelihood of a data set does not mean very much but its value is a measure of how well different sets of data fit a particular statistical model. The normal log-likelihood function is:

$$L = l(\mu, \sigma^2, x_1, ..., x_n) = -\frac{n}{2}\ln(2\pi) - \frac{n}{2}\ln(\sigma^2) - \frac{1}{2\sigma^2}\sum_{k=1}^{n} (\tau_{s_i s_j n_k} - \mu)^2 \tag{4.22}$$

The value for the normal log-likelihood is negative so the negative of the value is taken allowing the results to be minimised. The smaller the value for the negative log-likelihood the closer the data fits the model.

This method is suited to this problem because we are already informed about one of the parameters, μ. Ideally for the correct source location all the values should be zero therefore μ is taken to be 0. This somewhat trivialises the use of μ but for completeness it is still considered. The variance σ^2 is also somewhat arbitrary but tuning the value allowed for the results to be modified to help refine the results sensitivity. This is explored in the next chapter.

4.4 Network uncertainties

In any distribution network the exact properties of the pipe materials may not be known. In general, water companies will have records for the material and dimensions for all or at least most of the pipes in its systems but dimensions may not be specific, for instance, only recording a pipe's material and diameter, leaving approximations to the true diameter and wall thickness to be inferred from pipe property tables. The Young's modulus of the material will also have to be inferred from the literature and these may vary from the actual pipes in the ground, particularly for older pipes where manufacturing techniques were inconsistent. It is of considerable concern that large uncertainties exist in the properties of newer viscoelastic pipe materials such as PVC MDPE and HDPE where specified values for E can vary significantly. This is compounded further by wave speed retardation in viscoelastic pipes and the fact that specified values of E may not provide appropriate wave speeds. A greater understanding of the wave speeds in visco-elastic pipe materials still needs to be gained.

Uncertainties may exist for the actual network configuration this includes the existence of unknown pipes and whether valves are open or closed. While some of these issues are addressed later on, alternative methodologies may need to be adopted to establish the true configuration of a network.

One means of establishing approximations to pipe celerites is to directly measure wave transit times by intentionally triggering and observing a transient at one location and synchronously observing it at other locations. This approach could help achieve reasonable wave speed approximations but for complex systems it could prohibitive to carry this procedure out for each pipe.

If estimated wave speeds are to be used base on pipe parameters, an advantage of the efficiency of a graph theoretical approach is that network attributes can be readily changed and successive calculations performed for many possible variations. This allows the rapid assessment of the predicted source location for various sets of pipe parameters.

Without an extensively calibrated network model uncertainties will always exist and should be accounted for or accepted in the localisation result. This is explored further in chapter 5.

4.5 Sensor Deployment Locations

The localisation method outlined above will involve the deployment of data acquisition hardware (pressure loggers) in a live distribution. The most common means of achieving this is by connecting pressure loggers to hydrant caps via quick release fittings as in Figure 4-6.

Figure 4-6 Data Logger Connected to a Hydrant cap

Populating the entire network, with pressure loggers at every hydrant location would provide accurate results, but the number of loggers required and the time required to deploy them would make this prohibitive and unnecessary. The goal is therefore to minimise the number of pressure loggers required to achieve a practicable level of accuracy, by deploying an optimal number of loggers at optimal locations in the system. If a quantity of loggers s_l is placed in a network containing n_H hydrant locations then the number of possible logger configurations is given by:

$$\sum_{p=1}^{n_H-(s_l+1)} \dots \sum_{k=1}^{n_H-3} \sum_{j=1}^{n_H-2} \sum_{i=1}^{n_H-1} i, j, k, \dots p \tag{4.23}$$

For example, if a network has 40 possible sensor locations and the aim is to deploy 6 sensors, the number of possible sensor configuration is 3,838,380. While the adopted graph theoretical approach is relatively efficient, to evaluate every possible sensor configuration for this number of sensors would still prohibitive even for relatively small networks.

The source localisation method only compares the wave arrival times for sensor pairs, hence a more a suitable approach is to evaluate optimal locations for sensor pairs. If sensor pairs are used then for the same number of possible sensor locations there would be 780 different logger placement configurations, this is more feasible but still potentially prohibitive.

Alternative approaches to evaluate the optimal locations of a set of sensors is achieved by considering two different approaches with the aim to evaluate the uniqueness of the number of paths to a sensor location.

4.5.1 Time Difference Shannon Entropy Sensor Placement

When the estimated arrival time difference at a pair of sensors is the same or similar to a node which is not the actual source location and which is located in a different area of the network, ambiguities could occur in a source localisation result. Therefore, the objective is to find the sensor locations which when paired with any other sensor provide the least number of ambiguous results. Taking a single sensor location the arrival time differences for every possible source location for every possible sensor pair can be estimated. For example the arrival time differences between the first possible sensor pair and all possible source locations is calculated as in equation (4.15) giving equation (4.23).

$$T_{s_1 s_2} = \begin{matrix} & n_1 & n_2 & n_3 & \ldots & n_n \\ \tau_{s_1 s_2} & \tau_{s_1 s_2 n_1} & \tau_{s_1 s_2 n_2} & \tau_{s_1 s_2 n_3} & \ldots & \tau_{s_1 s_2 n_n} \end{matrix} \qquad (4.23)$$

Following this τ is found between the first sensor location and the third sensor location for all possible source locations giving equation (4.23).

$$T_{s_1 s_3} = \begin{matrix} & n_1 & n_2 & n_3 & \ldots & n_n \\ \tau_{s_1 s_3} & \tau_{s_1 s_3 n_1} & \tau_{s_1 s_3 n_2} & \tau_{s_1 s_3 n_3} & \ldots & \tau_{s_1 s_3 n_n} \end{matrix} \qquad (4.23)$$

This is repeated so that τ is estimated for all potential source locations for Sensor location S_1 and each other possible sensor location, hence $T_{s_1 s_2} \ldots T_{s_1 s_n}$ is found. All the vectors $T_{s_1 s_2} \ldots T_{s_1 s_n}$ are successively concatenated so that using the subscript c to denote concatenation:

$$T_{cs_1} = T_{s_1 s_2} \quad T_{s_1 s_3} \quad \ldots \quad T_{s_1 s_n} \qquad (4.23)$$

T_{cs_1} therefore stores every possible value of τ for every possible pair associated with sensor location S_1. Likewise T_{cs_2} can be generated for all possible pairs associated with sensor location S_2. The next stage is to consider the Shannon entropy.

The Shannon entropy of a set of discrete random variable is a measure of the randomness in a set of random data and is given by:

$$H(X) = -\sum_{x=i}^{n} p(x_i) \ \log_2 \ p(x_i) \qquad (4.24)$$

Shannon effectively quantifies the evenness or unevenness in a probability distribution and it can readily be applied to the T_{cs_i} vector to provide a value quantifying the evenness of all the values in that vector. On its own this value has little relevance but $H(T_c)$ can be calculated for each vector $T_{cs_1} \ldots T_{cs_n}$ and these can be stored in an optimal placement vector (Ω_0) so that:

$$\Omega_0 = H(T_{cs_1}) \quad H(T_{cs_2}) \quad \ldots \quad H(T_{cs_3}) \qquad (4.24)$$

Based on the understanding that ambiguous results may occur as a result of similar time differences from different parts of a network, the greater the evenness of the vectors T_{cs_i} the less optimal the sensor location.

4.5.2 Unique Paths Graph Based Sensor Placement

An output of finding the shortest paths between all locations in a graph using graph theory is an $n \times n$ paths matrix P. For any given node n_i the route of the shortest path to any other node n_j can be obtained by successively finding the adjacent node at P_{ij} until $P_{ij} = n_j$. The subscript j for the target node remains constant where as the subscript i is updated for every iteration and is determined by the value in P_{ij}.

In any column in the paths matrix P_i the values represent the first adjacent node along the shortest path to every other node P_{ij}. If all the values in P_i are the same this represents a unique path hence if we find the entropy for each column P_i similar to in 4.5.1 the smaller the value $H(X)$ represents a more unique path.

4.5.3 Composite of Shannon Entropy and Unique Paths Placement

The two previous sensor placement methods address different fundamental issues in deciding the most appropriate locations to deploy pressure sensors or pressure data loggers in a water distribution system. In essence the Unique Paths approach deals with the understanding that it is not possible to establish how far a transient source is located along a branch if a sensor is not placed further along the branch than the source location. The entropy method considers the relationship between each possible sensor placement location and every other possible placement location, theoretically identifying locations where the fewest similarities in arrival time differences exist. Both of these outcomes are desirable for their different reasons and it is logical to conclude that the most optimal sensor placement location would have strong results, or the lowest values for both methods. A composite of the two methods can be achieved by first zeroing the minimum value in each vector and offsetting each other value by the same increment, then normalising each vector. The two normalised vectors can now be added together to give a composite value for each location.

4.5.4 Sensor Placement Procedure

Two main considerations need to be taken into account when deciding optimal logger placement locations. Primarily, deciding where to deploy the loggers and secondly establishing the optimum number of loggers required. The sensor placement methods already discussed provide a starting point for optimal placement locations but they do not differentiate between the effectiveness of any given location based on the locality of loggers in the system.

4.5.4.1 Logger Location Decision Procedure

The logical reasoning for the proposed solution for deciding logger locations is that loggers in close proximity are in general, not optimally placed. It is observed in chapter 5 that by placing loggers at the extremities of the network being analysed provides optimal source localisation results.

Using either of the optimal placement methods above the output is a vector whose minima represent the most optimal placement location; this will be referred to as the optimal placement vector, Ω_0. The location of the first sensor is decided by finding the minima in Ω_0. , if more than one minima exist then the first can be chosen because at this stage they are equally optimal. The next step is to define an influence vector, r, which for the first step is taken to be the row corresponding to the first logger location from the shortest paths matrix Ts_i where i is the node number for the sensor location. For successive steps through the procedure with increasing numbers of sensors, r is given by the product of vectors from the corresponding rows in T giving:

$$r = \prod_{i=1}^{n} Ts_i \tag{4.25}$$

The placement vector Ω_0 is multiplied by the influence vector to give a new optimal placement vector Ω_i, which is influenced by the existing sensor locations:

$$\Omega_i = r\Omega_0 \tag{4.26}$$

The minima from Ω_i provides the next optimal sensor location and the process is repeated. Applying the influence r to Ω_0 makes the values at the established logger locations in Ω_i relatively small so that they are not chosen. Conversely, it magnifies the values at the extremities from the existing loggers to determine the most 'extreme' location.

4.5.4.2 Logger Quantity Decision

Having established a mechanism for successively defining optimal logger locations the next stage is to determine the quantity of loggers required. The logger location decision procedure could be applied until a logger is located at every location, which is clearly not a desirable outcome. The following method was therefore developed to aid in discerning the optimal number of loggers required.

The ability to make theoretical assessments of source localisation can be achieved by defining source and sensor locations and using theoretical wave arrival time estimates, this is discussed later in chapter 5. The efficiency of the graph theory based source localisation approach, makes it practical to evaluate the theoretical source location likeliness for every possible source location. Each time a new optimally placed sensor is added using the logger location decision procedure, the source location likeliness vector (L) can be calculated for every possible source location. As well as indicating the location of the transient source, the values in L are indicative of the effectiveness of source localisation. The most likely source locations are defined by the minimal values in L, therefore the more lower values that exist in L, the greater the ambiguity as to the true source location.

Finding the n^{th} percentile of L gives a metric for comparing the number of low values in L, providing a means for comparing the effectiveness of the localisation results. Comparatively, if the n^{th} percentile of L is lower, more low values exist in L and it is a more ambiguous result.

For each configuration of loggers the n^{th} percentile is found for L for every possible source location. The percentile values are stored in a matrix where the columns define the number of loggers and the rows define each specified source location providing the following matrix.

	$2Loggers$	$3Loggers$	$4Loggers$	...	$nLoggers$
$source_1$	nth % tile	nth % tile	nth % tile	...	nth % tile
$source_2$	nth % tile	nth % tile	nth % tile	...	nth % tile
...	...	...	...	...	...
$source_{sources}$	nth % tile	nth % tile	nth % tile	...	nth % tile

Figure 4-7 Logger quantity decision matrix

The arithmetic means of each column can be plotted against the associated quantity of loggers. The optimal quantity of loggers required can be ascertained by observing the resulting profile because as the ambiguity of the likeliness results reduces the value of nth percentiles stabilises. In other words further increasing the quantity of loggers does not significantly reduce the ambiguity the likeliness results.

4.6 Wave Front Arrival / Onset Detection

Measuring the arrival time of a wave may at first glance appear to be a trivial task as this can be ascertained by acquiring pressure data and taking the arrival of the primary wave front as the wave arrival time. Problems arise, however, when we consider the propagation of transients in real pipe systems, the onset of the primary wave is not an instantaneous step with a clearly defined start point, on the contrary, it is a gradual curve Tijsseling et al., (2008) and determining the precise onset of the wave is not clear. Tijsseling et al., (2008) highlights the effects of attenuation and dispersion, showing how these effects can change the shape of the primary wave front. As the primary wave travels along a pipe its gradient will reduce and the onset time may become less defined. A wave changes as it passes through a pipeline or system, hence it is not clear which specific portion of the primary wave front is an accurate/meaningful measure for the wave arrival time. The problem may be further complicated when we consider more complex pipe systems with branches, loops, multiple reflection points and background noise.

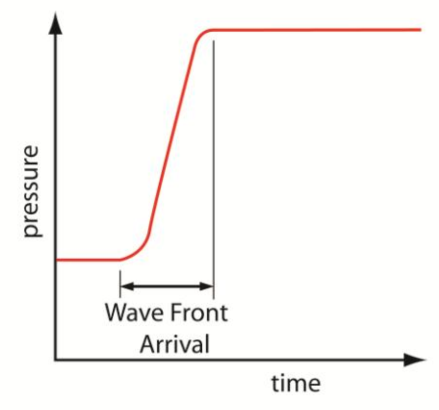


Figure 4-8 Schematic of wave front arrival

It is common practice to measure transient pressure waves with a pressure transducer and digital data acquisition device. Visual inspection of pressure signal profiles may make it possible to estimate the onset time of a wave front but conclusive determination of the precise onset of the signal may be difficult to attain through visual inspection alone. The challenge is to define a means by which the arrival time of a primary wave front can be decisively identified, such that the same or similar relative portion of the front can be temporally located in pressure data at different locations in a pipe system. Wave front location techniques enabling this need to account for, or negate the effects of attenuation, dispersion, reflections and wave fronts from multiple paths. Another objective is to minimise the data acquisition sample frequency (Fs) to a level where optimal arrival prediction is achieved with minimal Fs.

Nine signal analysis techniques were considered for identifying the onset, or arrival times of transient pressure primary wave fronts. Various onset detection techniques are applied to water pressure signals

4.6.1 Onset Detection Methods

A number means of detecting the onsets of musical signals are discussed in section 2.8 the process of determining arrival time form the methods proposed generally involve finding peaks in the detection function. Bello et al., (2005). If short time Fourier transform and Wavelet Transform Methods are used further processing of the time frequency data provides the output function to me maximised.

4.6.1.1 Spectral Flux

Refer to section 2.8.2

4.6.1.2 Negative log Likelihood (NLL)

Refer to section 2.8.3. To apply the NLL approach to a pressure signal a window can be defined to give the data set, $x_1 = n_{i-window1}...n_i$. The NLL of the data within this window can be compared to a second data set $x_2 = n_i...n_{i+window2}$. As rapid pressure changes occur there are greater differences in the model for x_1 and x_2 and the NLL increases. The model for x_1 can be established using the normfit function in Matlab and the NLL for x_2 can be found by using the parameter associated with x_1 and the normlike Matlab function.

4.6.1.3 Multi-scale Discrete Wavelet Transform (MSDWT)

Refer to section 2.8.1

4.6.1.4 Hilbert Transform (HT)

The Hilbert transform provides a real and imaginary temporal representation of a pressures signal. Ghazali et al., (2010) uses the instantaneous phase angle derived from HT to identify leakage features in transient signals. For the application as an ODF it was found that considering only the imaginary component of the Hilbert transform provides a useful ODF where Maxima coincide with the arrival of the primary wave front.

4.6.1.5 Continuous Wavelet Transform

The continuous wavelet transform (CWT) can be utilised in a similar manner to the MSDWT for onset detection; taking the maximum values associated with a particular decomposition scale is analogous to taking the maximum components in a particular frequency band. An advantage of using the CWT over MSDWT approaches is that temporal resolution is preserved across all scales. Matlab was used to perform the CWT, and a peak finding algorithm used to find the maximum for a particular scale.

4.6.1.6 Wavelet Regularity

The wavelet regularity method employed here is adapted from Bello et al., (2005) but uses the CWT

$$K_s[i] = \sum_{(j,k)} 2^{js} \left| d_{j,k} \right| \tag{4.27}$$

4.6.1.7 Spectral flux from CWT

The spectral flux can be attained from the CWT using a similar method as used to obtain the spectral flux from the STFT.

$$SF(n) = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} H\left(\left|X\left(n, Sc\right)\right| - \left|X\left(n-1, Sc\right)\right|\right) \tag{4.28}$$

Where Sc is now the decomposition scale.

4.6.1.8 Discrete Wavelet Transform (DWT)

The DWT was applied directly to the transient pressure signal to provide an ODF, using the DWT function in Matlab. The temporal resolution of the output from the DWT function is half the original signal, hence only providing half the resolution for primary wave arrival time detection. With the high sample frequencies used for data shown in later chapters the reduction is not too significant but if lower sample rates were use the significance would be increased.

4.6.1.9 Profile Method

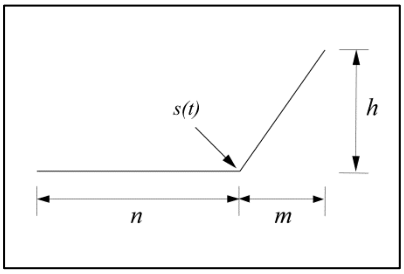


Figure 4-9 Simplified wave front profile W_p

The profile method was developed here as a means of comparing the profile of a primary wave front to a simplified analogue, indicative of a primary wave front represented in Figure 4-9. The profile W_p is defined by:

$$\left[W_p(x)\right]_{x=1}^{n} = 0$$
$$\left[W_p(x)\right]_{x=n+1}^{n+m} = \frac{h}{m}\left(x-n\right) \tag{4.29}$$

Where n is a function of the sample frequency Fs and m is a function of n, h is a function of the voltage range of the logged pressure data. W_p is moved along the sampled data $s(t)$ so that if follows the profile of the signal this is done by vertically shifting W_p by adding the value of the data point in question to all the values in W_p.

$$W_p(t) = W_p + s(t) \tag{4.30}$$

$$W_p(t) = W_p + s(t)$$

The detection function is given by inverse of the sum of W_p minus the sample data over the same window so the detection function DF is given by:

$$DF = 1/\left(\left[s(t)\right]_{t-n}^{t+m} - W_p(t)\right) \tag{4.31}$$

4.6.1.10 Gradient

The gradient at all locations of the pressure signal is calculated using the diff function in Matlab which simply finds the gradient of a line between consecutive data points. The maximum gradient indicates the point of maximum gradient along the primary wave front.

4.7 Discussion of Concept Design and Methodology

This chapter outlines a framework for the identification and localisation of problematic transient sources in water distribution systems. A novel methodology for locating transient sources based on graph theory was identified as were other novel procedures including:

- Combining data from multiple sensors by considering the results from multiple sensor pairs.
- Novel approaches to sensor placement based on the output from graph theoretical shortest path methods.

- Adapting existing wave arrival/onset detection procedures to discrete pressure data plus the development of a novel wave front arrival detection method.

The verification and validation of all these methods are addressed in later chapters

The need to develop a generic transient source localisation procedure was based on gaps in current understanding and previous research and partly through close collaboration with a U.K. water utility where the occurrence of undisclosed and unidentifiable transient sources was known to be a specific issue.

Due to known complexities and inaccuracies associated with conventional deterministic transient modelling approaches the desire was to adopt/develop practicable transient localisation procedures based on a more direct signal processing solution. The proposed solution being collaboration of ideas using high frequency data acquisition, GPS synchronisation, graph theory, signals processing and statistical evaluation.

The understanding and fundamental concepts for the methods identified rely on the capability of current state of the art technologies to acquire synchronised high frequency pressure data at multiple locations in a distribution system. This undertaking in itself is currently at the forefront of transient monitoring in water distribution systems and will be discussed in more detail in later chapters. The project was not driven by need to develop bespoke data acquisition hardware but around the novel application and deployment of such hardware.

This chapter outlined a complete source localisation procedure including a background assessment of whether a source localisation is necessary. Some procedures for the background assessment are in line with current practices by water utilities although more directed assessments could be implemented.

5 Concept Verification

5.1 Introduction

The previous chapter details the concept and development methodology for a transient source localisation procedure. The contents of this chapter aim to verify these ideas and methodology by means of a desktop based study. The implementation of a desktop based study facilitated the realisation of a number of key development objectives:

- Software development, increase understanding and software verification,
- Perform simulations on simple, ideal, pipeline and network configurations to verify the graph theoretical approach.
- Verify the procedure for increased network complexity.
- Evaluate sensor placement and quantities.
- Investigate the consequences of uncertainties primarily associated with pipe properties; wave speeds and transit times.
- Evaluate the source localisation procedure for previously acquired data, obtained from the literature.

The work carried out in this chapter is based on the understanding that it is possible or feasible to simultaneously observe transient pressures at multiple points in a water distribution system, and that the primary wave front arrival times can be identified with sufficient accuracy for the outlined methods to be applicable. The specific challenges involved in acquiring live field data and applying the source localisation procedure to live systems is addressed in later chapters, as such the work discussed here is theoretical and addresses the philosophical understanding and reasoning to a solution to the source localisation problem.

Much of the work in this chapter, with its particular application to water distributions systems has not been previously addressed in the literature. Due to the novelty of the graph theoretical source localisation methodology, by definition, the verification processes identified here are also novel and state of the art.

Four developmental stages were identified for the verification of the source localisation procedures. These stages are identified in Table 5-1 which also incorporates background and justification for each stage.

Table 5-1 Desktop based concept verification development stages

Developmental Stage	Justification /Objective fulfilment
Single pipe line	Evaluating the source localisation procedure on a single pipeline allowed for a simple verification of the methodology and software with minimal complexities and sensor placement locations. While this particular configuration could be construed to be a trivial case, situations could occur in a real system where a single pipeline could have multiple potential transient sources. For example, a large main could supply multiple DMAs each containing potential sources, successful localisation could identify the DMA where the source originates allowing for further, more refined investigation. The simplicity of this configuration facilitated a preliminary assessment of the effects of wave speed uncertainty on the source localisation result.
Simple pipe loop	A simple pipe loop was chosen as the second development stage so that the transit paths of multiple wave fronts could be considered, verifying that the method worked for looped systems. If a transient is generated at any point around the loop then a primary wave front will travel in each direction around that loop, with each front arriving at most locations around the loop at different times. This stage was needed to examine the circumstances under which the source localisation procedure would be successful.
Complex Network Evaluation	A more complex network was evaluated to closer represent that of a real distribution system with a combination of loops and branches. An idealised system was utilised to begin with, using unit pipe lengths. The model was then modified so that the effects of random variations in pipe length hence wave transit times could be assessed.
Sensor Placement Evaluation	Using the ideal complex network and sensor placement decision tools identified in chapter 4 optimal sensor placement locations were evaluated.
Uncertainties Evaluation	One of the most prominent uncertainties which could vary as a result of numerous factors is the wave speed and hence transit time of a wave. The idealised complex network was used to investigate the effects of such uncertainty on the localisation result.
Real Network Evaluation	Using data from the literature, from a real distribution where pipeline wave speeds had been calibrated and known transient sources had been observed and recorded at multiple sensor locations. The source localisation procedure was applied to try and correctly identify the known source location.

5.2 General Methodology

The transient Source localisation procedure defined in chapter 4 relies on the comparison of data from two models, these being:

- Estimated arrival time differences at specified sensor locations from all potential source locations using a graph theoretical model.
- Measured arrival time differences at specified sensor locations from a physical model or real water network.

For the desktop based verification, data from a physical model is not available. Data representing a live system is therefore generated using a similar graph theoretical procedure as is used to generate the theoretical arrival time differences. To achieve this, a source location is specified. Using the shortest path matrix T (shown below), the transit time between the source location and each sensor location can be estimated hence the arrival time difference of a wave travelling from the source location to any pair of sensors can be established.

$$\mathrm{T} = \mathit{sensors}\;\begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ \ldots \\ s_n \end{array}\overset{\textstyle \mathit{sources}}{\begin{array}{ccccc} n_1 & n_2 & n_3 & \ldots & n_n \\ 0 & t_{n_2 s_1} & t_{n_3 s_1} & \ldots & t_{n_n s_1} \\ t_{n_1 s_2} & 0 & t_{n_2 s_2} & \ldots & t_{n_n s_2} \\ t_{n_1 s_3} & t_{n_2 s_3} & 0 & \ldots & t_{n_n s_3} \\ \ldots & \ldots & \ldots & 0 & \ldots \\ t_{n_1 s_n} & t_{n_2 s_n} & t_{n_3 s_n} & \ldots & 0 \end{array}}$$

This will be referred to as a pseudo-physical model. Clearly, without modification, data from the pseudo-physical model would be exactly the same as theoretical model. This is fine for an initial verification and is representative of an ideal system where exact wave speeds and pipe properties are known but it is not suitable for the development of a robust solution where greater understanding and tolerance to uncertainties is needed. To closer represent data from a real system variations were put into the pseudo-physical model, which were either as fixed or random value variations.

The most appropriate means of implementing random value variations is by applying uncertainty to the data in the network definition matrices by either:

- Modifying pipe properties such as E, D, e, t
- Applying variation to calculated wave speeds having used fixed values of E, D, e, t
- Ignoring pipe parameters and applying fixed or variable wave speeds
- Altering pipe lengths by varying node locations

Applying the variations in this manner provides a controlled level of understanding as the specific mechanism for wave speed variation. Variations can be added pre or post the interpolation step, which respectively varies wave speeds globally for each pipe or locally for each pipe segment.

5.3 Stage 1 - Single Pipe Line

With Stage 1 being the initial assessment of the transient source localisation procedure the objective was to consider the simplest pipe configuration, this being a single pipeline with two sensor locations. Evaluation of this stage was divided into three specific cases, aimed at strategically furthering the understanding of the localisation procedure. The three cases are listed in Table 5-2.

Table 5-2 Stage 1 – Evaluation Cases

		Description
Case 1	Ideal Case	For the ideal case the wave speeds and therefore the transit times of the waves down each pipe and the arrival time differences at two senor locations, were identical for the theoretical model and the pseudo-physical model. Various source and sensor locations were evaluated with the overall aims being: • Verify that the source localisation procedure fundamentally works if exact wave arrival and transit times can be established. • Confirm the precise localisation of all sources when situated between the two sensor locations. • Confirm that exact source locations cannot be established if they are not between the sensor locations and show that the procedure will localise the source to the nearest sensor.
Case 2	Wave Speed Variation	Numerous variations and uncertainties could occur in a real water distribution system which could alter the effectiveness of the source localisation procedure. In practice it may be difficult to discern these variations from one and other, and multiple factors could contribute to a compound error in the localisation result. This case was chosen to isolate the variations associated with pipe celerity from other uncertainties. Fundamentally, a disagreement between the theoretically derived wave speeds and the actual wave speeds in the physical system would results in errors between estimated arrival time differences and the measured arrival time differences hence adversely affecting the localisation result.
Case 3	Wave Arrival Detection Variation	Errors or inaccuracies in wave front arrival time detection were identified as having the potential to significantly influence the effectiveness of the source localisation procedure. In reality, it may be difficult to discern these inaccuracies from wave speed uncertainties but for completeness it was necessary to consider each uncertain element in isolation. For this case, the theoretical and pseudo-physical model are as the ideal case. The variation is given by calculating the arrival times based on the ideal models then applying an error to the arrival time differences for the pseudo-physical model.

5.3.1 Model Definition

The configuration for stage 1 constituted a Single pipe 100 m long. The discretisation definition consisted of 5 Nodes in a straight line, equally spaced at 25 m intervals and 4 25 m connecting pipe sections as shown in Figure 5-1. The pipe parameters were specified as for 25 mm MDPE pipe with

Internal Diameter= 20 mm

Wall Thickness= 2.5 mm

Young's Modulus= 1 GPa

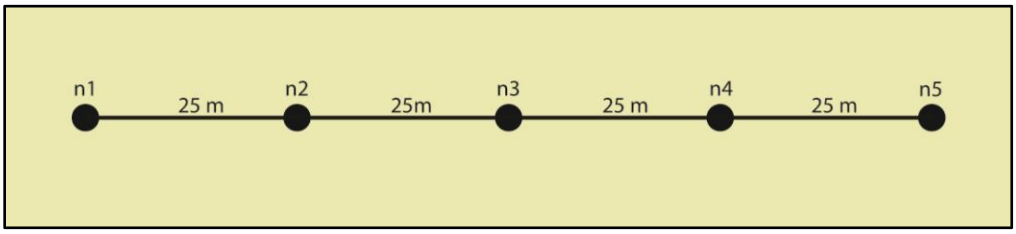


Figure 5-1 Stage 1 - Single pipe network schematic

To increased discretisation resolution, intermediary nodes were added along each pipe at 2 m spacings. The definition node coordinates and pipes are shown in Table 5-3 and Table 5-4 respectively.

Table 5-3 Coordinates Definition

Node	x-coordinate	y-coordinate
1	0	0
2	25	0
3	50	0
4	75	0
5	100	0

Table 5-4 Pipes Definition

Start Node	End Node	Internal Diameter	Wall Thickness	Young's Modulus
1	2	0.02	0.0025	1000000000
2	3	0.02	0.0025	1000000000
2	4	0.02	0.0025	1000000000
3	5	0.02	0.0025	1000000000
4	5	0.02	0.0025	1000000000

5.3.2 Stage 1-1 Ideal case

For the ideal case, the model discretisation and parameters for the pseudo-physical model and the theoretical model are identical. Therefore, the transit times from the source location to each sensor location is exactly the same for both models.

Having defined the two models the transient source localisation procedure could be applied. To evaluate the effectiveness of the localisation procedure for various source locations, a number of simulations were performed with the source and sensors at the following locations:

- Sensor locations spaced along pipe, Source location between sensors
- Sensor locations spaced along pipe, Source location outside sensors

5.3.3 Stage 1-2 Wave speed variation

A preliminary assessment was made as to the effect on the wave speed of varying pipe parameters E, D, e within specified tolerances for a specific pipe material type. Using data for three different diameters of MDPE pipe, estimated wave speeds were calculated using the wave speed equation. Each parameter was varied individually while each other parameter was kept at its mean level. Finally an extreme case minimum and maximum wave speed was calculated for each pipe diameter.

Informed about potential wave speed variability for MDPE pipe from the preliminary wave speed assessment, desktop simulations were performed on the single pipe using fixed sensor and source locations. With a source placed equidistant between two sensors, varying the wave speed in the pseudo physical model would not affect the localisation result because the arrival time difference at the two sensors will always be zero. The source location was therefore specified between the two sensors but at an offset location, closer to one of the sensors. Independent simulations of the localisation procedure were performed with varying pipe celerity in the pseudo-physical model. The baseline wave speed was the mean value from the preliminary assessment and for each simulation the wave speed in the pseudo-physical model was varied as a percentage of the baseline wave speed.

5.3.4 Stage 1-3 Arrival detection variation

For case 3, a desktop simulation was performed using the ideal case as for case 1. A representation of an error in arrival time detection was imposed by applying an arrival detection error to the arrival time differences in the pseudo-physical model. The value for the arrival detection error was either added or subtracted from the arrival time difference prior to comparison to the theoretical time difference.

At this stage the actual value for arrival error is somewhat arbitrary. Informed by the data loggers discussed in later chapters, which have a sample frequency of 100 Hz, errors were defined as multiples of 0.01second, this being the duration one sample period at this frequency. The reason for this decision being that wave arrival detection could only be accurate to one sample period and that there could also be potential for drift in logger synchronisation of one sample period.

5.3.5 Stage 1 Results - Single Pipe

5.3.5.1 Stage 1-1 Ideal case

A source was specified at three different locations along the stage 1 single pipeline. The source localisation procedure was applied to each simulation to generate the source location Likeliness plots shown in Figure 5-2.

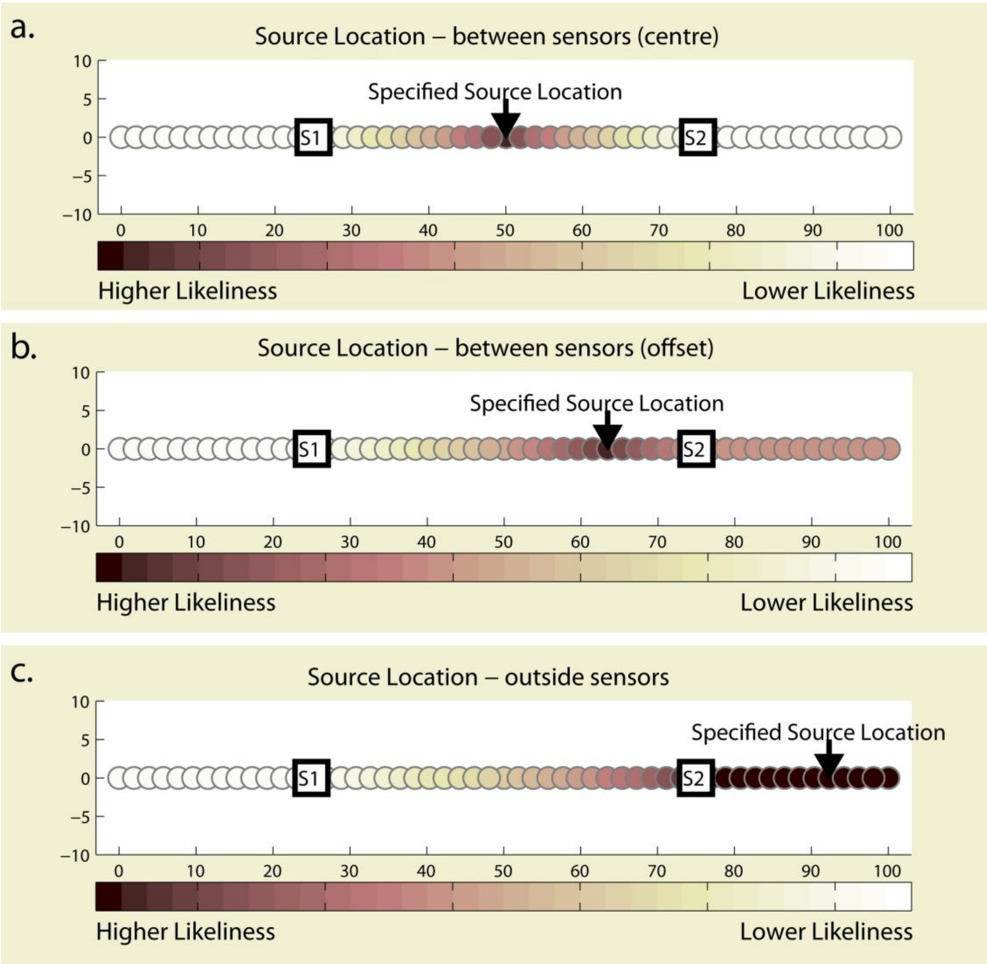


Figure 5-2 Single pipe ideal case source location Likeliness plots. a) source at the centre. b) source offset from sensor. c) source outside sensors

With the source located between the two sensors as in Figure 5-2 a. and b. the highest source location Likeliness coincides with the actual source location. This verifies the expected outcome that using exactly the same wave speeds and without errors the method can accurately predict the source location provided it is situated between the two sensors. A positive localisation result would be seen for any location between the two sensors. Figure 5-2 c. differs in that the source is outside (not between) the two sensor locations. As expected in this scenario the procedure cannot identify the exact location of the source. This is because the arrival time difference at S1 and S2 is the same for every node to the right of S2. While in this situation the method cannot predict the exact source location it still identifies an appropriate area of the pipe line, which for practicable purposes could be sufficient to indicate a source location. For a persistent transient event a further search could be performed using different sensor placements having been informed by these results.

5.3.5.2 Stage 1-2 Wave speed variation

The preliminary task for Stage 1-2 was to evaluate the potential for wave speed variability in the MDPE pipe material.

Table 5-5 Pipe wave speed evaluation

	25 mm ø		125 mm ø		315 mm ø	
	Nominal Diameter	0.0202	Nominal Diameter	0.1013	Nominal Diameter	0.2558
	Mean Wall Thickness	0.0025	Mean Wall Thickness	0.01205	Mean Wall Thickness	0.0301
	Mean young's Modulus	680000000	Mean young's Modulus	680000000	Mean young's Modulus	680000000
	Mean Wave speed	284.71	Mean Wave speed	279.32	Mean Wave speed	277.86
	Min Dia.	Max Dia.	Min Dia.	Max Dia.	Min Dia.	Max Dia.
	0.0199	0.0205	0.1008	0.1018	0.2555	0.2561
Wave Speed	286.76	282.69	279.99	278.66	278.02	277.71
	Min e	Max e	Min e	Max e	Min e	Max e
	0.0023	0.0027	0.0114	0.0127	0.0286	0.0316
Wave Speed	273.48	295.44	271.94	286.48	271.09	284.45
	Min E	Max E	Min E	Max E	Min E	Max E
	290000000	1070000000	290000000	1070000000	290000000	1070000000
Wave Speed	187.92	353.42	184.29	346.87	183.31	345.10
Wave Speed	181.70	363.93	179.77	354.75	178.86	352.92

Table 5-5 evaluates the wave speeds for MDPE pipe of three different diameters. For each diameter, wave speeds are calculated using the lower and upper permissible values of internal diameter, wall thickness and Young's modulus based on manufacturers literature. The results show that while internal diameter and wall thickness variation can have a significant effect on the pipe celerity, by far the largest contributor to wave speed variability comes from the prescribed values for the Young's modulus. The definition of Young's modulus for visco-elastic pipe materials is not consistent with the requirements of dynamic loading analysis. The Young's or tensile modulus is defined by the British Standards Institution (BSI) as the secant modulus between strains of 0.0005 and 0.0025 at room temperature as illustrated in Figure 5-3. Due to creep and temporal variation in strain in the visco-elastic pipe material this value does not truly represent the initial gradient of a stress strain curve.

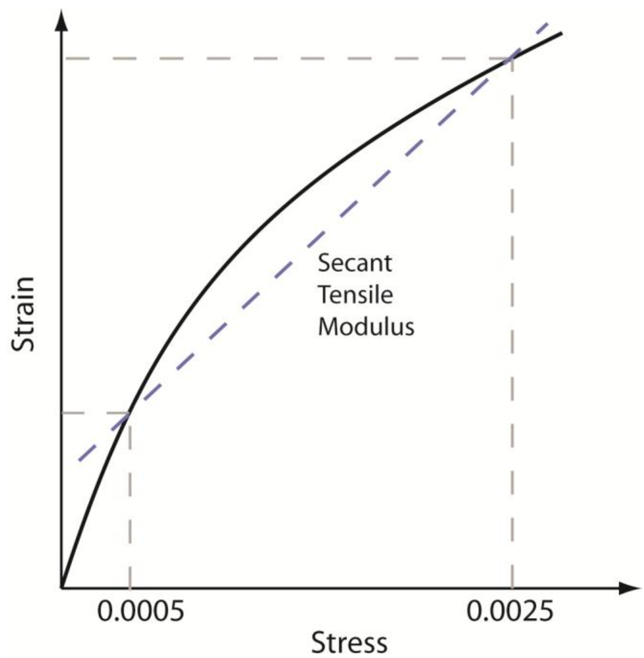


Figure 5-3 Illustration of Tensile Modulus

Transient pressure wave speeds have not been well characterised in plastic visco-elastic pipes. As such the Young's Modulus defined in manufacturers' literature may not necessarily be relevant for an accurate estimation of pipe wave speeds. The dimensional tolerances provided in the literature are more reliable but over the tolerance range have limited effect on the pipe wave speed, the most significant contributor being the Young's modulus.

A Young's modulus of 1.0 GPa was used as this was consistent with the upper values of E for HPPE from manufactures data and consistent with the higher values of E shown in Covas et al., (2004), this provided a baseline wave speed of 342 m/s. From Table 5-5 the maximum permissible variations in wave speed from the mean due to variation is pipe characteristics are less than 60%, for this reason the value of wave speed was kept constant in the theoretical model but was varied from -60% to +60% in 20% increments in the pseudo-physical model. Variations of this magnitude would represent an extreme worst case and in practice variation should be considerably less than 60%.

Location Likeliness plots with varying wave speeds are shown in Figure 5-4, showing that wave speed variations can considerably alter the localisation results by shifting the highest Likeliness prediction to either side of the actual source location. The distance that the prediction is offset from the source is skewed depending on whether the wave speed in the physical model is greater or smaller than the theoretical prediction. The skew occurs because as the wave speed in the pseudo-physical model is increased, the arrival time difference tends to zero therefore moving the highest Likeliness towards the centre.

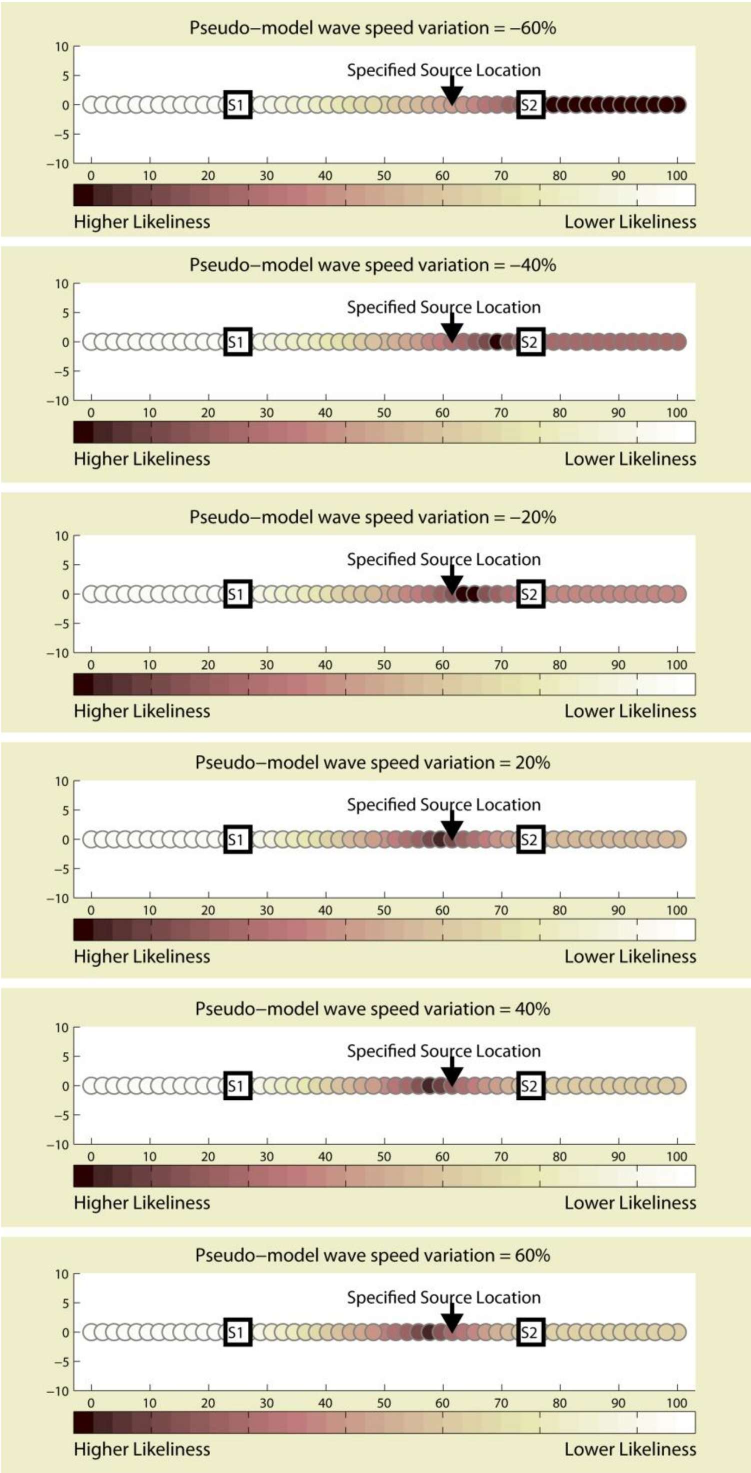


Figure 5-4 Wave speed variation results

One indication from Figure 5-4 is that varying the wave speeds in the pseudo physical model provides a nonlinear source location error. This is shown more clearly in Figure 5-5, which plots the location errors resulting from varying the wave speed in the pseudo physical model.

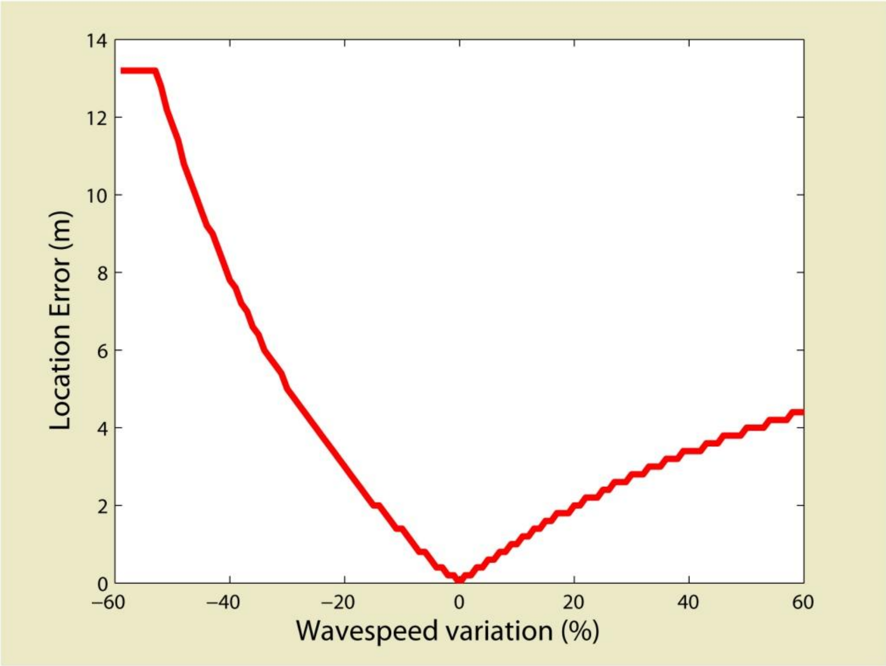


Figure 5-5 Source location error vs pseudo physical model wave speed variation

Figure 5-5 represents the uncertainty in the actual wave speed that could be present in a 'real' distribution system. The clear nonlinearity in the location error has implications on the wave speed estimates for the theoretical model. An estimated wave speed needs to be specified in the theoretical model and without empirical measurement it is not known whether the actual wave speed in the pipe is greater or lower than the theoretical estimate. Figure 5-5 shows that if the actual wave speed is lower than the estimate, the location error is more likely to be greater than if the actual wave speed is higher than the estimate. Therefore, when specifying the theoretical wave speed, prudently underestimating its magnitude as opposed to overestimating it could help in minimising potential location errors.

The reason for the non linearity in the location error can be understood by considering equation (4.5) :

$$\tau_{s1,s2} = \frac{1}{a}\left(l_1 - l_2\right) \qquad (4.5)$$

Where l_1 and l_2 are the distance to Sensor$_1$ and Sensor$_2$ respectively and a is the wave speed, by observation, as $a \to 0,\ \tau_{s1,s2} \to \infty$ and as $a \to \infty,\ \tau_{s1,s2} \to 0$. This is shown in Figure 5-6, which plots $\tau_{s1,s2}$ against wave speed for the same pipe configuration shown in Figure 5-4.

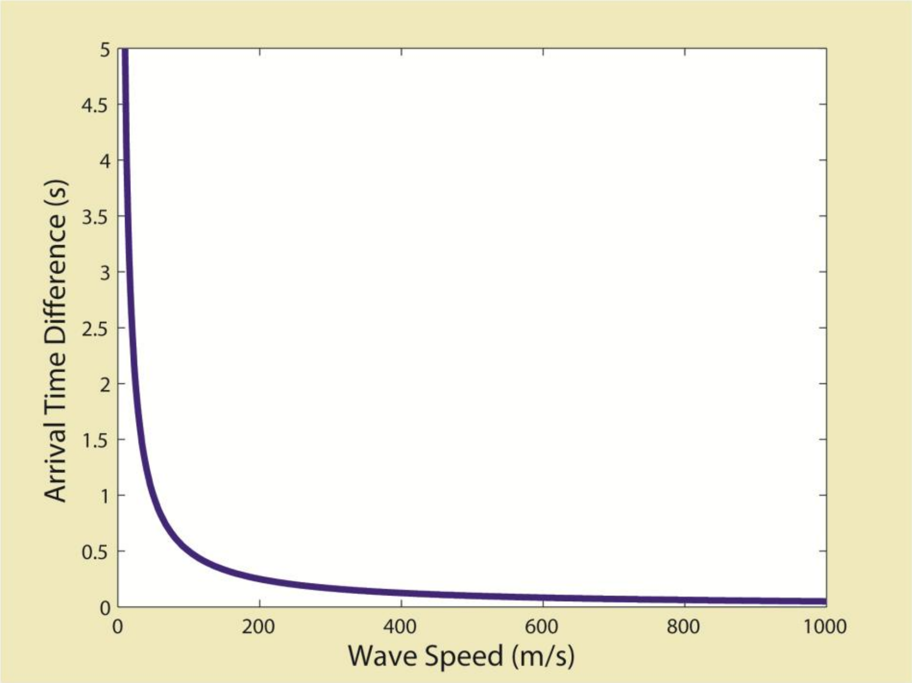


Figure 5-6 Arrival time difference vs wave speed variations

The limitations of the skew in the Likeliness plots is shown in Figure 5-7. With an over exaggerated wave speed variation, the source location prediction tends to half way between the two sensor locations.

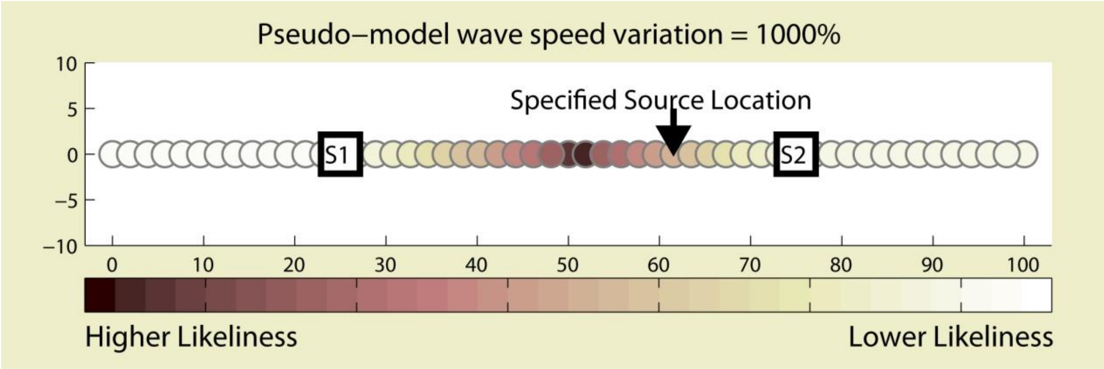


Figure 5-7 1000% wave speed variation

In reality, the large errors in wave speed estimation shown in Figure 5-4 to Figure 5-7 are unlikely and it should be feasible to make informed estimates to within 10% of the actual wave speed.

5.3.5.3 Stage 1-3 Arrival detection variation

The results for stage 1-3 are representative of a situation where an error occurs in the arrival prediction. This error could be attributed to two main mechanisms, these being, poor synchronisation of data acquisition or error in the accurate detection of the primary wave arrival time.

The localisation results with imposed arrival time errors are shown in Figure 5-8. Similarly to with the wave speed variation, and in line with the expected outcome, an offset occurs as a result of inaccurate arrival time detection. There is no skew in localisation results as experience with the wave speed variation, the offsets are proportional to the detection error. With a wave speed of 342 ms^{-1} a 0.01s error translates to a wave transit distance of 3.42 m this would be an offset of 3.42/2 =1.71 m. For 0.05s offset distance would be 1.71x5=8.55 m, this is consistent with the results where an offset of 4 nodes at 2m interval is 8 m. The results show the potential for considerable localisation error. In pipes with higher wave speeds, for instance cast iron where wave speeds could be approximately four times higher at 0.05 s arrival time difference error translates to approximately 35 m localisation error. Any amount of error is undesirable but some level of error is inevitable, the best means of mitigating errors is to maximise the accuracy of the wave arrival time estimation methods.

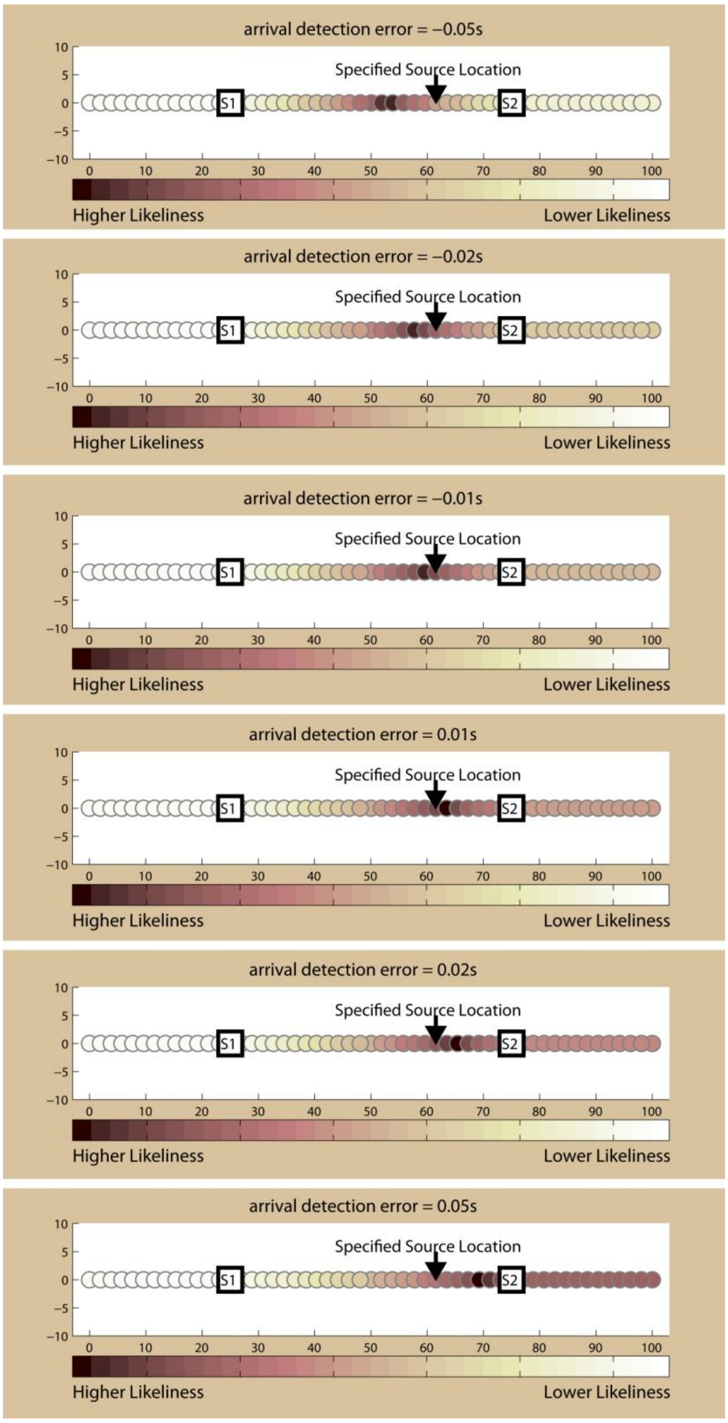


Figure 5-8 arrival time error

The findings confirm that uncertainties in wave speeds and accuracy of wave arrival detection can have significant impact on the localisation result. Small variations are inevitable and are manageable provided that the errors are understood. Millisecond accuracy is achievable with GPS and GPRS procedures therefore one factor which needs to be ruled out is drift in acquired data so the only potential for drift is in the reliable detection of the wave front arrival time.

5.3.6 Stage 1 Discussion

Given that a source location lies between two sensors and reliable values for pipe properties are known, then at least for single pipelines the transient source localisation procedure being discussed has a high level of prediction accuracy. This verifies the expected outcome and the concern around the effects that uncertainties can have on the localisation results.

Varying the wave speed can significantly alter the localisation result but within 20% variation provides a reasonably small error in the localisation result. With informed decision making it should be possible to have sufficiently accurate wave speed estimates and in a worst case scenario speeds could be characterised by direct measurement. The use of variable wave speeds could be incorporated into the localisation procedure. Different localisation results could be attained by inferring the wave speed variability based on extreme wave speed estimates. While this clearly won’t provide a definitive solution it provides a mechanism for working with wave speed uncertainties to explore different possible solutions. The findings from case 2 indicate that airing towards lower wave speed estimates may minimise localisation errors.

The results from the arrival time detection variation highlight the need to mitigate the mechanisms which allow errors to occur. This can be achieved by ensuring that data synchronisation is accurate and by establishing reliable methods for wave front arrival time detection.

As intimated throughout this work one of the main goals is to identify whether the source localisation procedures being discussed are suitable for practicable purposes. The findings of these experiments help to clarify the extent to which uncertainties could impact on the localisation result. Large uncertainties could considerably affect the results but provided uncertainties are minimised the procedure is a viable approach for transient source localisation. For large networks, small localisation errors would be acceptable for many practicable applications.

Small variations in wave speeds and arrival time detection have similar results. It may be possible to adopt a solution for a compound worst case scenario i.e. slowest wave speed with earliest arrival time detection. Fastest wave speed with the latest arrival time detection, but where multiple sensors are involved this approach could be prohibitive.

The use of multiple sensors on larger networks raises the questions: Would increased network complexity with more sensors reduce or increase the accuracy of the localisation result? Could more sensors be added to improve the solution? Does increasing the number of sensors also increase the level of uncertainty?

5.4 Stage 2 - Simple Pipe loop

The objective for stage 2 was to increase the network complexity from a single pipe to something more representative of a distribution network while keeping the network simple enough to perform meaningful and constructive analysis. Any network could be defined as a series of loops and branches and the configuration for stage two aimed to incorporate both these features while minimising the complexity. Incorporating loops into the network facilitates multiple transit paths for transient pressure primary wave fronts.

Four specific evaluation cases were identified for the stage 2 network configuration as shown in Table 5-6.

Table 5-6 Stage 2 - Evaluation cases

		Description
Case 1	Simple looped network with two sensors	Using the stage 2 simple looped system and evaluation of source localisation was performed using all possible combinations of two sensors
Case 2	Simple looped network with three sensors	Using the stage 2 simple looped system and evaluation of source localisation was performed using all possible combinations of three sensors
Case 3	Simple looped network with three sensor with varying wave speed	Wave speeds were varied, similarly to explored on the stage 1 configuration to asses localisation errors in the stage 2 configuration
Case 4	Simple looped network with cross connection	To slightly increase the network configuration a cross connection to asses if further numbers of sensor locations would be required to achieve a positive unambiguous localisation result

5.4.1 Method

5.4.1.1 Model Definition

The configuration for stage 2 shown in Figure 5-9 Stage 2 - Simple looped network consisted of a simple looped network formed from six nodes six 20 m long pipe sections. The discretisation definition consisted of a loop defined by four of the nodes with the remaining nodes defining the ends of two branches. The specified pipe material was the same as was specified for stage 1, using 25 mm MDPE pipe with:

Internal Diameter= 20 mm

Wall Thickness= 2.5 mm

Young's Modulus= 1 GPa

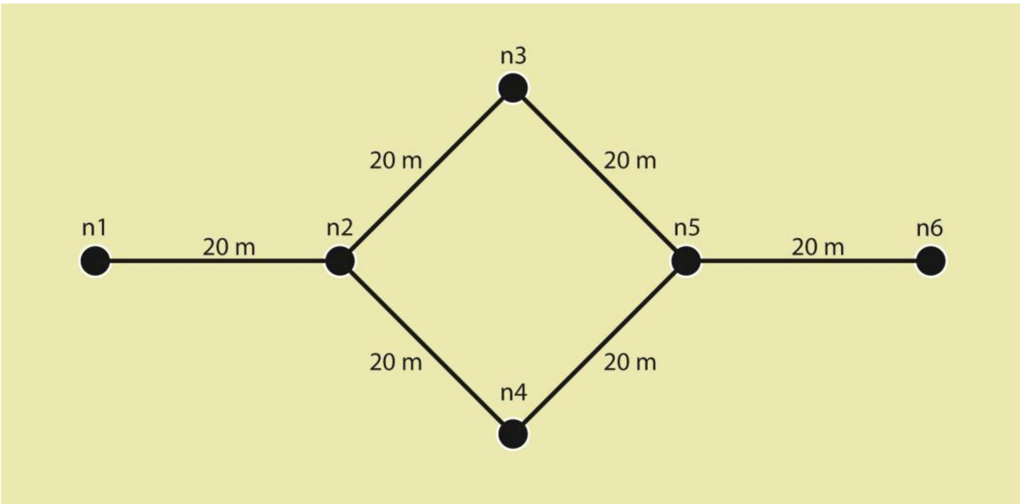


Figure 5-9 Stage 2 - Simple looped network schematic

The node coordinates and connectivity are shown in

Table 5-7 and Table 5-8 respectively.

Table 5-7 Coordinates Definition

Node	x-coordinate	y-coordinate
1	0	0
2	20	0
3	34.142	14.1421
4	34.142	-14.1421
5	48.2842	0
6	68.2842	0

Table 5-8 Pipes Definition

Start Node	End Node	Internal Diameter	Wall Thickness	Young's Modulus
1	2	0.02	0.0025	1000000000
2	3	0.02	0.0025	1000000000
2	4	0.02	0.0025	1000000000
3	5	0.02	0.0025	1000000000
4	5	0.02	0.0025	1000000000
5	6	0.02	0.0025	1000000000

The model discretisation resolution was increased by adding extra nodes along each pipe at 1 m spacings.

5.4.2 Stage 2 Results

5.4.2.1 Stage2, Case 1 – Simple Looped Network with Two sensors

Using a simple looped system configuration and using the ideal condition where wave speeds are the same in both models, a source was specified with two sensor location. The source location was varied and the sensor locations were also varied. Four examples of the results are shown in Figure 5-10

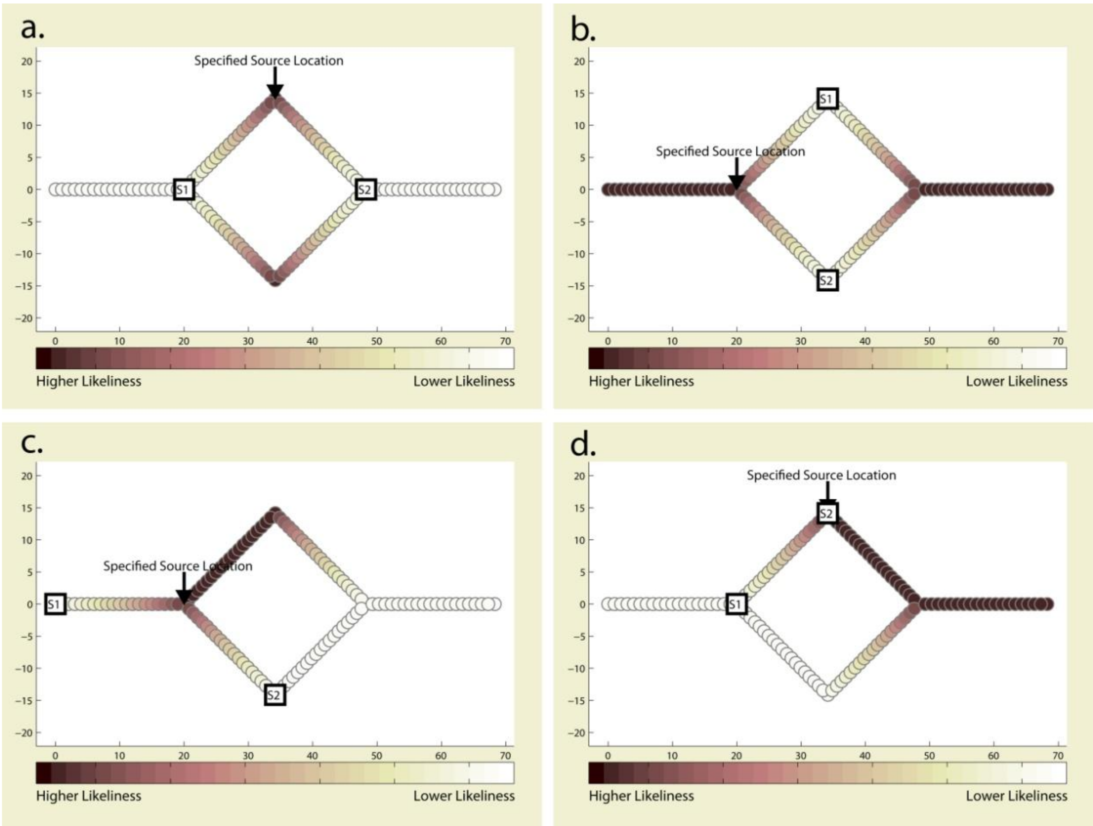


Figure 5-10 Localisation results on a simple loop using two sensor locations

Ambiguities in the localisation results, when only two sensor locations are used, can clearly be seen in Figure 5-10, most prominently in Figure 5-10 a and b. The ambiguities occur because the arrival time difference would be the same should the source be located at the alternate location. In Figure 5-10 c and d valid localisation result is achieved but similarly to as observed for the single pipe line the whole pipe adjacent to the source location has a high location Likeliness.

To ensure the source location is between the two sensors the sensors were placed at the extremities of the network as shown in Figure 5-11. This eliminates the scenario observed in Figure 5-10 c and d although an ambiguous result will still be observed if the source is on the looped part of the network.

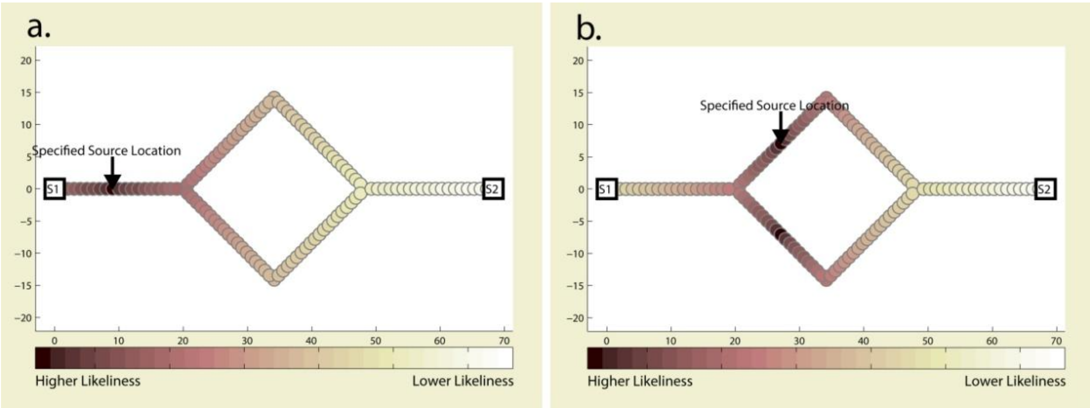


Figure 5-11 Simple looped network with sensor place at the extremities

5.4.2.2 Stage2, Case 2 – Simple Looped Network with Three sensors

Having verified that ambiguities were observed when only two sensor locations were used, the logical development was to increase the number of sensors. The results in Figure 5-12 show that informed by the results from 5.4.2.1two sensor locations were placed at the extremities of the network a third sensor was place on the looped section of the network. Using this sensor configuration it is possible to attain a positive, unambiguous source location for any location in the network. The sensor pair results were amalgamated using the Negative log likelihood method identified in 4.3.5.3, for the ideal case no discernible differences were observed using the root mean squared method and absolute mean method identified in 4.3.5.1.

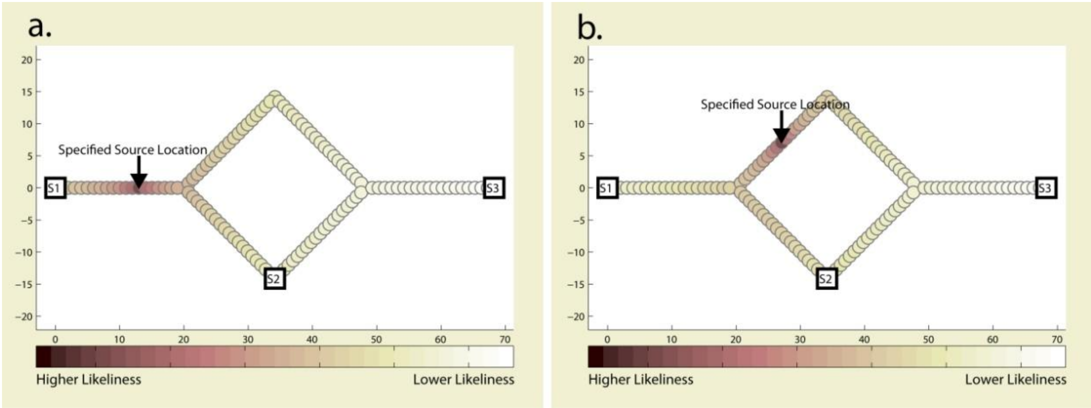


Figure 5-12 Simple looped network with three sensor locations

5.4.2.3 Stage 2-3 Wave Speed Variation

Wave speeds were varied using the same method as in stage 1-case 2, results are shown for +-20% and +-40% wave speed variation in Figure 5-13. Consistent with the results from stage 1-case 2 a greater offset in localisation result can be seen when the wave speeds in pseudo-physical model are smaller than in the theoretical model. Again, no discernible differences were present in the localisation result between each sensor pair grouping method.

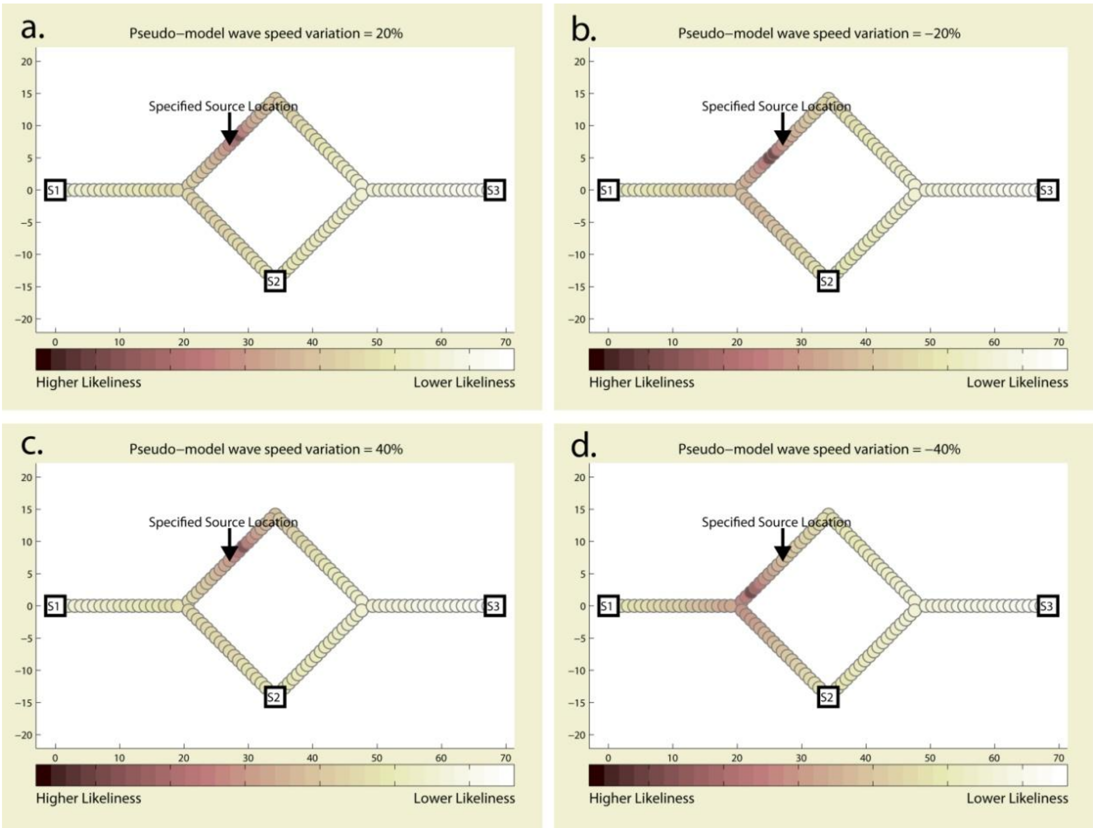


Figure 5-13 Localisation results for wave speed variation on a simple looped network with three sensor locations

5.4.2.4 Stage 2-4 Simple loop with cross connection

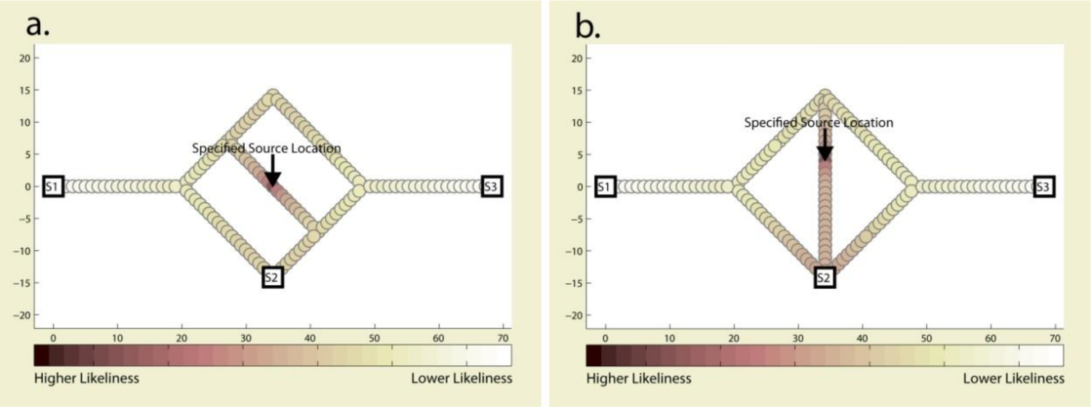


Figure 5-14 Localisation results for a simple looped network with cross connection and tree sensors

An assessment was made using a cross connection in the looped system and it was shown that a positive source localisation results could be attained by using only three sensor locations

5.4.3 Stage 2 Discussion

Generally the results for stage 2 affirm that the graph based source localisation procedure should be successful in determining the source of a transient pressure wave for simple looped pipe networks. The results confirm that ambiguities could occur if too few sensors are used. Having these ambiguities in the results when not a desirable outcome but for practicable purposes this could still possibly produce a positive source identification result provided no potential source exists at the alternate location.

Increasing the number of sensors, in this case to three, and placing them in appropriate locations provided accurate unambiguous localisation results for all potential location. An initial indication of optimal sensor was gained by verifying that placing sensors at the extremities of branches helped to minimise ambiguities. Variations in arrival time detection and specified wave speeds imposed an offset in the source location prediction. A significant result is that, if the wave speeds in the physical model were greater than those in the theoretical model, the offset was smaller than if the wave speed was lower in the physical model.

Regarding arrival detection errors the most effective solution would be to minimise these errors in future stages of development with the limiting factor will always be the ability to accurately synchronise data loggers and determine the arrival of the primary wave front.

Three loggers are sufficient to establish the source for every location therefore a sensor is not needed at every location.

5.5 Stage 3 - Complex network Evaluation

Stages 1 and 2 have helped to verify the source localisation procedure and analysis of these simple pipe systems has provided valuable understanding as to the limitations of the procedure. Any pipe network can be defined in terms of loops and branches so having verified the procedure on these constituent parts of a system it is reasonable to assume that provided sensors are placed throughout a larger more complex network then the procedure would be effective. One aim of this stage was to verify that this is the case but it is also clear that to fully populate a large network with multiple loggers could be prohibitive. It has been shown that a limited number of sensors could provide successful results so the other objective is to establish the minimum number of loggers required to achieve a successful unambiguous result in a larger more complex network.

Table 5-9 Stage 3 – Evaluation Cases

		Description
Case 1	Even Network Sensor Placement evaluation	The objective for this case was primarily to evaluate the optimal sensor placement procedures described in 4.5: • Unique path placement • Shannon Entropy Sensor Placement
Case 2	Uneven Network Evaluation	The Stage 3 network was distorted so that pipe lengths were no longer regular lengths. This was done to ascertain whether the placement methods were still applicable in uneven networks and confirm that the regularity of the even network was not biasing the results.

5.5.1 Model Definition

The network configuration for stage 3 was attained by extending the understanding that a network can be defined as a series of loops and branches and that the inclusion of loops introduced the possibility of ambiguities in the localisation result. An equilateral grid configuration was chosen comprising of nine loops and 16 branches on the basis that the equal pipe lengths and high level symmetry would maximise the potential for localisation ambiguities. A schematic of the network is shown in Figure 5-15, the spacing between the definition nodes hence pipe length was 20 m and the discretisation resolution was increased using 2.5 m subdivisions.

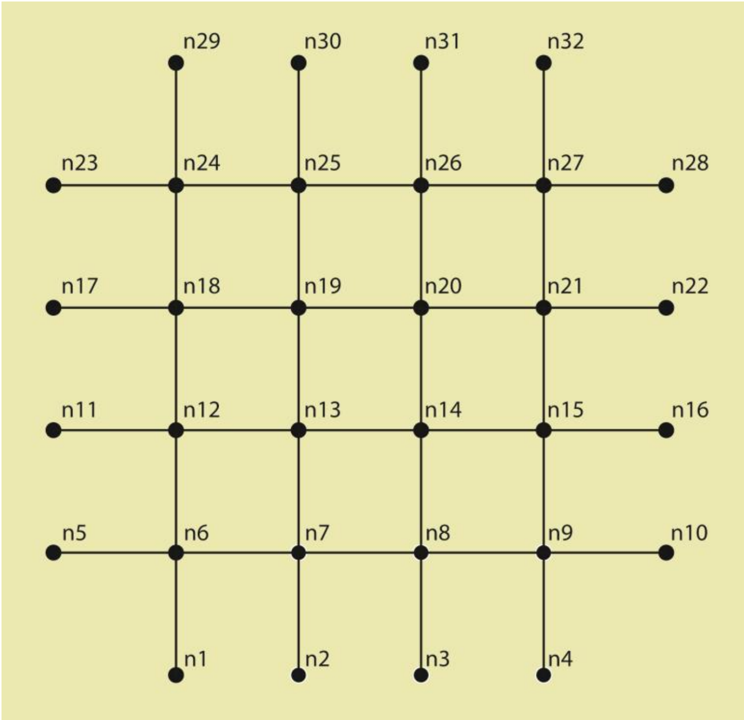


Figure 5-15 Stage 3 - Complex network schematic

5.6 Methods

5.6.1 Stage 3-1 Sensor Placement Evaluation

The indications from Stages 1 and 2 were that placing sensors at the extremities of a network, at the end of branches, provided the best chances for positively localising a source. Having defined the network the two sensor placement methods defined in 4.5 were applied discern whether they verified this understanding. A composite of the two methods was also developed. This was achieved by normalising the results for each method and adding them together. Sensors were placed at the locations prescribed by the sensor placement methods and the ideal case source localisation procedure was applied.

5.6.2 Stage 3.2 – Uneven network Evaluation

It was necessary to establish that the regularity and symmetry of the Stage 3 network configuration was not biasing the results by either overestimating the effectiveness of the sensor placement procedures or increasing the effectiveness of the localisation procedure. It is clearly not possible to evaluate every possible network configuration and the method chosen to investigate this was through the modification of the network configuration. The networks were modified by moving the network definition node locations a random distance. The movement of each node was limited to a +- maximum value and different random value between these limits was generated for each definition node.

5.6.3 Stage 3 Results - Complex network Evaluation

5.6.3.1 Stage 3.1 Results - Sensor Placement Evaluation

Results are shown here for both sensor placement methods plus a composite of the two methods.

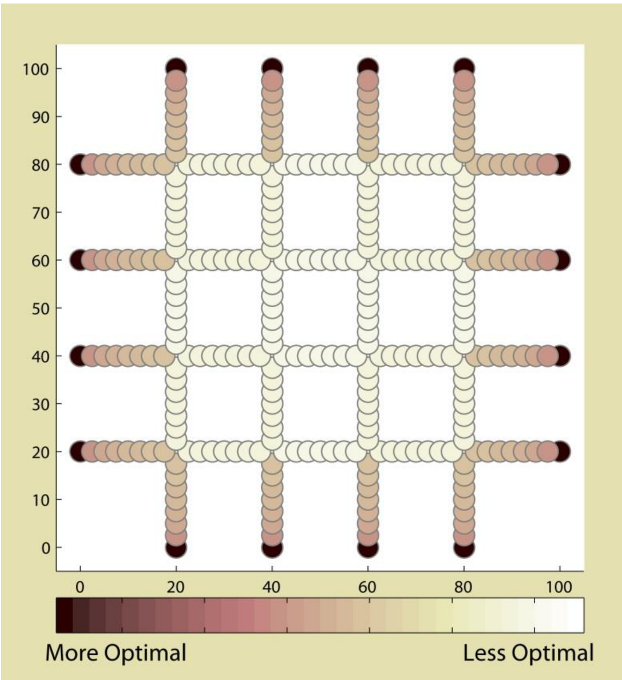


Figure 5-16 Result for the unique paths sensor placement method

The unique paths sensor placement procedure shown in Figure 5-16 agrees with the findings that placement of sensors at extremities of the network at the end of branches provides the best chance of attaining a positive, unambiguous localisation result. The unique paths procedure does not however identify which branches would be most optimal for successful source localisation.

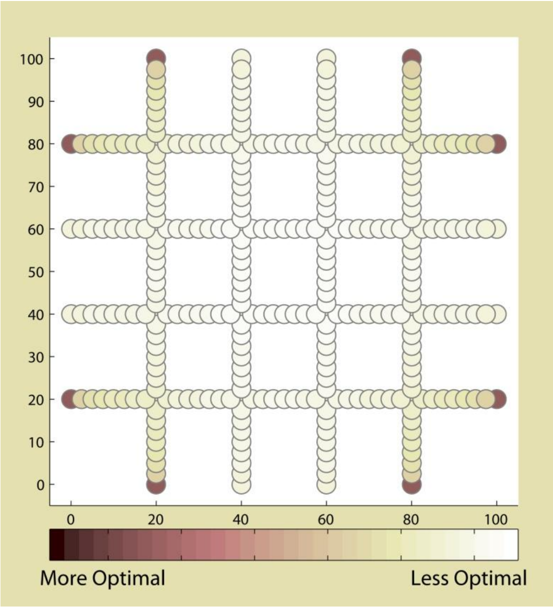


Figure 5-17 Result for the Shannon entropy sensor placement method

The Shannon Entropy placement method results in Figure 5-17 appear to provide a more refined sensor placement solution by limiting the optimal location to eight of the sixteen branches. The procedure also agrees with previous findings, by placing the optimal locations at the network extremities. The composite of the two placement methods in Figure 5-18 still indicates that the most optimal placements are as determined by using the Shannon Entropy method but also show that optimal placements form the unique paths procedure.

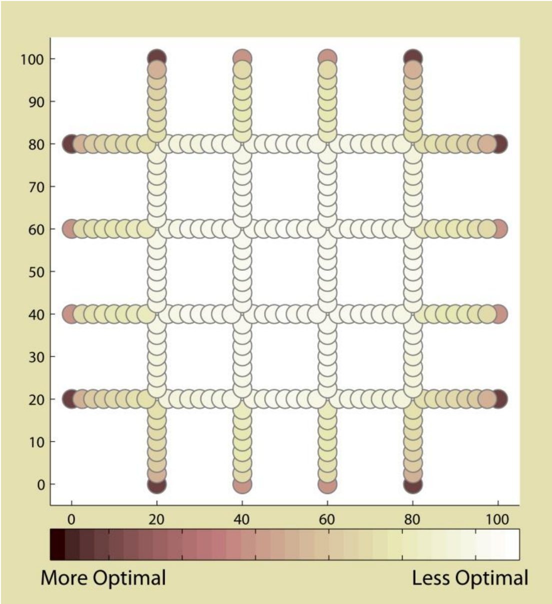


Figure 5-18 Result for the composite of the Shannon Entropy and Unique Paths sensor placement methods

5.6.3.2 Sensor placement decision

The sensor placement decision procedure identified in section 4.5.4 was applied to the complex network using vector o_0 from the composite optimal placement method.

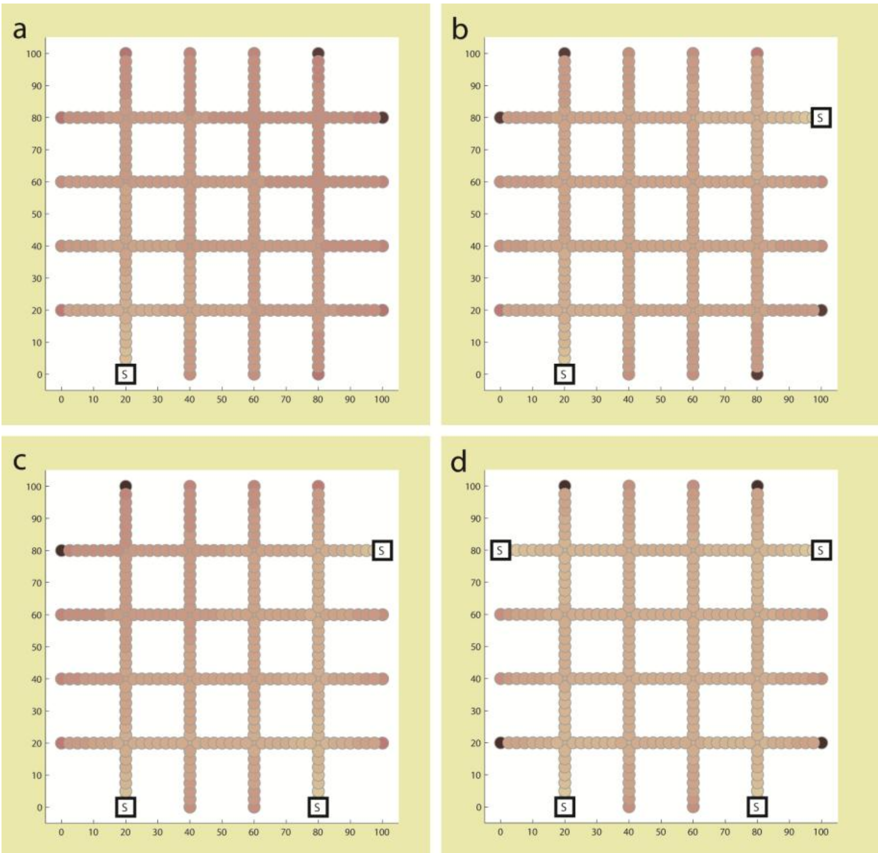


Figure 5-19 Optimal sensor placement of a) one b) two c) three and d) four sensors

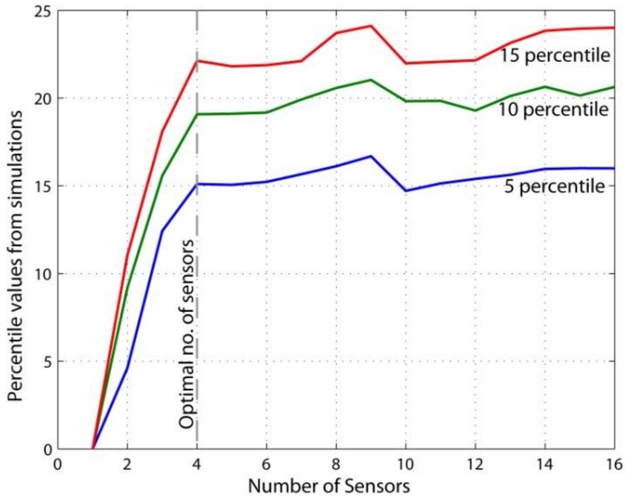


Figure 5-20 Optimal number of sensors by finding the nth percentile from the source location Likeliness from multiple simulations

Figure 5-19 shows four optimally placed sensors using the sensor placement decision procedure. Figure 5-20 shows plots of the corresponding averages of the n^{th} percentiles of the likeliness vectors from multiple simulations with the source at different locations as described in 4.5.4.2. All three percentile plots suggest four is the optimal quantity of loggers required. By continuing with the sensor placement procedure, all sixteen nodes defined as being the most optimal when using the composite placement method this is shown in Figure 5-21.

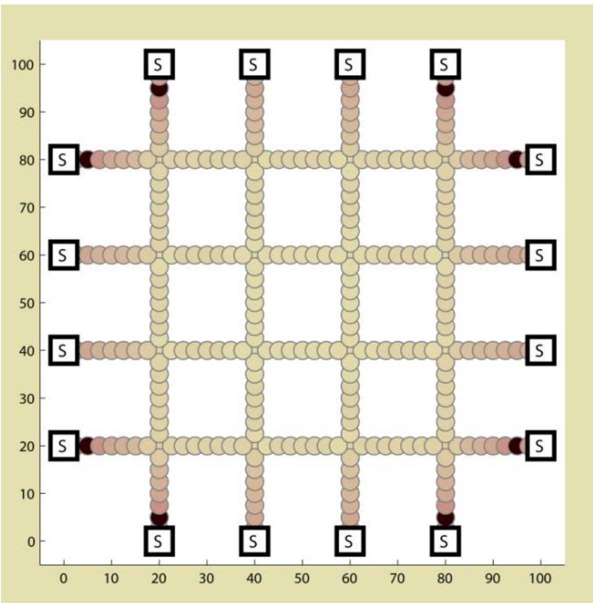


Figure 5-21 Sixteen sensor placements, identified using the sensor placement decision procedure

5.6.3.3 Sensor placement verification

To verify the optimal sensor placement predictions simulations were performed using three sensors. In Figure 5-22a. where two sensor locations are placed at the optimal locations a positive localisation result is achieved, with the only ambiguities occurring along the branch connected to the specified source node. With only one sensor at an optimal location, as shown in Figure 5-22b. the localisation ambiguity is increased with two separate branches showing a high source location Likeliness.

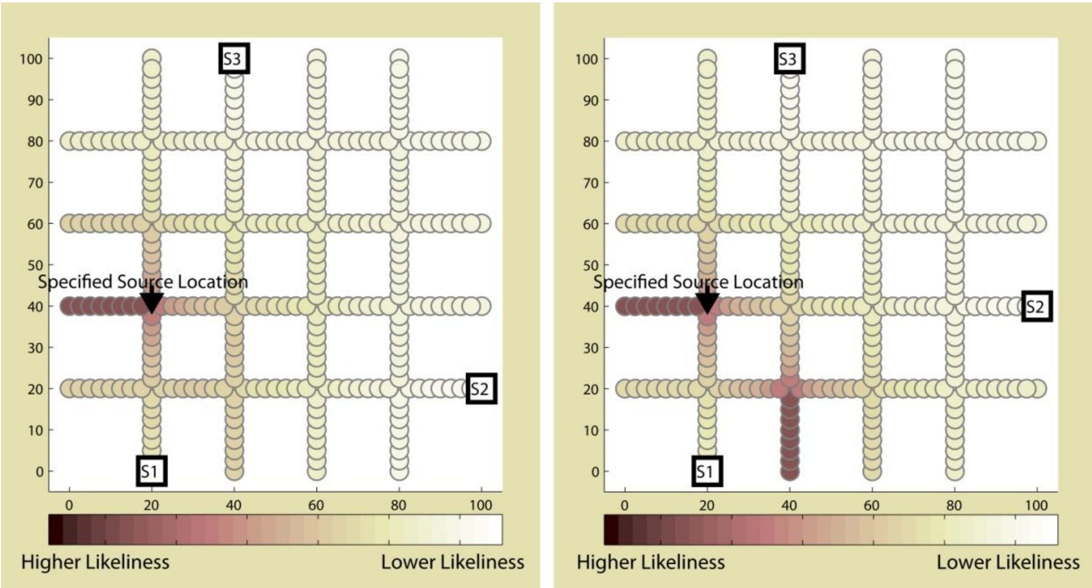


Figure 5-22 Comparison for the varying placement of Sensors using three sensor locations

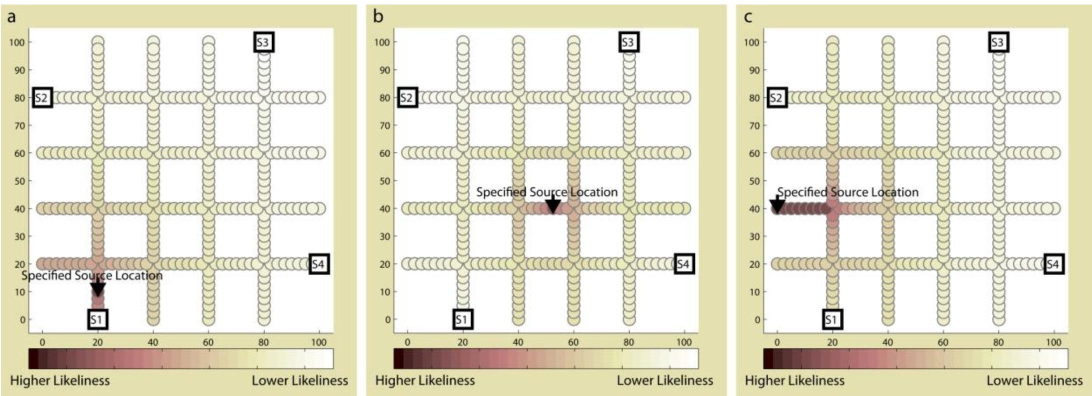


Figure 5-23 Confirmation of successful source localisation with four sensors placed as prescribed by the Shannon Entropy sensor placement method

With sensors placed at four of the eight optimal locations as seen in Figure 5-23, only a representative selection of results is shown but ambiguities do not occur for any specified source location other than along individual branches as observe in Figure 5-23c.

5.6.3.4 Stage 3.2 Results – Uneven Network Evaluation

The grid network was distorted by moving the definition nodes randomly within +-25 m limits to generate the network in Figure 5-24. Sensor placements were applied and the results were in agreement with the findings from the even network evaluation. The Shannon entropy method did appear to respond appropriately to the variations in the network configuration by suggesting more individually weighted placement locations. The unique paths method still strongly indicates all branch extremities with a high rating and as shown in Figure 5-22 this method does not necessarily provide optimal sensor locations for attaining an unambiguous solution. The composite method shown in Figure 5-24 appears to provide a balanced placement hierarchy for making an informed decision for sensor placement.

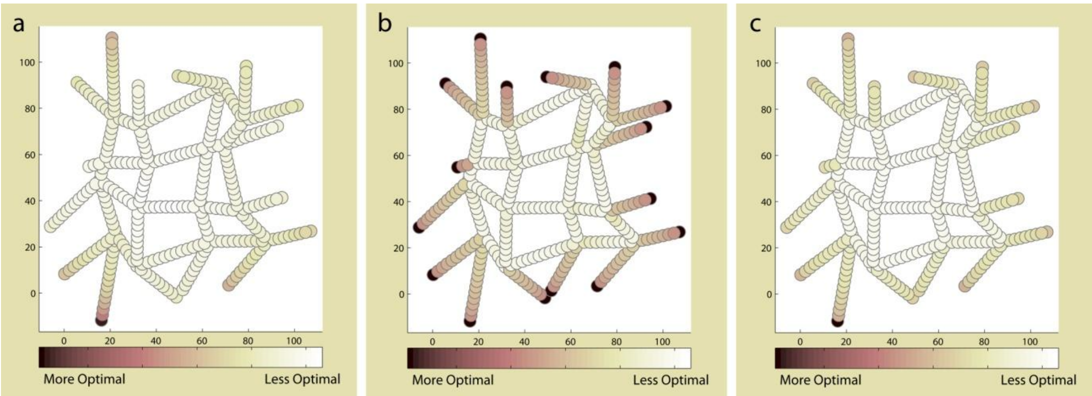


Figure 5-24 Optimal sensor placement results for Stage 3 network configuration a) Shannon entropy method. b) unique path method. c) composite method

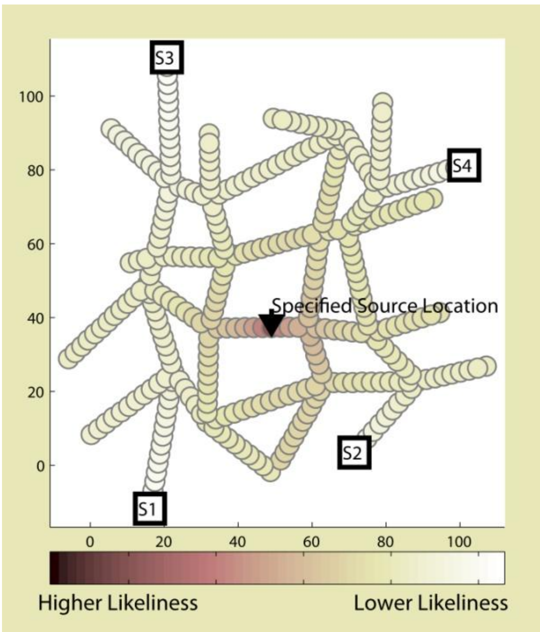


Figure 5-25 Example of successful localisation results for stage 3 network configuration

Placing four sensors a locations informed by the Shannon entropy method was able to generate unambiguous solution for every specified source location, excluding ambiguities along individual branches. An example is shown in Figure 5-25.

5.6.4 Stage 3 Discussion

Primarily, the findings from stage three indicated that the sensor placement methods identified were successful to varying degrees. The indication was that the Shannon entropy method provided the most reliable sensor placement decisions. While the unique paths method did appropriately specify the ends of branches as optimal placement locations it did not make clear definitions between individual branches.

In a real water distribution system numerous reasons could exist which made it difficult or even impossible to place a sensor at a specific location for example a hydrant may be faulty of inaccessible. Therefore while it may be desirable to place a sensor at a particular location this may not be achievable and alternative locations may need to be used. For this reason the composite placement method could provide a suitable means of identifying an alternate location when an ideal one is not available.

Regarding the quantity of sensor locations required; The implication is that provided locations close to those specified as being optimal by the Shannon entropy method are used than a positive solution can be achieve. Increasing the number of sensors should provide stronger less ambiguous results. The number of sensors required is difficult to quantify and really need to be assessed based on each individual network. The findings should suggest that for a mainly looped network, ignoring branches, then using only four loggers should provide a positive result. Through observation if the grid used for stage 3 had increasing number of pipes added by subdividing each square and this process was repeated multiple time the grid would start to represent a surface. In this instance the localisation procedure should still be able to predict the correct source location. The limiting factor would then be the ability to accurately determine arrival time of the primary wave have experience a very large number of intersections. These thoughts reaffirm that the success of the localisation fundamentally lies in successful data acquisition and analysis.

5.7 Stage 4 - Large network simulation

Data was acquired from Stephens et al., (2011), where transients were generated in a live distribution system and pressure data was acquired synchronously at three different locations. The wave speeds in the network were characterised by direct measurement and found to be in the range 1040 ms^{-1} to 1150 ms^{-1} with an average of 1100 ms^{-1}. Providing all the information required to perform a live network source localisation verification.

5.7.1 Model Definition

A discretisation of the Willunga network was created using data from. Instead of calculation the pipe wave speeds for the theoretical model based on pipe parameters, the calculated wave speed of 1100 ms^{-1} was used.

5.7.2 Stage 4 Results - Large network simulation

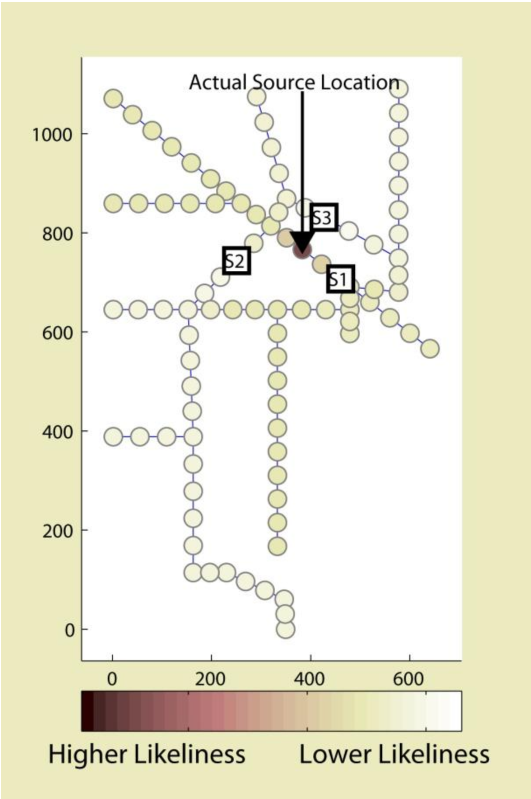


Figure 5-26 Localisation results for transient generation source A

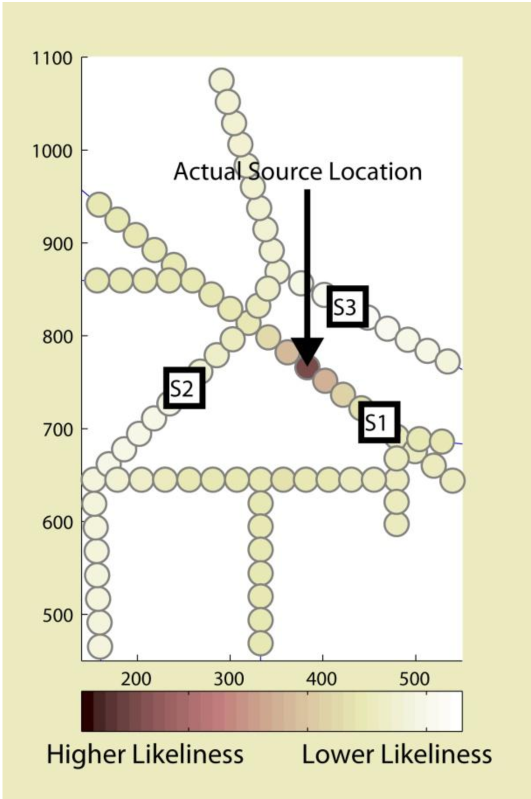


Figure 5-27 Close up of localisation results for transient generation source A

The results shown in Figure 5-26 and Figure 5-27 verify the effectiveness of the source localisation procedure on data acquired from a real water distribution network.

5.8 Discussion of Concept Verification

This chapter verifies the graph theoretical source localisation methodology. The effects of varying wave speeds and arrival times on the accuracy of the localisation result are assessed and while they can considerably affect the result, developing accurate arrival time methods should minimise some of these errors. A practicable level of accuracy should achievable in real distribution systems.

Underestimating wave speeds rather than overestimation them appears to provide smaller localisation errors.

Methods are verified for optimally placing sensors and for determining the quantity of sensors required.

6 Laboratory Verification

6.1 Introduction

Conclusions to chapter 5 indicate that the source localisation methodology fundamentally works for complex looped and branched network configurations. It was identified that successful application of the localisation procedure to real distribution systems would be dependent on the ability to:

- Accurately detect transient pressure primary wave front arrival times at discrete locations in a distribution system.
- Acquire accurately synchronised pressure data at multiple locations in a distribution system.
- Determine minimum feasible sample frequency rates.
- Develop a good understanding of in-situ pipe parameters and wave speeds.

Using data from Stephens et al., (2011), source localisation was shown to be successful when applied to data acquired from a real distribution system, going part way to confirming the above objectives in branched pipe networks. Unfortunately pressure data for the work was acquired between midnight and 5 am to ensure low usage and therefore low system noise. This was ideal for the work's particular purposes, and combined with the relatively simple transit paths, made primary wave fronts and their arrival times easy to identify. Unfortunately this would not necessarily be the case for most practicable source identification purposes. Transients could occur at any time of day or night and in dynamically active systems, increasing the difficulty of estimating wave arrival times. A need was highlighted, to further investigate novel applications of wave arrival detection algorithms, for the successful identification of primary wave front arrival times.

At present, it is possible to acquire high frequency pressure data in the range 500 - 2000 Hz. Whittle et al., (2011)Stephens et al., (2011). While this high frequency data is ideal for transient analysis, the acquisition and storage of high frequency data has significant hardware implications, with large memory requirements for data storage and the increase in power requirements of higher frequency data acquisition. Selective data acquisition could be adopted to optimise storage requirements but for source localisation, this approach could pose its own problems. For example, if a sensor is located a significant distance from a source and the path from the source to that sensor experiences multiple intersections, then the transient pressures observed at the sensor would be attenuated such that they may not be captured were selective data acquisition adopted. The pressure response at this sensor location could still be useful for source localisation. A robust and practicable solution to avoid these problems is to log data continuously at a lower sample frequency providing the facility to collect uninterrupted non selective data for extended periods. This approach facilitates the observation of less significant transient events and in doing so potentially providing a greater understanding as to the long term dynamic variations in a system. The underlying question was; could the novel application of wave arrival detection algorithms provide adequate wave arrival detection at lower sample frequencies? And what sample frequencies would be permissible?

The appropriate means to address these challenges was to develop a physical laboratory based model. Plastic pipe was chosen as the material initially due to the lower wave speeds hence a shorter pipe length and sample frequency could be used. Visco-elastic properties associated with plastic pipes, which facilitate variable pipe wave speeds, added further complexities to the data analysis and source localisation procedure.

The conventional approach for much of the previous analysis of transients in physical laboratory models is to develop systems with single pipelines. The desire was to generate novel datasets using simple looped branched systems by means of a modular pipe test loop system, which could be changed to different system configurations with relative ease. The objectives were to verify the source localisation procedure on physically acquired data, while evaluating novel wave front arrival or onset detection algorithms defined in chapter 4.

6.2 Physical Laboratory Model – Materials and Methods

The objective was to construct a modular test pipeline, allowing the system configuration to be readily changed. This was to enable transient generation and data acquisition on systems of varying complexity. A simple configuration could be adopted to evaluate wave propagation in the chosen pipe material, as well as evaluation of the various wave front onset detection algorithms. The network could be changed, to increase complexity, to evaluate the effectiveness of the source localisation procedure on physically acquired data in a well characterised pipe type, and to further test onset detection algorithms.

6.2.1 Materials

The decision to make a modular test pipe facility, guided the choice of pipe material and the decision was made to use 25 mm Medium Density Polyethylene (MDPE) pipe based on the following reasons:

- Previous work has been undertaken in characterising visco-elastic pipes but a level of uncertainty still exists regarding generic properties of visco-elastic materials suitable for transient pressure analysis. The uncertainties in the behaviour MDPE pipe, even on a simple pipe system, highlight uncertainties which could be present in a real distribution system.
- The low tensile modulus of MDPE ensured relatively slow wave speeds so that meaningful analysis could be achieved, on relatively short sections of pipe.
- MDPE is a homogeneous material routinely used in water distribution system in the U.K. To minimise the risk of bursts subsequent field trials discussed in chapter 7 the aim was to perform the trials in newly laid plastic pipe.(predominantly PE and PVC)
- The availability of quick release couplings and fittings was ideally suited to building a modular reconfigurable system.
- The flexibility of 25 mm pipe ensures a small radius of curvature so that it can be coiled into easily manageable sections.
- The relatively low weight made sections easily manageable.

Two armatures were fabricated to retain the coiled pipe sections; each consisted of a base with four uprights and was constructed from 40 mm steel box section. The pipe was secured to the armatures using plastic tie-wraps.

6.2.2 General Test System Configuration

A schematic of the general configuration of the laboratory test apparatus is shown in Figure 6-1. The objective was to retain much of the rig configuration for each experimental phase and to have a modular test section which could be modified to create the various configurations required. The system was supplied by a header tank, which measured 1 m x 1.2 m x 1m. The free surface of the water in the tank was 4.5 m above the base of the test section. A downstream reservoir collected water once it has passed through the system; this was then returned to the header tank via another 25 mm pipe using an 8 l/s submersible pump. The header tank was fitted with an over flow to maintain a constant pressure head which also fed to the downstream collection reservoir. A 7.4 m pipe connected the header tank to the test section, this was fitted with a ball valve to isolate the pipe and header tank from the test section, this ball valve could also be used to generate transient pressures. All equipment described so far in this subsection remained unaltered for each system configuration.

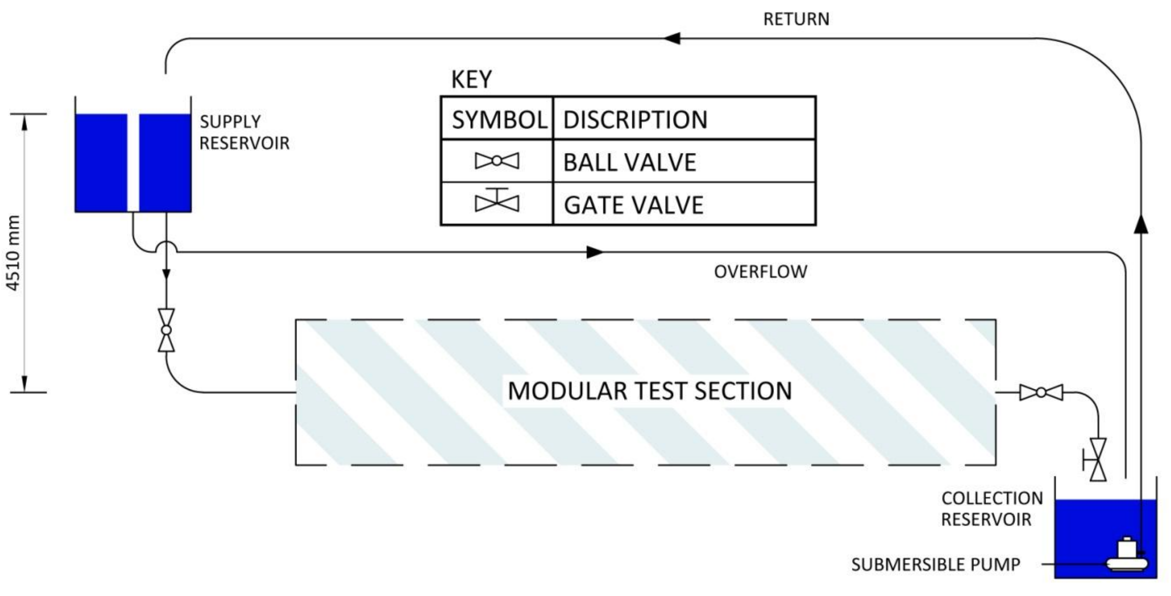


Figure 6-1 Schematic of experimental test pipe configuration

The test section, downstream from the aforementioned ball valve varied for each system configuration. The outlets of the test system were always fitted with gate valves for flow regulation. Immediately after each gate valve an upturned 90° bend was fitted to stop the downstream pipe draining following a valve closure, hence providing a constant reflection boundary at atmospheric pressure.

Figure 6-2 Collection reservoir with submersible pump showing pipe outlets with 90 bends to stop system drainage

6.2.3 Phase I – Single Pipe Configuration 4 Loggers High Fs

The objectives for phase I was to provide a detailed analysis of the wave propagation in the viscoelastic MDPE pipe material. The goals were to characterise the wave speed in the 25 mm pipe and to evaluate the primary wave front arrival time estimation methods (onset detection methods) defined in chapter 4.

Table 6-1 Phase I system overview

Phase VI - Single pipe line High Frequency data acquisition.	Data Logger	National Instruments 6009
	Sample Frequency	4 kHz
	No. Sensors	4
	Sensor range	-1 – 9 bar
	No Ball valves	2 Upstream valve Downstream valve

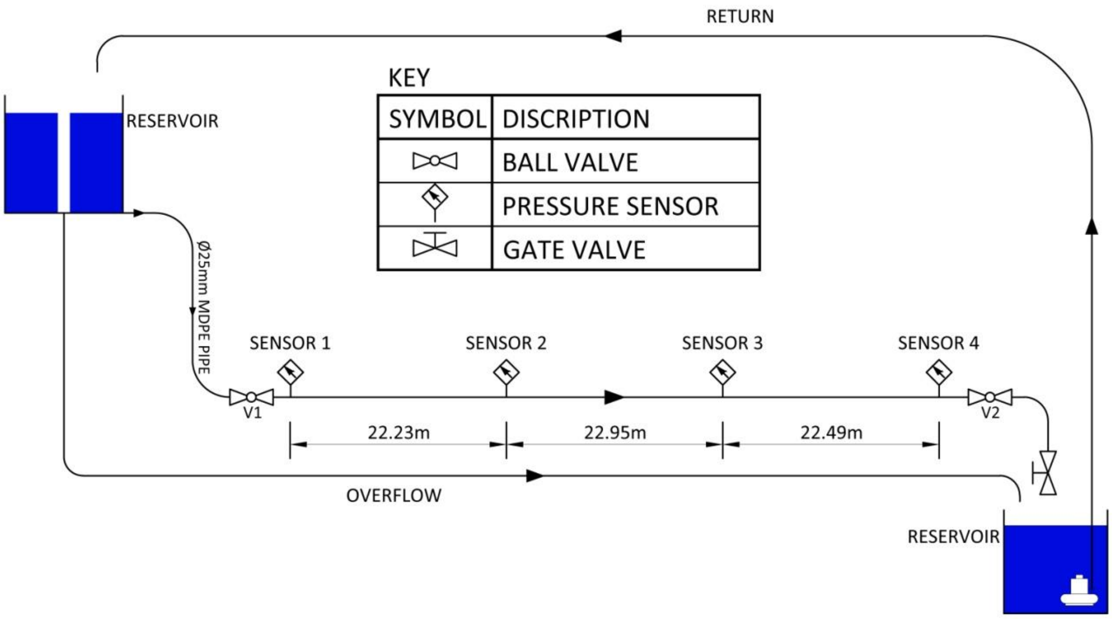


Figure 6-3 Phase I schematic

The configuration for phase I was kept as simple as possible. It consisted of a single pipeline with two manually operated ball valves for transient generation. Four pressure sensors were installed along the length of the test pipe, at locations specified in Figure 6-3. The number of sensor locations was kept to a minimum because each sensor installation would have some influence on the propagation of the generated transient pressure waves. Four sensors was deemed sufficient to asses wave speed variations, by providing three pipe lengths to measure wave speed variations with distance.

The four sensors were connected to a USB data acquisition board, which had a maximum sample frequency of 40 KHz and when used in differential mode 16 bit resolution. Each of the four acquisition channels was set to acquire data at a sample frequency of 4 KHz. This sample frequency was chosen because the max response to the pressure transducers was 2 KHz, therefore ensuring that data from the transducers would be captured at all frequencies without the need to apply anti-aliasing filters.

A 22m pipe coil was situated between the downstream transient generation valve and the collection reservoir to ensure reflected transient waves did not reach the ball valve prior to full valve closure. Flow rate through the pipe was governed by a gate valve fitted to the outlet. The test section pipe coil was secured inside one of the steel pipe support armatures.

6.2.4 Phase II – Long T Configuration

The objectives for phase II were to:

- construct a simple branched system for a preliminary validation of the transient source localisation procedure,
- acquire data that could be used to evaluate the source localisation based on the 10 different wave arrival time estimation methods defined in chapter 4.

Phase II – Long T	Data Logger	Measurement Computing
	Sample Frequency	300 Hz
	No. Sensors	4
	Sensor range	-1 – 9 bar
	No Ball valves	3 Upstream valve Downstream valve – main line Downstream valve – T

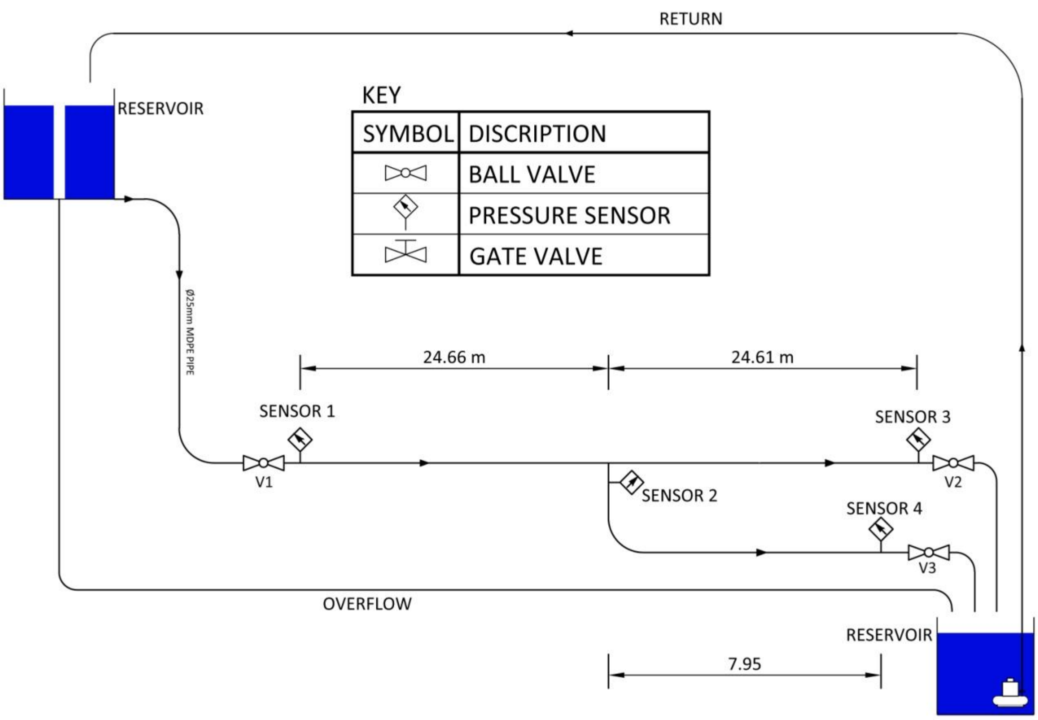


Figure 6-4 Phase II schematic

To simplify subsequent analysis a simple system configuration was used, which consisted of a main pipe section with an upstream and a downstream ball valve, V1 and V3 respectively, with a T-junction and branch pipe located approximately half way between the two valves. Both pipes fed to the collection reservoir. A manually operated transient generation ball valve (V2) was located along the branch, the objective being to generate physical acquired results which were comparable to those modelled theoretically in section 5.3. Transients could also be generated by using valves V1 and V2, giving the option to generate data where the source was not equidistant between the two localisation sensors. Flow in the main pipe and the branch was governed by gate valves at their respective outlets.

Four pressure transducers were place in the system, one next to each ball valve and one at the T-junction as specified in Figure 6-4. The pressure transducers were connected to a single USB data acquisition board which had a maximum sample frequency of 1.2 KHz. Four channels on the board were used, each set to sample at a frequency of 300 Hz.

Figure 6-5 Phase II pipe coil configuration

To aid the modularity of the test rig, pipe coils were retained by pairs of steel flat bar, one length was place inside the coil and one placed on the outside then the two lengths were joined by bolts at either end, 5 mm foam sheets were placed between placed between the steel bars and the pipe to help minimise compression of the pipe. The branch pipe was attached to a timber armature. This configuration can be seen in Figure 6-5.

6.2.5 Phase III – Looped & Branched Configuration

It was identified as a critical step prior to undertaking field experiments to evaluate the success of the transient source localisation procedure on data from a simple looped system as identified in phase III. It constituted the simplest configuration necessary to validate the applicability of the source localisation methodology. The Objectives for phase III were to:

- construct a looped branched system similar to the theoretical system in section 5.4 to validate the results on a physical acquired data,
- further evaluate the wave arrival time estimation methods in a looped system were wave fronts diverge to create multiple transit paths and subsequently converge creating interference,
- Confirm that localisation ambiguities could be mitigated by considering the results from multiple sensor pairs.
- establish the extent to which wave speed retardation affects the source location predictions in more complex pipe configurations.

Phase V – Loop with long downstream section	Data Logger	National Instruments 6009
	Sample Frequency	4 kHz
	No. Sensors	4
	Sensor range	-1 – 9 bar
	No Ball valves	3 1 Upstream valve 2 Downstream valve

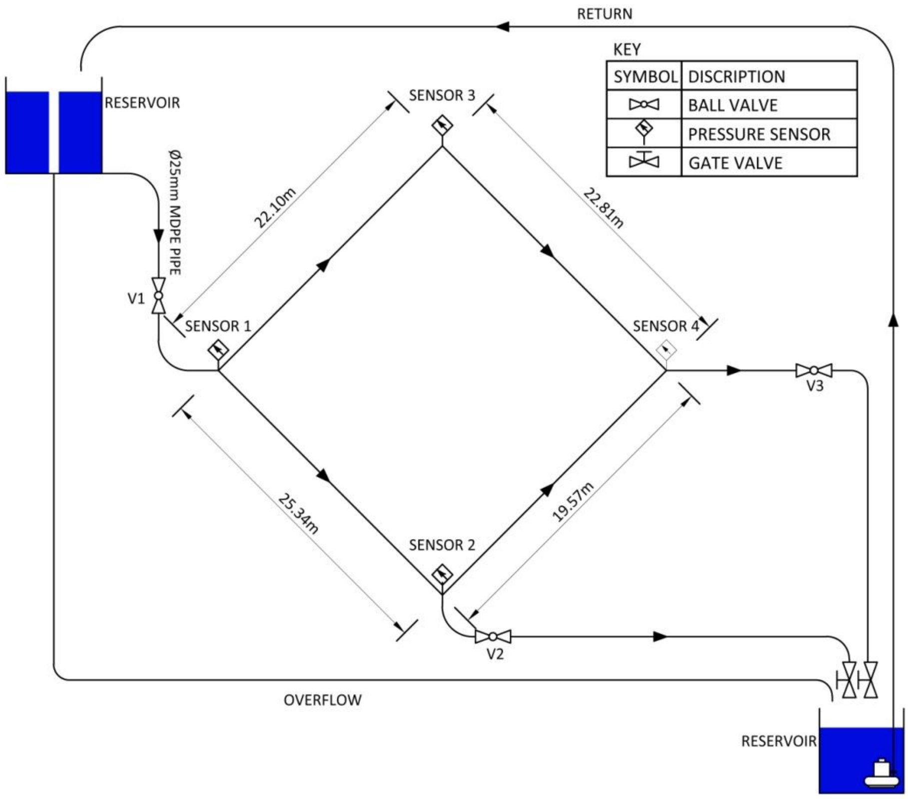


Figure 6-6 Phase III schematic

The test pipe configuration for phase III represented a simple looped branched pipe network with the looped section of rig facilitating wave front divergence from any of the transient generation valves. Two branches from the main loop fed to collection reservoir and each branch was fitted with manually operated ball valve for transient generation and a gate valve at the outlet for flow control. Having two branches meant that transients could be generated at more than one downstream location to provide a more comprehensive data set, it also permitted flow through the system via a branch that remained open after the closure of one of the downstream valves.

Four -1:9 bar pressure transducers were installed in the test rig, the location of these and the three manually operated transient generation ball valves are best shown in Figure 6-6. The four transducers were connected to the same USB data acquisition board used in phase I and data was acquired simultaneously for all four sensor locations at a sample frequency of 4 KHz.

If a transient is generated along a branch from a main pipe and the pressure transducers used for observing the transient event are situated on the main pipe, then theoretically, the fundamental source localisation procedure can only localised the source to the node connecting the branch to the main pipe. To verify this, one of the downstream ball valves was place at a distance away from the junction.

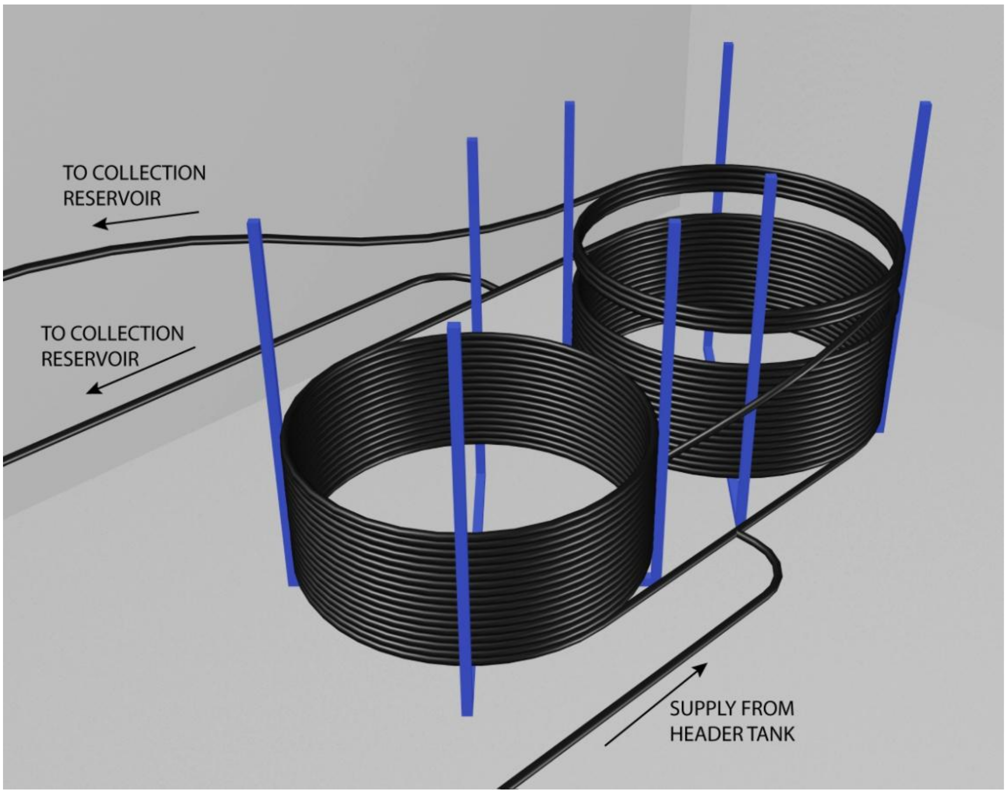


Figure 6-7 Phase III pipe coil configuration

6.3 Test Methodology

For each test phase, transients were generated by the manual operation of a ball valve at locations specified in the previous schematics. Following each valve operation at least one minute was allowed to elapse before the next valve operation was performed, to allow the steady state system pressure to stabilise.

Data capture was triggered automatically when the pressure at a specified sensor (trigger sensor) exceeded a defined threshold. To determine the trigger threshold the steady state pressure at the trigger sensor location was acquired for a period of 2 seconds, the acquired data was averaged to find the mean steady state pressure. The trigger threshold was set above or below the observed steady state pressure at an increment which exceeded the observed noise.

Following the operation of a transient generation valve, data acquisition was triggered once the pressure at the trigger sensor exceeded the predetermined threshold. A pre-trigger sample of 10 seconds was acquired and 20 seconds of data post trigger was acquired for all pressure transducers.

The flow was controlled by closing the outlet gate valve. The main reason to reduce the flow was that due to the relatively low head provided by the header tank, if a transient was generated with full flow conditions, it was possible to generate ‘negative’ pressures of such a magnitude that would lead to cavitation and column separation. Cavitation was undesirable as it could lead to increasing the complexity of the analysis.

With manual operation of the ball valve, the rate of closure could easily be varied to generate transient pressures with differing wave profiles. Flow rates were measured by timed filling time of a 10 l container.

6.3.1 Pipe wave speed Characterisation

To provide suitable data to ascertain pipe wave speeds, transients were generated in the phase I test configuration by operating the downstream ball valve. A valve operation cycle consisted of a rapid valve opening with subsequent time allowed for a steady state to resume followed by a rapid valve closure. This cycle was performed twenty times to confirm the repeatability of the results.

6.3.2 Wave front Arrival time detection

Wave arrival time estimation methods were evaluated using the same dataset generated to evaluate the pipe wave speed.

6.3.3 Application of source localisation Laboratory Data

To verify the transient source localisation methodology, data sets were acquired from the phase II and phase III test configurations. Transients were generated through the manual operation of ball valves in the respective systems with simultaneous data acquisition triggered for all four sensors, as previously mentioned.

6.4 Results

In this section results are shown from all three test phases in order of phase I, phase II then phase III, with objectives addressed in the following order.

Phase I

- Pipe wave speed and elastic modulus characterisation
- Evaluation of wave arrival (onset) detection algorithms

Phase II

- Wave arrival time estimation
- Source localisation evaluation

Phase III

- Wave arrival time estimation
- Source localisation evaluation (linear wave speed)
- Source localisation evaluation (non linear wave speed)

Early results show pressure as head (m) later results use a voltage scale on the vertical axis emphasising that the focus was on relative variations in the observed signals and that temporal occurrence of these variation is of prime importance.

6.4.1 Phase I

6.4.1.1 Pipe Wave Speed Characterisation

The main objective of the phase I pipe configuration was to measure the propagation speed of a transient pressure primary wave front in the 25mm MDPE pipe. Due to the apparent wave speed reduction in viscoelastic pipes, four pressure transducers were installed at four locations along the test pipe so that for comparison the wave speed could be measured in three different sections of pipe.

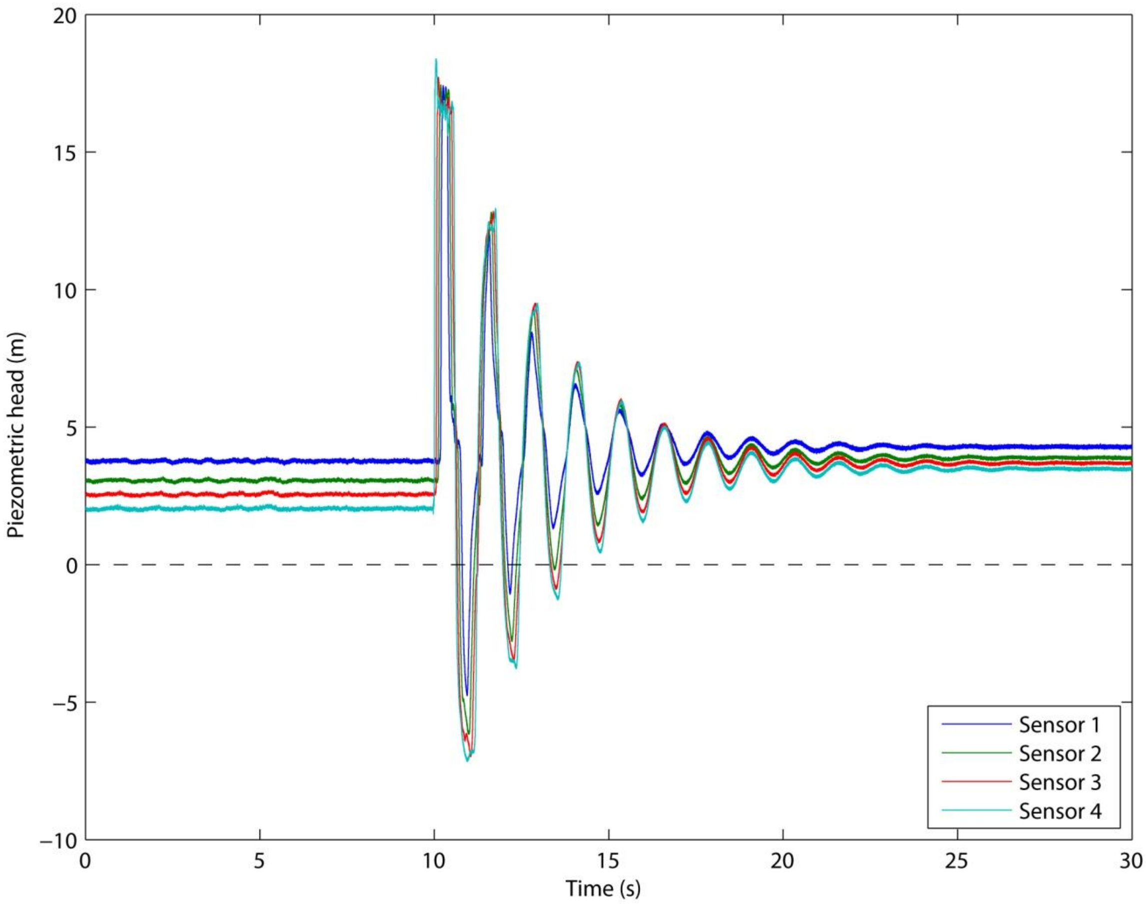


Figure 6-8 Full plot transient resulting from a downstream valve closure for single pipe configuration

The transient pressures observed in Figure 6-8 were generated by a fast closure of the downstream ball valve V2. The pressure profile shows typical characteristics associated with transient pressure response in viscoelastic pipe material. This can be observed in greater detail in Figure 6-9 where the pressure is plotted over a shorter time interval. The viscoelastic response is represented by the gradual curve of leading edge of each successive peak or trough excluding the primary wave front. Observing the first pressure peak for all sensor locations approximately between 10 and 10.5 seconds, the pressure has a number of small fluctuations at the part of the wave. In an ideal situation, following the initial pressure spike the pressure should show a smooth gradual pressure reduction before the following downsurge. These small fluctuations are most likely attributed to the sensor and valve fittings where small changes in diameter and stiffness momentarily occur. On a pipe of this size it isn't possible to remove these fluctuations and they should not substantially affect subsequent analysis.

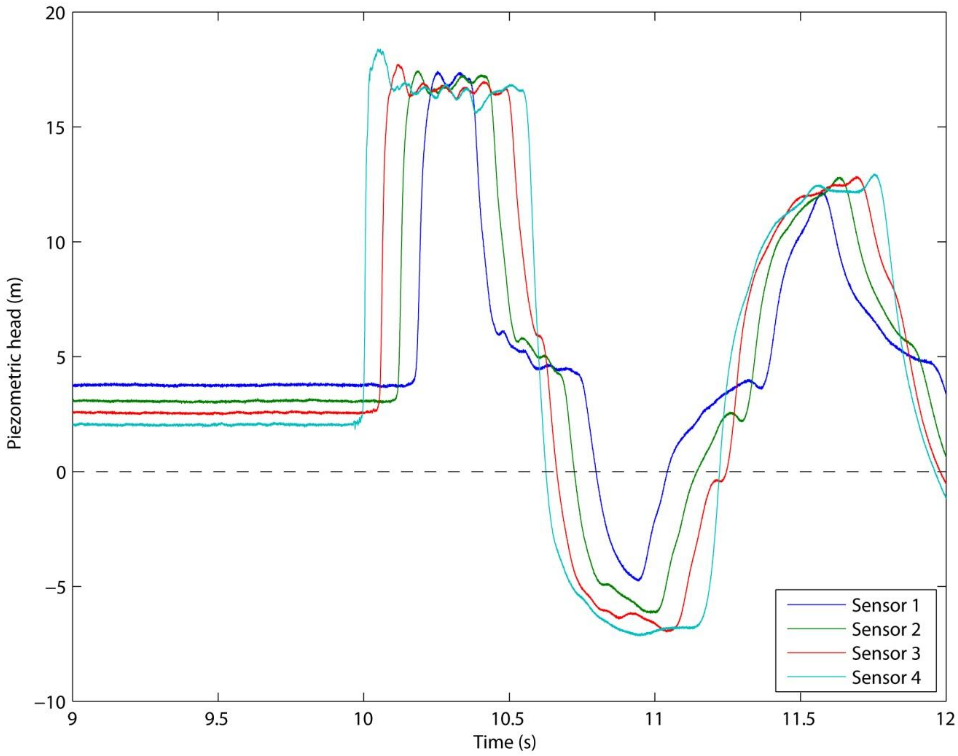


Figure 6-9 Close up of transient caused be downstream valve closure of phase I configuration

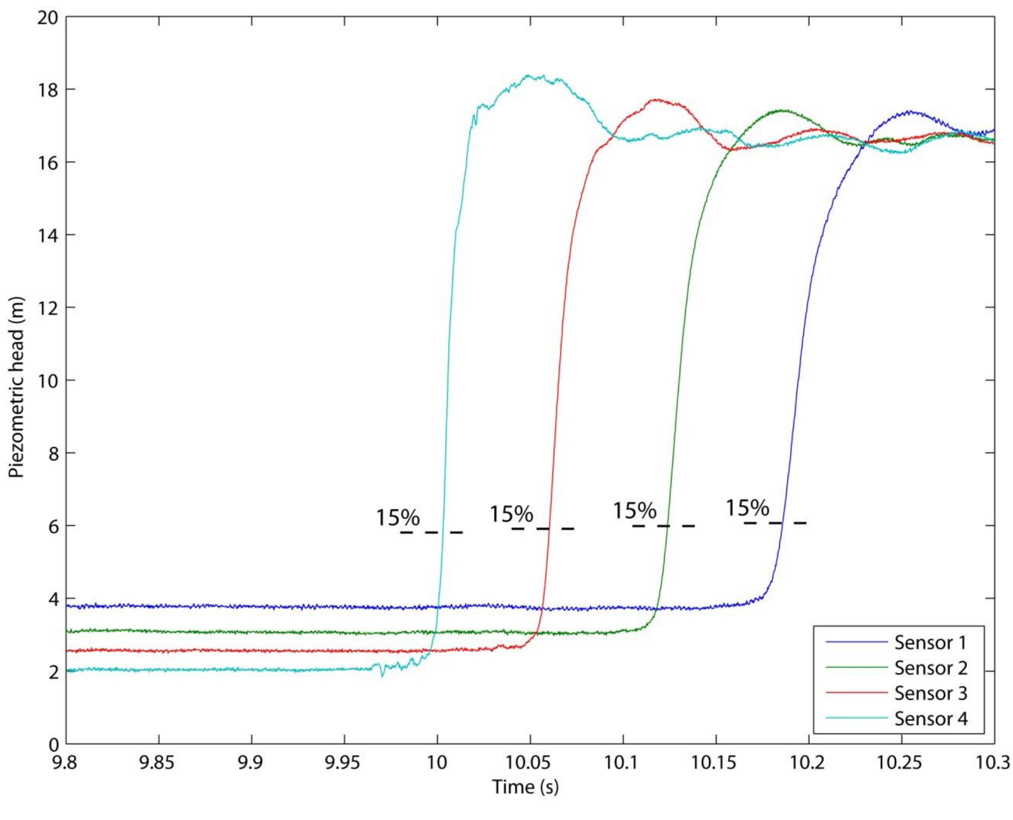


Figure 6-10 Primary wave front arrival at four sensor locations in phase I configuration following a downstream valve closure. 15% pressure rise indicates wave arrival as in Covas et al., (2004)

As the primary wave front progresses along the pipe its profile changes as a result of dispersion and attenuation (referred to as degradation in Keramat et al., (2012)). Wave front degradation is apparent in Figure 6-10 as the wave travels further from its source location. It is apparent due to the reduced steepness and increased length of the wave front with a less defined onset curve.

The first step to measuring the speed of the primary wave front is to definitively determine the arrival time of the wave front at each sensor location. Apparent in Figure 6-9, and shown more clearly in Figure 6-10, the primary wave front is not an instantaneous step but as described previously it has a gradual slope. The gradient changes gradually at the start and the end of the primary wave front and at sensor 1 the greatest pressure rise occurs between approximately 10 and 10.02 seconds. Due to the gradual gradient increase at the start of the pressure rise the precise identification of the onset times of the primary wave fronts through visual inspection is difficult. A more specific arrival time can be obtained by using the method referred to in Covas et al., (2004). This method involved finding the mean pressure prior to the wave front onset then identifying the 15% pressure rise between this pressure and the peak pressure of the primary pressure rise. Using this approach to determine the wave arrival times and knowing the distance between each sensor, the following wave speeds were calculated. Sensor4-Sensor3=393.18 ms^{-1}, Sensor3-Sensor2=360.43 ms^{-1}, Sensor2-Sensor1=359.87 ms^{-1}. These wave speeds show that retardation is consistent with the findings in Covas et al., (2004) but due to differing specific pipe parameters the actual values are different. Rearranging the wave speed equation to make the Young's modulus the subject gives equation (4.32) which can be used to estimate dynamic Young's Modulus.

$$E = \frac{K}{\left(\frac{K}{\rho a^2} - 1\right)\frac{e}{D}} \tag{4.32}$$

The maximum and minimum implied dynamic Young's Modulus were calculated, these were 1.34 GPa and 1.11 GPa respectively. These values for Young's Modulus are considerably higher than values specified in manufacturers literature where the upper value for E for MDPE is generally around 0.8 GPa with a minimum of around

0.4 GPa, highlighting the higher values required when dynamic loading is being considered.

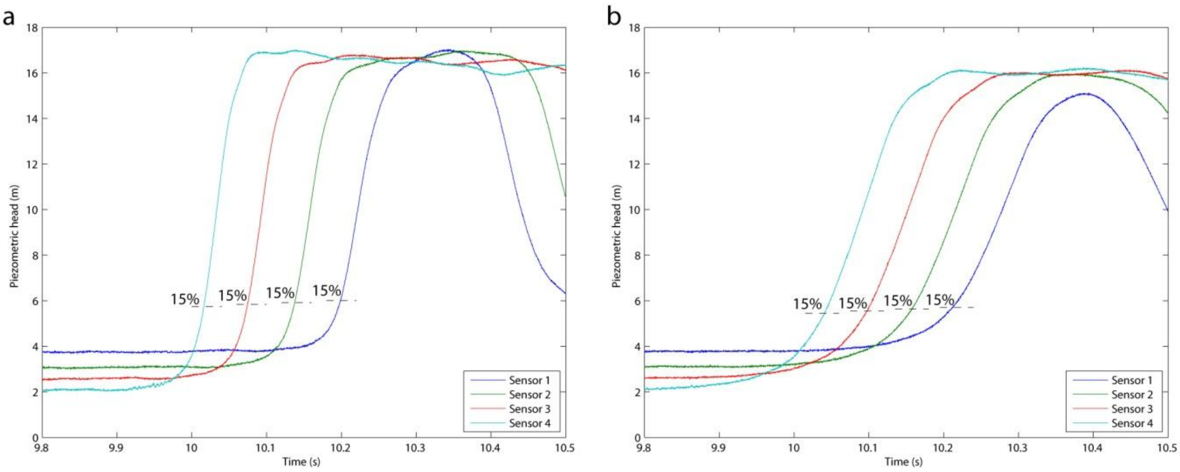


Figure 6-11 Pressure response following slow valve closures at two different closure speeds a) slow valve closure b) very slow valve closure. 15% pressure rise indicates wave arrival as in Covas et al., (2004)

Figure 6-11 shows pressure plots of the primary wave front at all four sensors following slow valve closures at two different closure rates. 15% pressure rises were calculated for each sensor and are marked on the primary wave front for each sensor location. The effect of the reduced valve closure rates can be seen, with reduced gradient of the primary wave front and a slower increase in gradient at the start of the pressure rise. In Figure 6-11 b, which is for the slower of the two closure rates, the shallower gradient means that at sensor 1, the start of the wave front has reflected at the supply reservoir and arrived back at the sensor 1 location, before the primary front has fully passed. The result of this is that the peak pressure at sensor 1 is not as high as at the other sensor locations impacting on the ability to determine the wave arrival time using the 15% pressure rise method. This is highlighted below in Table 6-2.

Table 6-2 Wave speeds calculated at the 15% pressure rise for different valve closure rates

Closure Speed	Wave Speed (ms-1)		
	S4-S3	S3-S2	S2-S1
Fast valve closure	393	360	360
Slow valve closure	385	363	365
Very slow valve closure	398	383	407

It is clear in Table 6-2 that the wave speeds calculated for the very slow valve closure, vary considerably from those of faster closure speeds. This highlights the need to explore more robust methods for determining the arrival times of the primary wave front and also to compare the estimated wave speeds using these methods.

Following the rapid closure of valve 2 no residual flow exists in the pipe other than that associated the associated transient flow. This means that successive pressure oscillations are attenuated minimally and that the pressure wave can make numerous transits of the test pipe, this can be observed in Figure 6-12. Considering one full pressure oscillation, by this meaning from mean pressure, to positive, to negative and back to mean, represents four transits of the test pipe, from valve 2 to the supply reservoir reflection boundary. Therefore every time the pressure crosses the mean line represents two transits. Knowing the length of the pipe and the period of oscillation is another indicator of the pipe wave speed

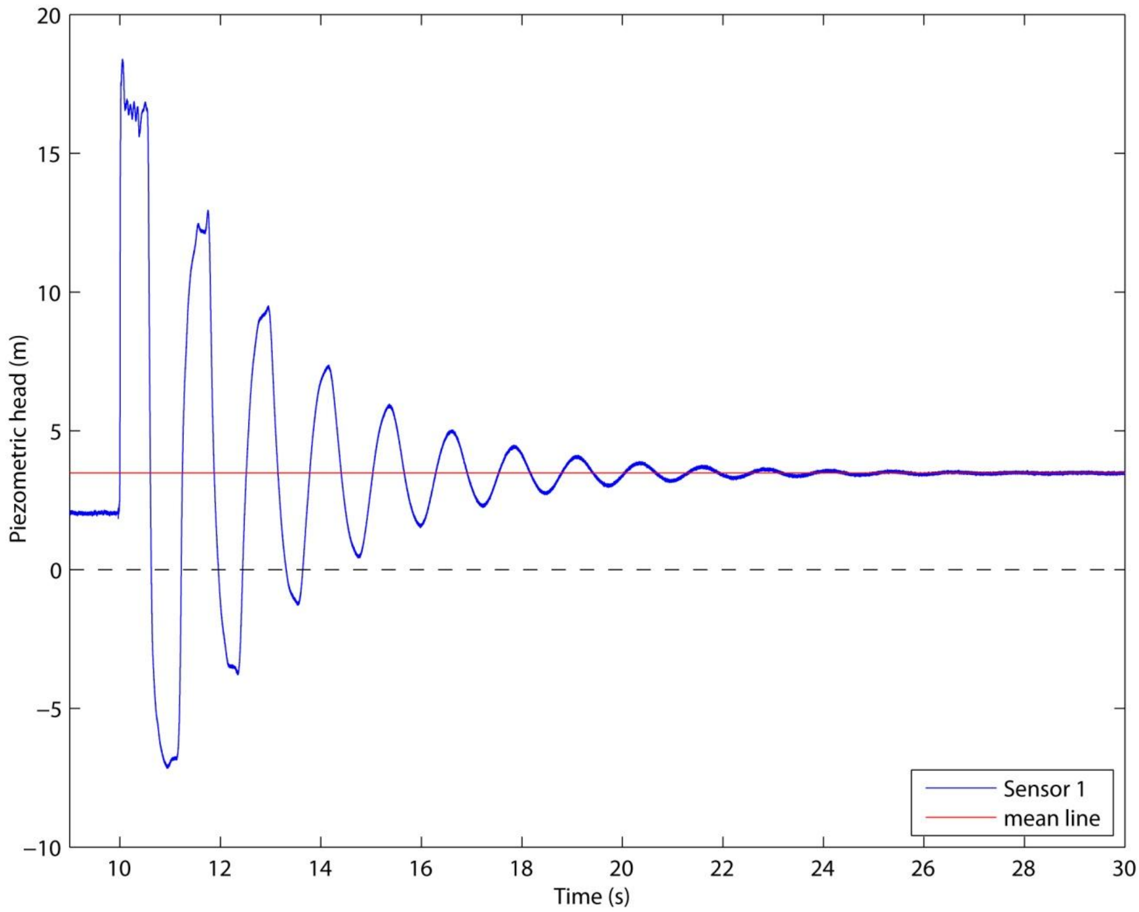


Figure 6-12 Pressure/time plot for sensor 4 following a rapid downstream valve closure, with the mean of the final steady state pressure indicated.

The length of the pipe from valve 2 to the supply reservoir was 75.3 m the arrival times for each oscillation were manually recorded and the relative wave speed was calculated. The wave speed against total distance travelled is shown in Figure 6-13

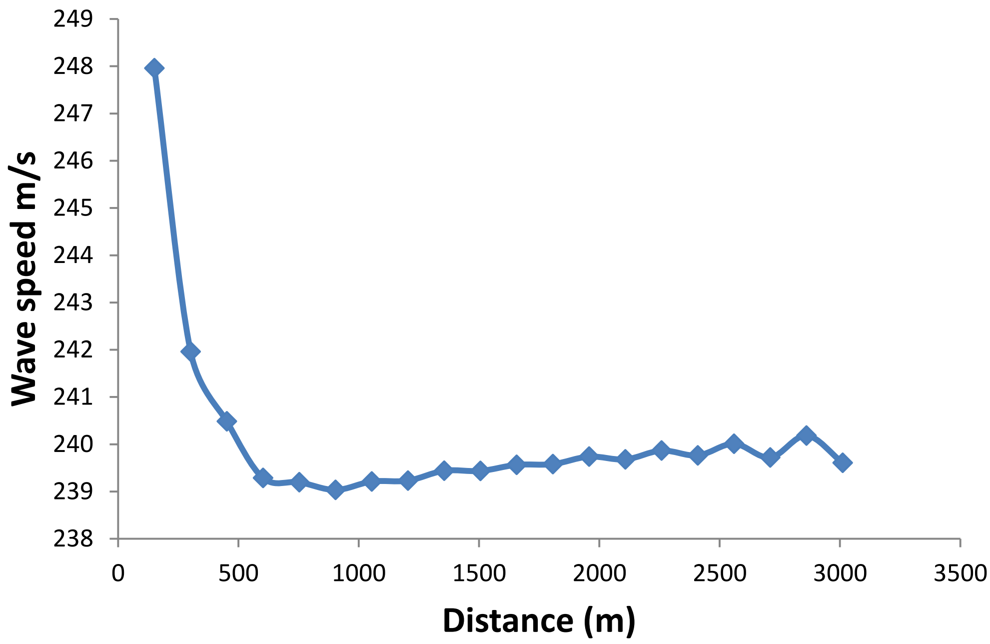


Figure 6-13 Wave speed/total distance travelled from pressure oscillations across the mean final steady state pressure

The wave speeds shown in Figure 6-13 are far lower than those calculated using the primary wave front, which would either indicate a considerable retardation in the wave speed or non instantaneous reflection at either or both of the reflection boundaries. The later of these two outcomes has significant implications on the source localisation method. The aim of the method is to only consider the transit times of the primary wave front to minimise uncertainties which could be present in a fully deterministic model. The large variation in wave transit times caused by the reflection boundary would significantly alter localisation predictions if reflected waves were to be considered and these variations were not fully accounted for.

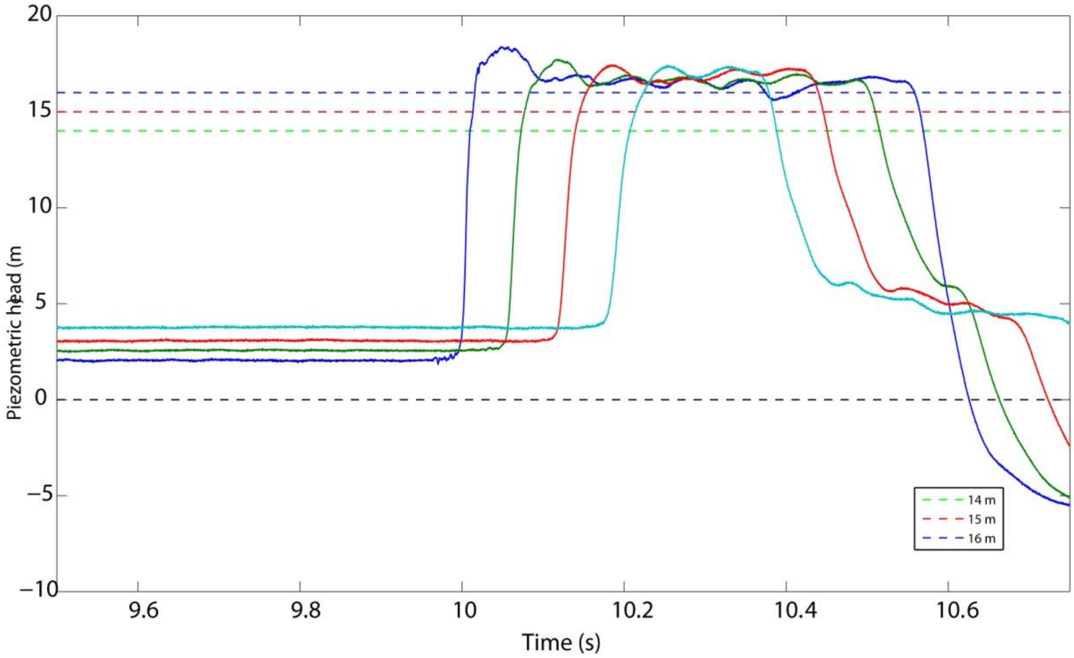


Figure 6-14 14, 15 and 16 m lines to determine arrival time of reflected wave front

To verify that the wave speed had not reduced to values indicated in Figure 6-13 and show that reductions must be associated with interactions at the reflection boundary, the speed of the first reflected wave was measured based on its arrival time at the four sensors. The wave arrival time was estimated by observing the time at which the pressure reached a specific threshold. Observations were made for three different thresholds to provide comparative results, which are shown in Table 6-3. These results confirm that the reflected wave has not significantly reduced from the speed of the primary wave front. More significantly, the results indicate that the wave speed does not continue to retard but advances as it approaches the generation source. This point is not noted widely in the literature. Researching this phenomenon further was not a key objective for this work because only the primary wave front was being considered for source localisation. It does however highlight a need for greater understanding of the dynamic behaviour of viscoelastic pipe material and implies that using anything other than the primary wave front for source localisation increases complexity and uncertainties.

Table 6-3 Reflected wave arrival time and estimated wave speeds

Method	Arrival Time (s)				Wave Travel Time (s)			Wave Speed (ms-1)		
	S1	S2	S3	S4	S1-S2	S2-S3	S3-S4	S1-S2	S2-S3	S3-S4
16 m pressure line	10.379	10.440	10.503	10.559	0.061	0.063	0.055	364	364	406
15 m pressure line	10.384	10.446	10.510	10.565	0.062	0.064	0.055	360	358	408
14 m pressure line	10.389	10.451	10.515	10.569	0.062	0.065	0.054	359	356	416

6.4.1.2 Wave Front Arrival Time/Onset Detection

Estimating primary wave front arrival times using the location of the 15% pressure rise may be suitable for the analysis of laboratory data but may not be as suitable in real water distribution systems which could be dynamically active due to numerous varying demands, therefore having high levels of background noise. In a real system. considerable dispersion and attenuation would be experienced by the primary wave front as it propagates large distances from the initial source location. The objective was to evaluate the effectiveness of a selection of onset detection methods defined in chapter 4. The data from phase I provided ideal test data to compare the results from the various onset detection procedures. While it is possible to make approximations to the wave arrival time by visual inspection it is difficult to explicitly define the arrival time because the specific time of onset is not clear, hence the need to explore onset detection or wave arrival detection functions to determine this.

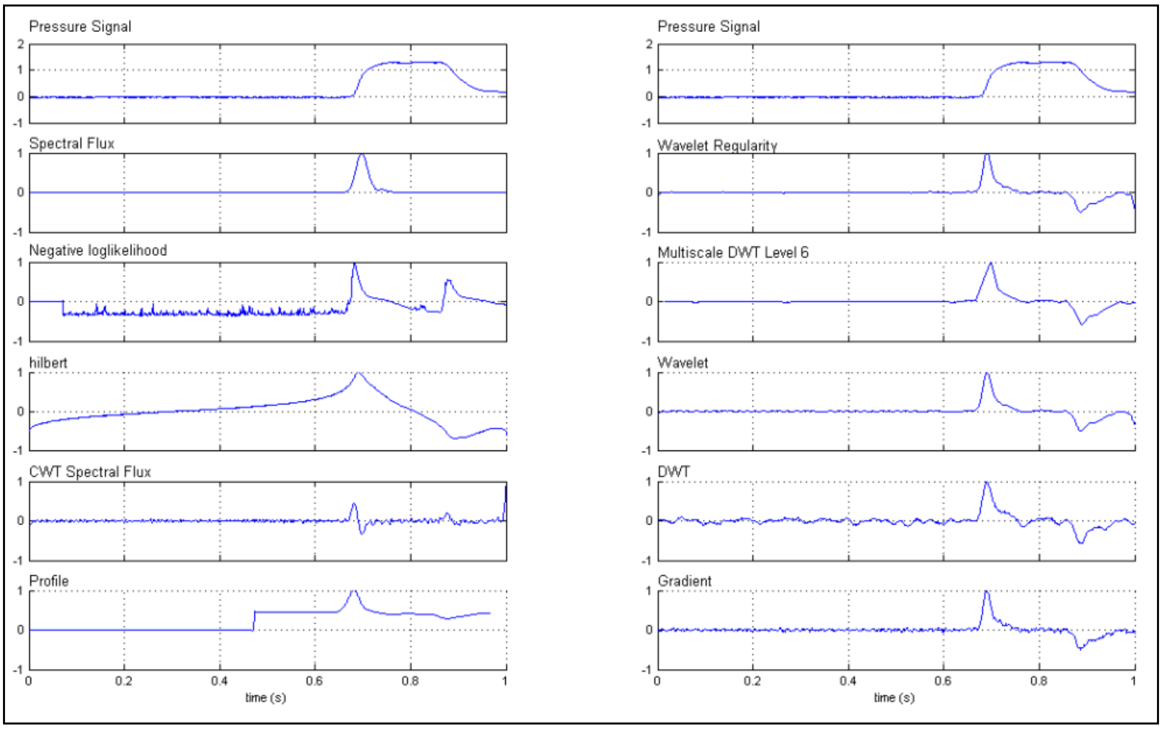


Figure 6-15 Example plots for all ten wave arrival detection (onset detection) methods

Examples of the outputs from the ten wave front arrival detection functions are shown in Figure 6-15, showing that all ten functions have maxima which coincide with part of the primary wave front. A peak finding algorithm is used to automatically find the time that the maxima occurs. All detection methods can identify the wave front but because the front is not an instantaneous step each method tends to maximise at a different location along the wave front.

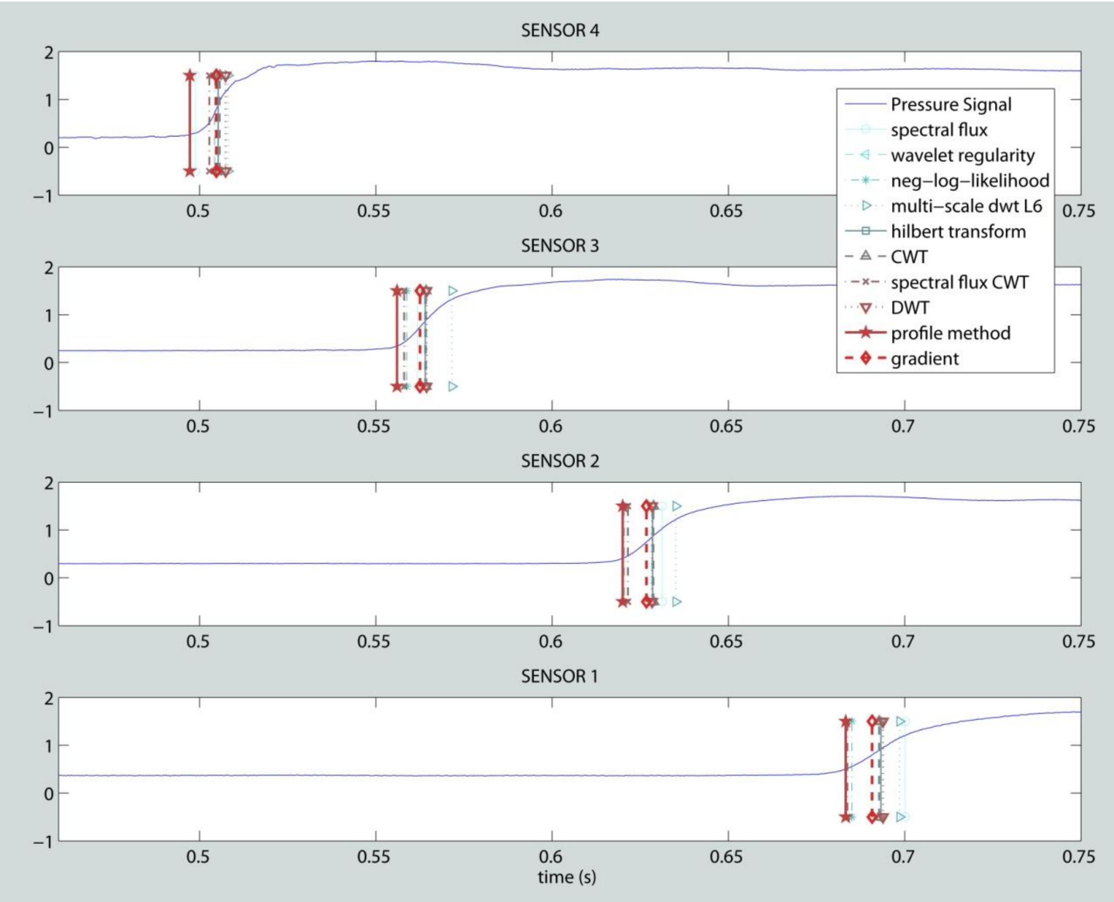


Figure 6-16 Onset locations from onset detection functions, Phase I results

This can be observed in Figure 6-16, which shows the sensor response at all four sensor locations displaying the primary wave front over a 0.3 s range. The markers in Figure 6-16 indicate the wave arrival times as determined by the various wave arrival detection functions. It is evident that the majority of these methods do not find a point on the front that would conventionally be associated with the onset (the start) of the wave. Due to the wave front experiencing attenuation, dispersion and retardation, It is difficult to say whether one location on the wave front is more appropriate than another. The desired outcome is to identify the same relative point on the wave at each location or in other words identify the point which would be consistent with the estimated travel times. The adopted approach to assess this further was to use each method to estimate wave speeds and then compare the results.

Table 6-4 Fast valve closure - wave arrival times, travel times and speeds , using detection functions

Method	Arrival Time (s)				Wave Travel Time (s)			Wave Speed (ms-[1])		
	S4	S3	S2	S1	S4-S3	S3-S2	S2-S1	S4-S3	S3-S2	S2-S1
Spectral Flux	0.497	0.561	0.631	0.699	0.065	0.069	0.068	348	331	325
Wavelet Regularity	0.504	0.563	0.628	0.692	0.059	0.065	0.064	381	356	346
Neg. Log likelihood	0.502	0.558	0.620	0.683	0.056	0.062	0.063	402	369	353
Multi-scale DWT L6	0.508	0.572	0.635	0.699	0.064	0.064	0.064	354	361	350
Hilbert Transform	0.504	0.564	0.628	0.693	0.060	0.064	0.066	375	359	339
CWT	0.504	0.563	0.627	0.692	0.059	0.064	0.065	383	357	341
CWT Spec. Flux	0.501	0.558	0.621	0.682	0.057	0.064	0.061	395	362	368
DWT	0.505	0.564	0.629	0.693	0.058	0.065	0.064	384	351	348
Profile	1.050	1.110	1.180	1.250	0.060	0.070	0.070	375	328	318
Gradient	0.503	0.562	0.626	0.691	0.059	0.064	0.065	384	357	341
							Average	378	351	338

Table 6-4 shows wave speed arrival times, arrival time differences and estimated wave speeds for all four sensor locations using the results associated with a fast valve closure. Visual comparison between each method can be made by referring to Figure 6-17.

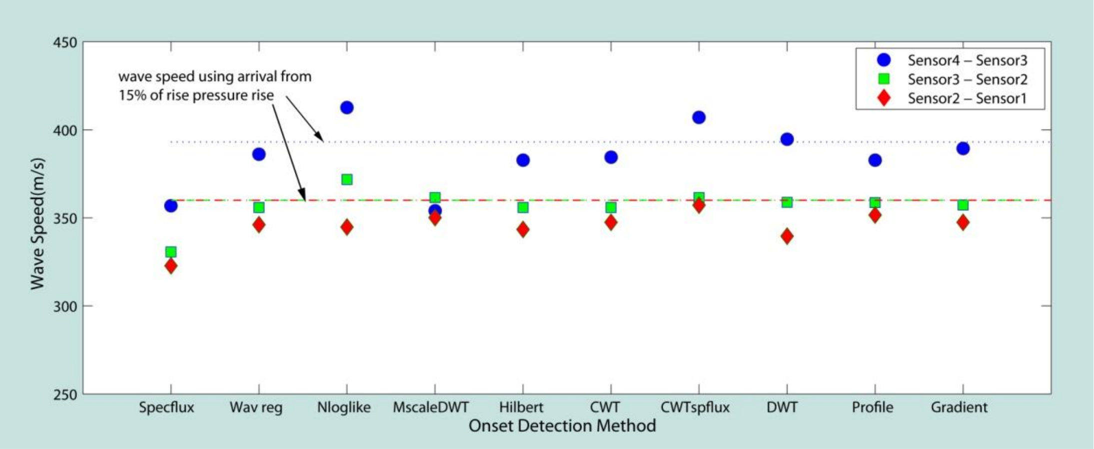


Figure 6-17 Estimate wave speeds following a fast valve closure, calculated using wave arrival time identified by the various onset detection methods on 4 KHs data

The dotted lines in Figure 6-17 shows the wave speeds calculated using the wave arrival times calculated using the 15% pressure rise wave arrival detection method presented in Covas et al., (2004). These wave speeds were used as a benchmark by which to compare the effectiveness of the other proposed wave arrival time detection methods. The reason for using a benchmark was due to the uncertainty in wave speed associated with viscoelasticity and also uncertainty as to the degradation of the primary wave front. Current best practice was shown to use empirical evaluation for wave speed measurements. It was not appropriate to merely compare the apparent arrival times determined by each method, because each method maximises at a different location on the primary wave front. Comparing the apparent wave speeds between two points provided a means for establishing whether each method was identifying the appropriate point on the primary wave front in data from different sensor locations. As well as comparing the wave speeds to those from the 15 % pressure rise the wave speeds defined by each method could also be compared.

There is reasonable agreement between the wave speeds using all arrival detection methods and they are comparable to the wave speeds calculated using the 15 % pressure rise. Most methods confirm the retardation in the wave speed. An exception is the multi-scale DWT method, where the considerable reduction in temporal resolution influences the arrival time interval for wave speed calculation so that the time difference is between each sensor pair is exactly the same. The spectral flux method provides noticeably lower wave speeds, with the most consistent wave speeds being obtained from the Gradient, Hilbert Transform, Wavelet, Profile and Wavelet regularity methods, which all provide similar wave speeds between each sensor pair. This does not necessarily indicate that these methods are the most accurate wave arrival detection methods but it implies that these methods are sensitive to the same significant features in the wave front and indicates that they are potentially suitable for the source localisation procedure.

When using the 15 % pressure rise arrival detection method no discernible difference in the wave speed was observed between sensors 2-3 and sensors 2-1, where as all other ‘successful’ onset detection methods show further reductions in wave speed between these intervals.

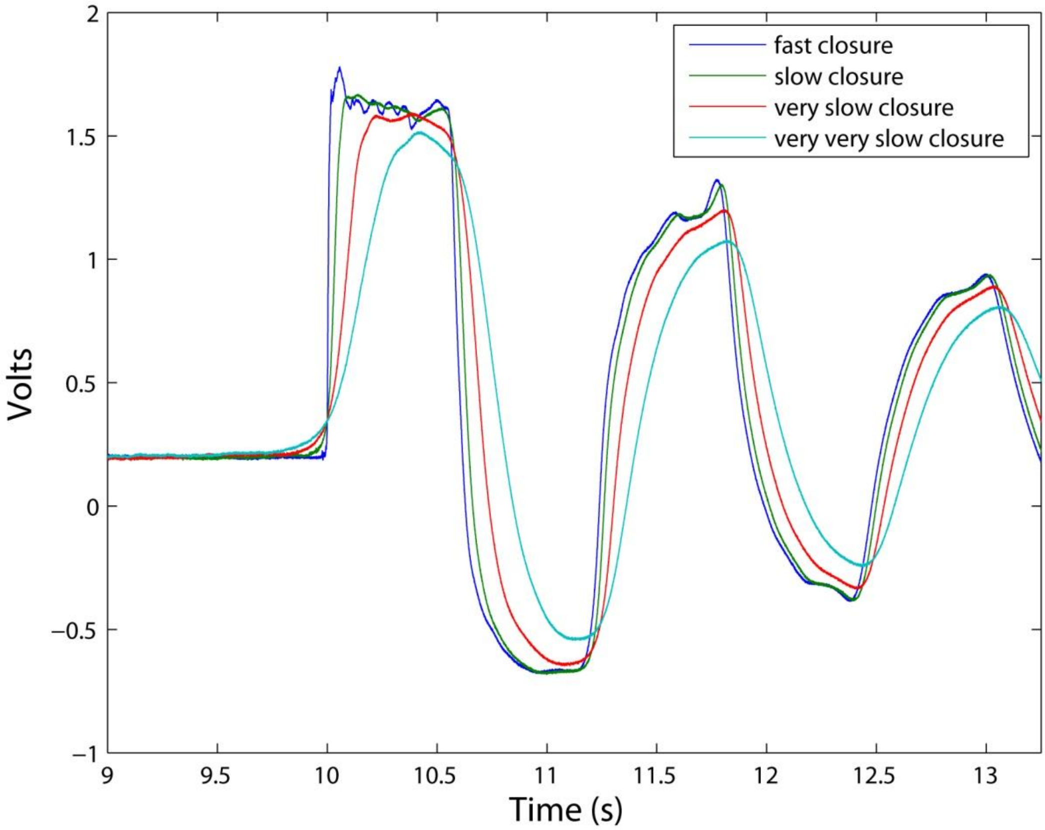


Figure 6-18 Pressure/time plots for four different valve closure rates

Pressure plots associated with four different valve closure rates can be seen in Figure 6-18. Changing the valve closure rate can be clearly seen to alter the profile of the primary wave front. The wave arrival detection methods were used to determine the estimated wave speeds, for comparison.

Table 6-5 Slow valve closure - wave arrival times, travel times and speeds , using detection functions

Method	Arrival Time (s)				Wave Travel Time (s)			Wave Speed (ms-^{1})		
	S4	S3	S2	S1	S4-S3	S3-S2	S2-S1	S4-S3	S3-S2	S2-S1
Spectral Flux	0.534	0.595	0.666	0.734	0.061	0.070	0.068	366	326	328
Wavelet Regularity	0.535	0.594	0.659	0.722	0.059	0.065	0.062	380	353	357
Neg. Log likelihood	0.521	0.579	0.643	0.705	0.058	0.064	0.062	389	360	359
Multi-scale DWT L6	0.540	0.603	0.667	0.730	0.064	0.064	0.064	354	361	350
Hilbert Transform	0.532	0.594	0.658	0.718	0.062	0.064	0.060	364	357	371
CWT	0.536	0.594	0.659	0.726	0.058	0.065	0.068	389	352	329
CWT Spec. Flux	0.513	0.570	0.637	0.701	0.057	0.067	0.064	393	341	347
DWT	0.524	0.589	0.659	0.719	0.065	0.070	0.059	346	326	374
Profile	0.520	0.579	0.644	0.709	0.060	0.065	0.065	376	355	345
Gradient	0.535	0.593	0.658	0.726	0.058	0.066	0.068	391	350	329
							Average	379	350	345

6-6 Very Slow Closure - wave arrival times, travel times and speeds , using detection functions

Method	Arrival Time (s)				Wave Travel Time (s)			Wave Speed (ms-^{1})		
	S4	S3	S2	S1	S4-S3	S3-S2	S2-S1	S4-S3	S3-S2	S2-S1
Spectral Flux	0.597	0.661	0.732	0.811	0.064	0.071	0.079	354	323	281
Wavelet Regularity	0.582	0.671	0.732	0.798	0.090	0.061	0.066	251	379	337
Neg. Log likelihood	0.569	0.625	0.688	0.932	0.056	0.064	0.244	405	360	91
Multi-scale DWT L6	0.603	0.667	0.730	0.794	0.064	0.064	0.064	354	361	350
Hilbert Transform	0.589	0.646	0.706	0.764	0.057	0.061	0.058	398	378	383
CWT	0.579	0.673	0.737	0.788	0.094	0.065	0.051	239	356	434
CWT Spec. Flux	0.575	0.611	0.967	0.007	0.036	0.356	-0.960	625	65	-23
DWT	0.552	0.669	0.710	0.772	0.116	0.041	0.061	193	553	362
Profile	0.578	0.637	0.707	0.772	0.059	0.070	0.065	384	328	342
Gradient	0.579	0.671	0.737	0.808	0.093	0.066	0.071	243	349	315
							Average	325	353	312

6-7 Fast valve closure 100 Hz - wave arrival times, travel times and speeds , using detection functions

Method	Arrival Time				Wave Travel Time			Wave Speed		
	S4	S3	S2	S1	S4-S3	S3-S2	S2-S1	S4-S3	S3-S2	S2-S1
Spectral Flux	1.049	1.112	1.174	1.237	0.063	0.063	0.063	357	365	353
Wavelet Regularity	1.030	1.090	1.150	1.200	0.060	0.060	0.050	375	383	445
Neg. Log likelihood	1.000	1.060	1.120	1.190	0.060	0.060	0.070	375	383	318
Multi-scale DWT L1	1.007	1.007	1.007	1.007	0.000	0.000	0.000	407	416	403
Hilbert Transform	1.020	1.070	1.140	1.200	0.050	0.070	0.060	450	328	371
CWT	1.030	1.090	1.150	1.220	0.060	0.060	0.070	375	383	318
CWT Spec. Flux	0.500	0.260	0.270	0.260	-0.240	0.010	-0.010	-94	2296	-2224
DWT	1.073	1.133	1.093	1.093	0.060	-0.040	0.000	377	-578	Inf
Profile	1.050	1.110	1.180	1.250	0.060	0.070	0.070	375	328	318
Gradient	1.010	1.070	1.130	1.200	0.060	0.060	0.070	375	383	318
							Average	383	364	348

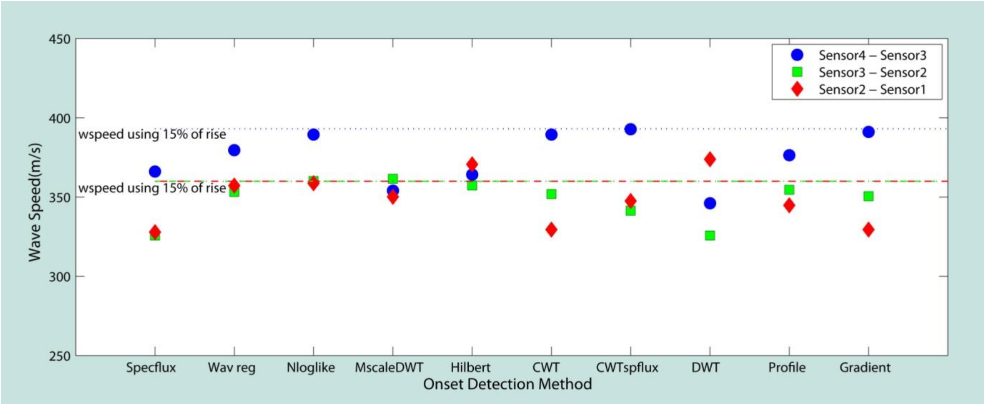


Figure 6-19 Estimate wave speeds following a slow valve closure, calculated using wave arrival time identified by the various onset detection methods on 4 KHs data

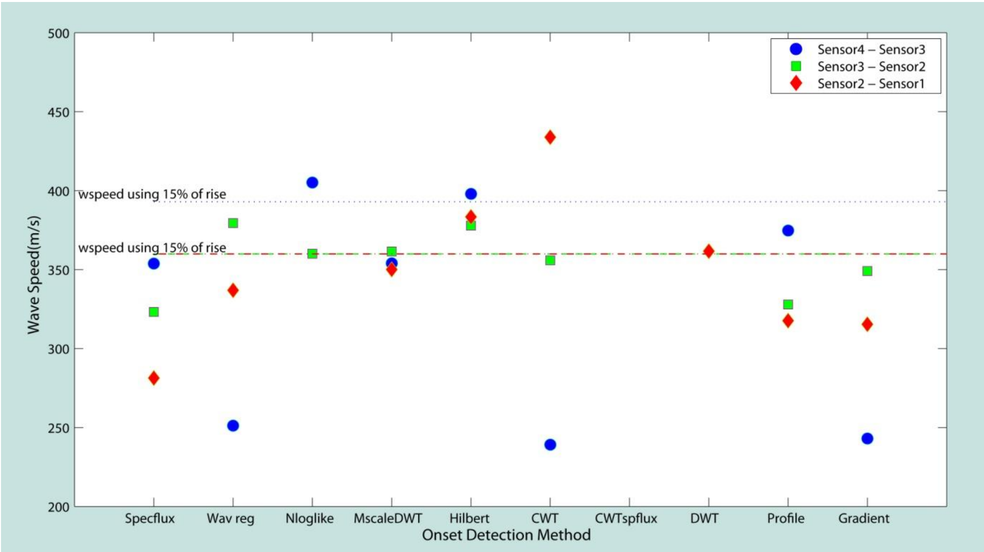


Figure 6-20 Estimate wave speeds following a very slow valve closure, calculated using wave arrival time identified by the various onset detection methods on 4 KHs data

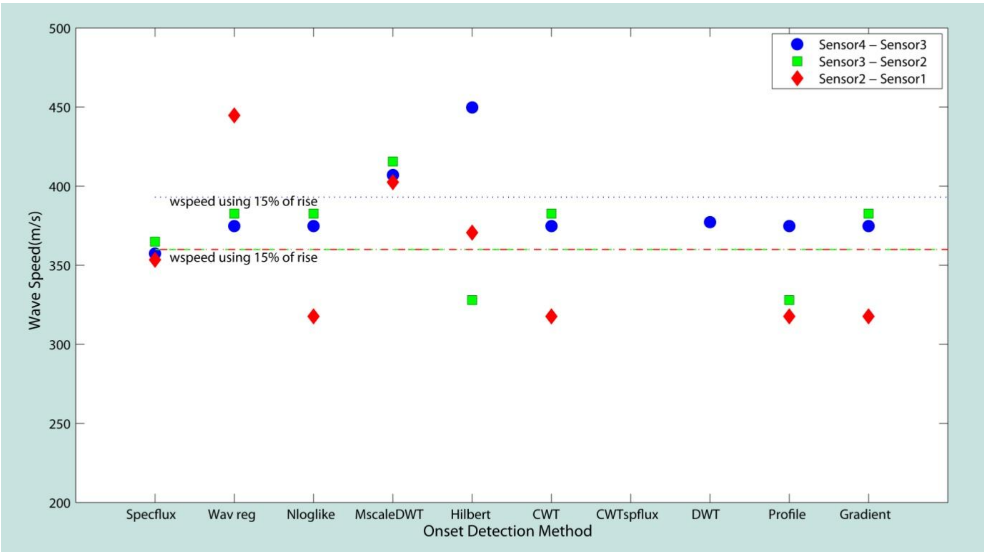


Figure 6-21 Estimate wave speeds following a very slow valve closure, calculated using wave arrival time identified by the various onset detection methods on 100 Hz data

Comparing the wave speed estimates in Figure 6-19, Figure 6-20 and Figure 6-21 while also addressing the results in Figure 6-17 it is clear that greater coherence can be seen in the results for the faster valve closures. For the very slow valve closure the wave speed estimates vary widely but the ability to estimate wave speeds within the limits shown still confirms that these methods are identifying a location on the wave front. The implication is that for transient with a shallower gradient on the primary wave front such as for slow valve closures or pump trips then a localisation result may be less accurate. The 15% rise method also lost accuracy at slower closure rates. Comparing Figure 6-21 to Figure 6-17, the CWT spectral flux and DWT methods appear to fail when the sample frequency is reduced to 100 Hz but the other methods provide reasonable results. This result is crucial because 100 Hz is the desired sample frequency for later field measurements. To make the multi-scale DWT method work L1 was used instead of L6, which still looses temporal resolution, which again explains the similar wave speed estimates along all pipe sections. The most effective detection methods seem to be the negative log-likelihood, the profile method and the gradient method. Although the CWT method shows large variations for slower valve closure rates, it generally performs well and works well for 100 Hz data.

6.4.2 Phase II T-configuration

Results are shown from the phase II T- configuration otherwise described as pipe with a single branch. The objectives for this phase were to acquire data to physically verify the source localisation results from Chapter 5 and to further explore the wave arrival detection methods.

6.4.2.1 Wave Arrival Time Estimation

Taking data for the closure of valve 2, wave arrival estimation functions were applied. This time the data sample used, allowed more than the primary wave front to be analysed by the arrival functions. The reason for allowing a larger sample was to test the robustness of the wave arrival functions. With the increased complexity and the longer transit times that would be expected in data from real distribution systems, isolating the primary wave front from reflections and other pressure fluctuations is likely to be increasingly difficult. Allowing a larger data sample includes other reflections to test the wave arrival functions robustness. Plots of the results are shown in Figure 6-22.

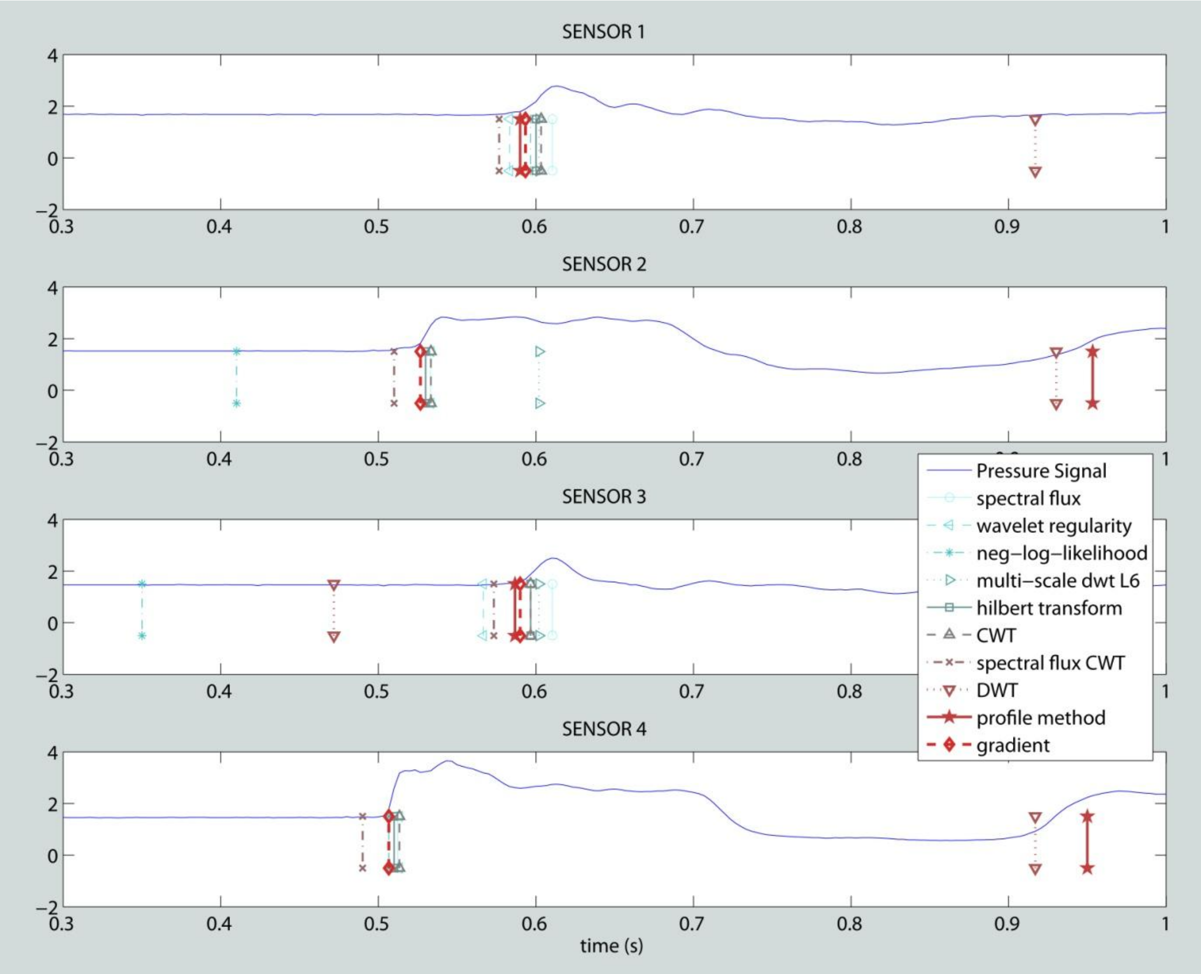


Figure 6-22 Wave front arrival detection results for the closure of valve 2 for the T-configuration

Inspection the results in Figure 6-22 the gradient, CWT and Hilbert transform appear to provide the most consistent wave front arrival detection results. Through visual inspection the other methods show clear discrepancies in their ability to successfully identify the primary wave front let alone the relevant part of the front at different sensor locations. Two attempts were made to manually determine the wave arrival times at all sensor locations.

6.4.2.2 Source Localisation Results

Source localisation was applied to the phase II configuration using the arrival times determined above by the successful wave arrival detection methods and the two manual detection attempts. A graph theory representation of the phase II configuration was generated with a 1 m discretisation resolution. Source localisation was applied using the arrival times at sensor 1 and sensor 2. Wave speed retardation was ignored and a fixed value for E of 1.1 GPa was used based on the lower values attained empirically from the phase I results.

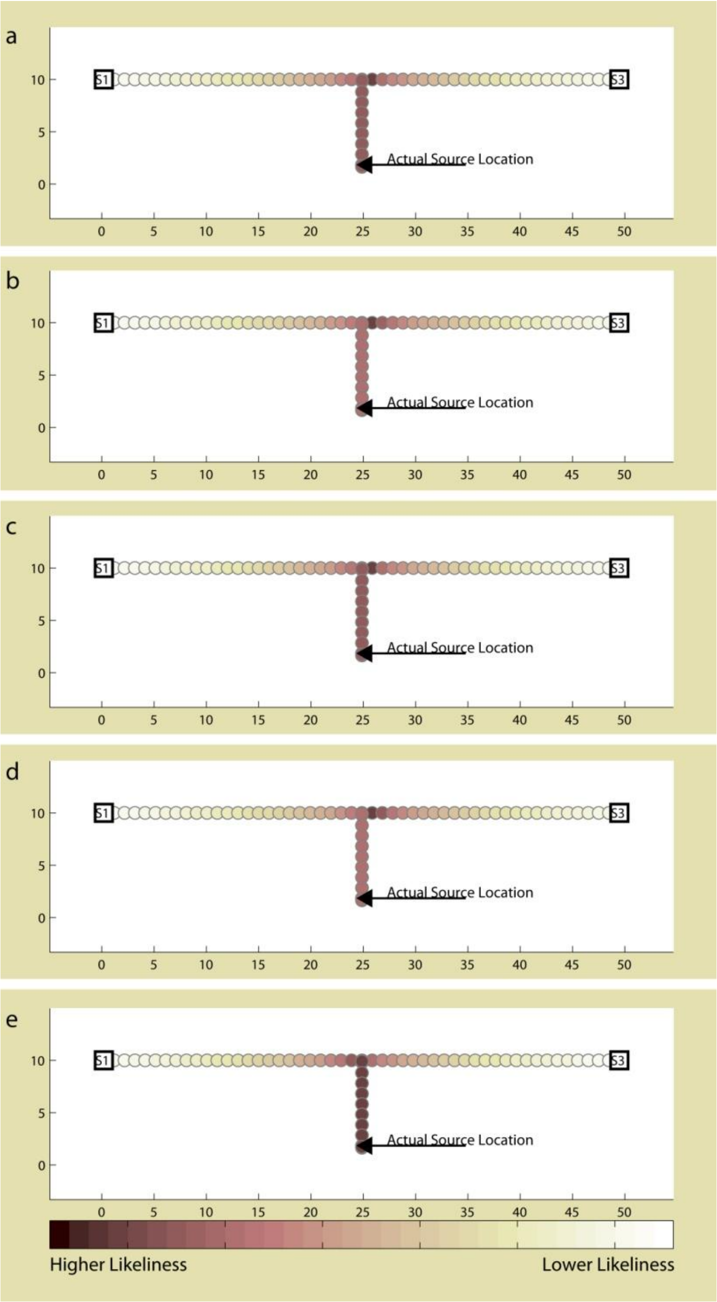


Figure 6-23 Source localisation using different wave arrival detection methods a) Hilbert. b) CWT c) gradient d) manual 1 e) manual 2. E=1.1 GPa

The results in Figure 6-23 show a reasonably high success at source localisation for all wave arrival detection methods, with all methods giving a highest Likeliness to within one discretisation node of the actual branch where the transient was generated. Of the two manually determined arrival times one was very precise in localising the correct pipe intersection, while the other attempt was as successful as the other wave arrival detection methods. This highlights an element of chance for manual wave front arrival detection but also indicates that where practicable manual arrival time estimation could provide reliable localisation results.

The accuracy of the localisation result in Figure 6-23 is suitable for practicable purposed although as small error did occur. The intention was not to overlook the localisation error, ideally no error would occur but a small error could be expected due to slight differences in pipe lengths and the fact that a linear wave speed is defined in the model when it is know that the wave speed is nonlinear. Of all the wave arrival detection methods evaluated there is slight variation in the estimation times which would also be expected to manifest itself as a small localisation error.

Operating valve 2 generated a transient source approximately equidistant between the two sensors used for localisation. By analysing data with a transient generated at valve 3 the transient source will be closer to one sensor than the other. The wave arrival estimation resulting from the closure of valve 3 are shown in Figure 6-24.

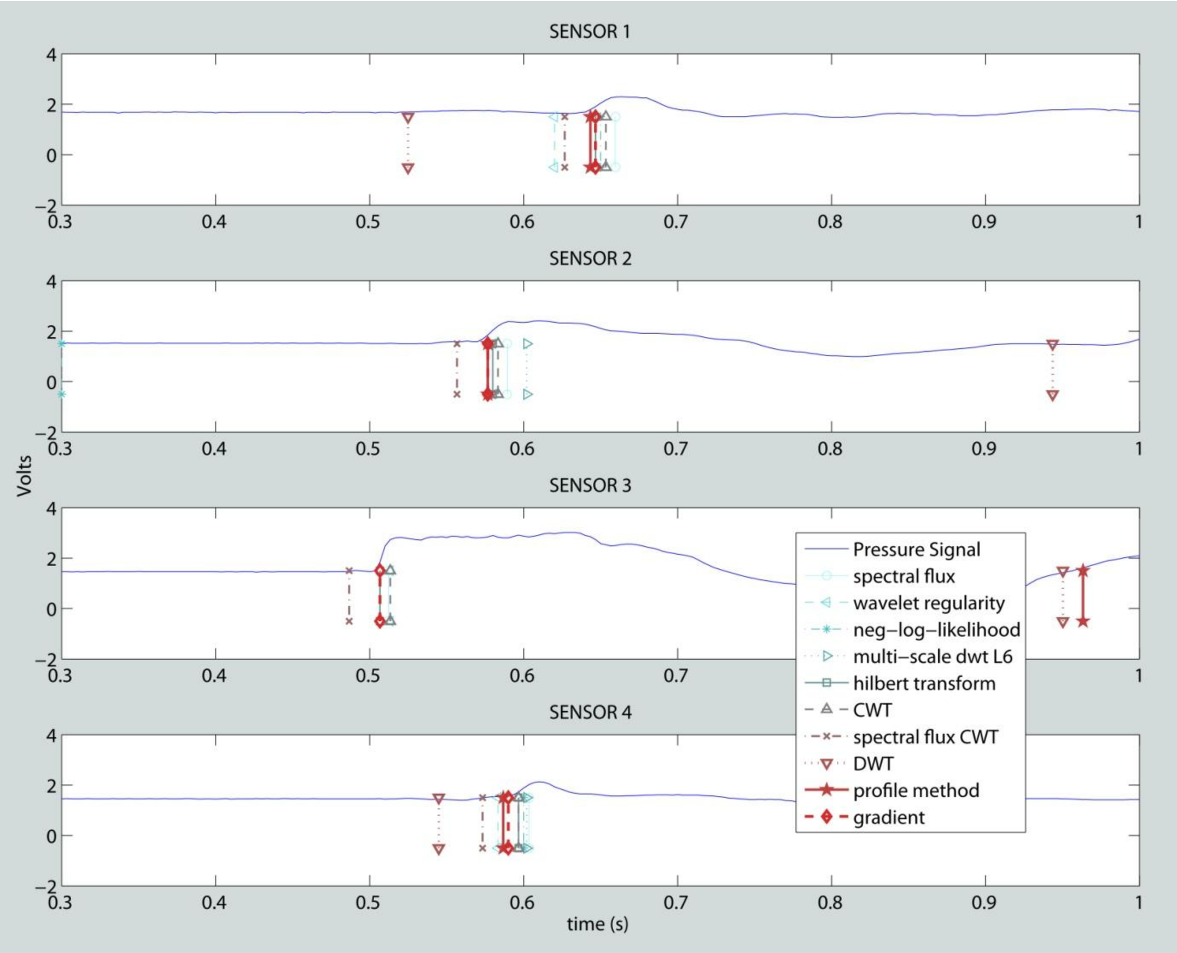


Figure 6-24 Wave front arrival detection results for the closure of valve 3 for the phase II T-configuration

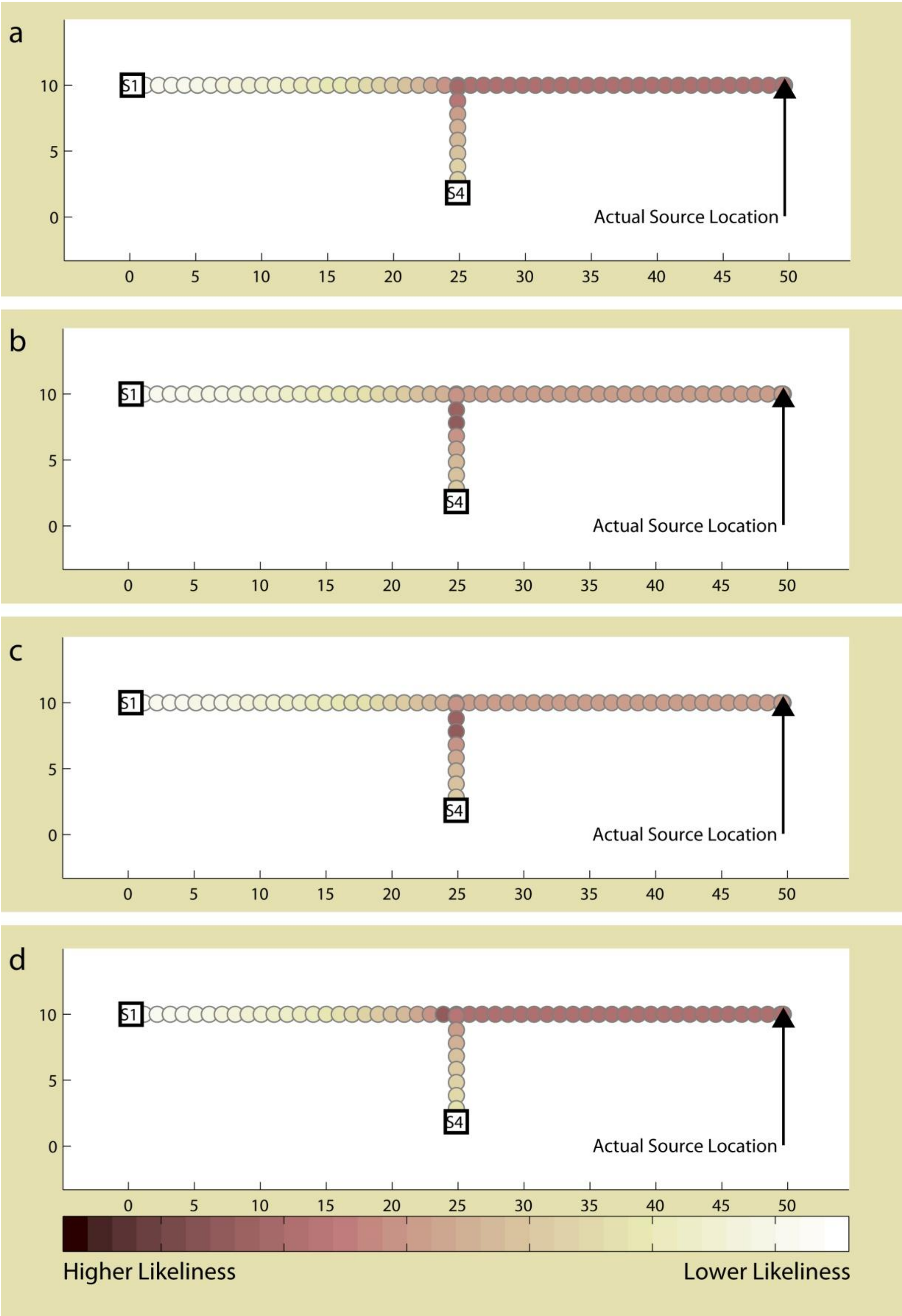


Figure 6-25 Source Localisation V3 closure, E=1.1 GPa, a) Hilbert b) CWT c) Gradient e) manual observation

Figure 6-25 shows the localisation result for the valve 3 closure. The Hilbert transform detection method localises to the correct branch but for all the other wave arrival detection methods small error exists. Noticeably, manually determining the wave arrival times provides an error in the opposite direction to the other methods but variability in results from manual arrival time estimation has already been noted and is expected. The errors for the CWT and gradient methods are larger than for the valve 2 closure, which could imply that due to the offset location of the branch between the two sensors, the wave speed in the pipe is actually lower than defined in the model, similar to observed in chapter 5.3.5.3. This could be attributed to wave speed retardation but another explanation could be that fluid structure interaction, hence movement in the pipe coil has reduced the wave speed. The restraint for the phase II configuration was different from phase I and phase III, to try and maximise the modularity of the system. To discern the possible causes of the errors source localisation was performed using a lower wave speed. This was achieved by specifying a Young's Modulus of 0.8 GPa; the results are shown in Figure 6-26.

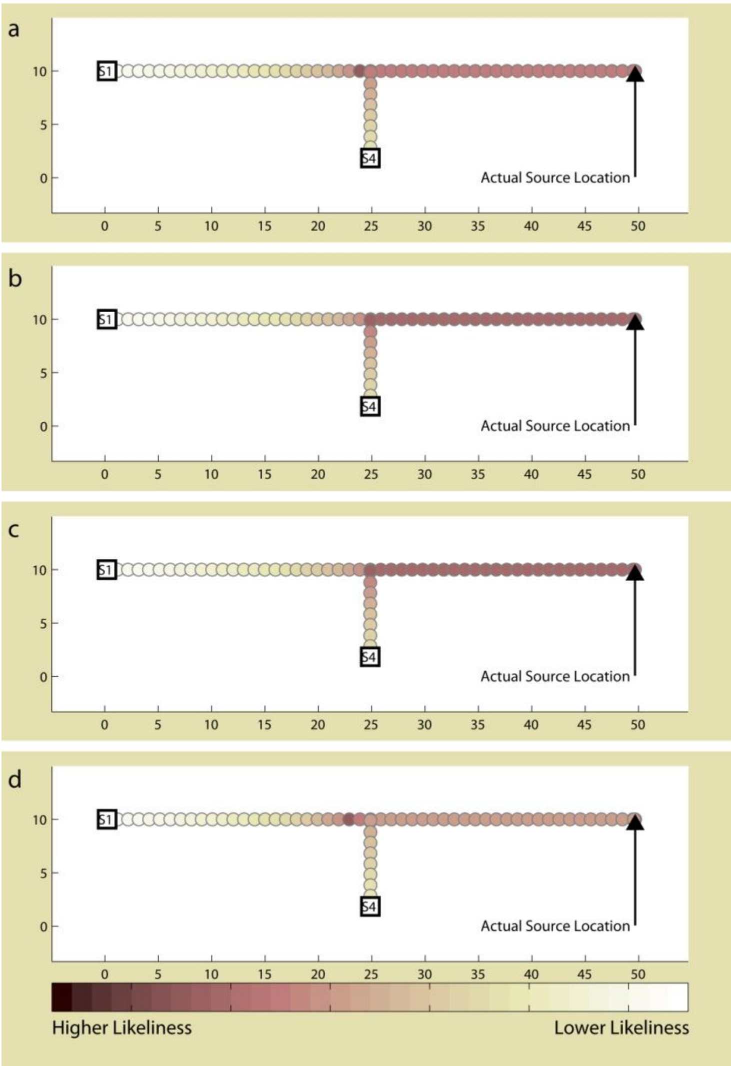


Figure 6-26 Source Localisation V3 closure, E=0.8 GPa, a) Hilbert b) CWT c) Gradient e) manual observation

Using a lower wave speed considerably increases the accuracy of the CWT and Gradient results but as a consequence increases the errors of the other two methods. Leaving aside the manual method because of the known variability, the three remaining predictions provide a very strong localisation result. This is consistent with the findings from chapter 5 that specifying lower wave speeds in the theoretical model can help to minimise localisation errors. The results indicate that for practicable purposes, using the results from more than one wave arrival detection method and using upper and lower values for theoretical wave speeds could provide an intuitive means to assess extremities of localisation results. A means of applying wave speed retardation to the source localisation procedure is discussed later in section 6.4.3.3; this was applied to the results for the valve 3 closure and did not considerably change the localisation errors.

6.4.3 Phase III Looped configuration

The objectives for the phase III configuration were to:

- Evaluate the wave arrival detection methods on a novel looped laboratory dataset
- Verify the source localisation procedure on physically acquired data from a looped network.
- Incorporate wave speed retardation into the source localisation model.

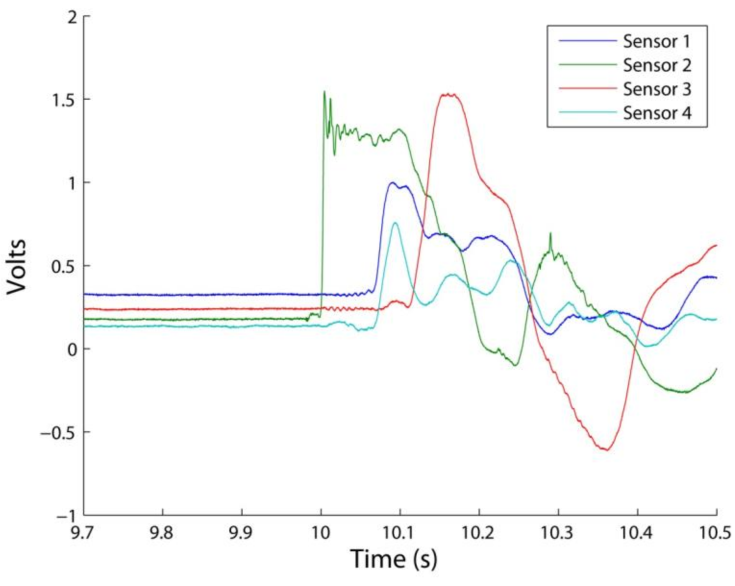


Figure 6-27 Pressure wave resulting from the operation of valve 2 on the phase III pipe configuration, sample frequency 4 kHz sample frequency

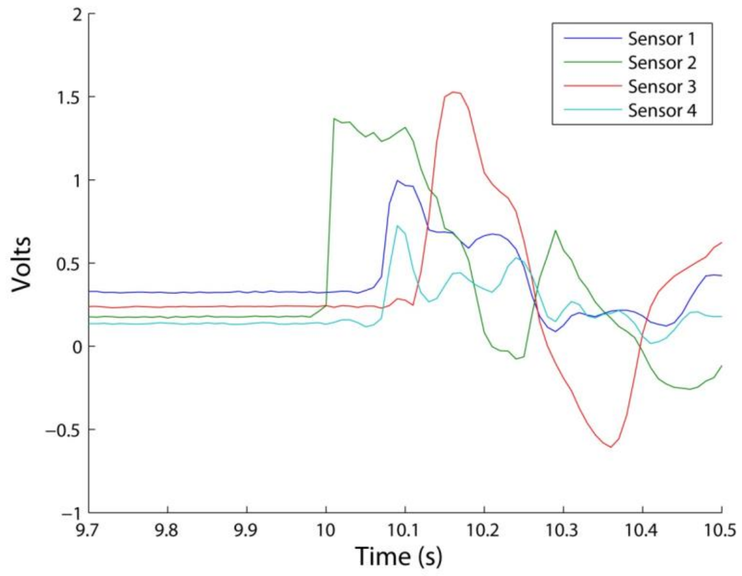


Figure 6-28 Pressure wave resulting from the operation of valve 2 on the phase III pipe configuration, sample frequency 100 Hz sample frequency

Figure 6-32 and Figure 6-33 show the arrival of the primary wave fronts at all four sensor locations for the phase III pipe configuration, following a closure of valve 2 with sample frequencies of 4 kHz and 100 Hz respectively. Both figures represent the same dataset but the 100 Hz data was acquired by sampling the 4 KHz data. Both gate valves were partially open and the other ball valves in the system were fully open, hence, following the closure of V2 and the attainment of steady state conditions there was still flow in the system.

The varying arrival times of the primary wave fronts can be seen and their orders of arrival agree with the expected differences associated with the varying pipe lengths. The amplitude of the wave can be seen to be reduced at sensors 1 and 4 due to divergence of the wave front, then to increase again at sensor 3 as the wave fronts converge. Some detailed pressure fluctuations are missing in the 100 Hz data plot but the general shape of the pressure profiles is similar. The wave arrival time difference can still clearly be seen in the 100 Hz plot but the reduced temporal resolution by definition reduces the potential accuracy for wave front arrival detection.

The higher resolution of the 4 KHz plot reveals small pressure fluctuations prior to the arrival of the wave at the sensors further from the transient source; these are most likely attributed to small vibrations in the test rig but should not significantly alter the localisation results.

6.4.3.1 Wave arrival time detection estimation

Wave speed estimation was performed on the data from three separate closures of valve 2 and these are shown in Figure 6-29. The dotted horizontal lines represent the expected wave speeds calculated using the data from phase I

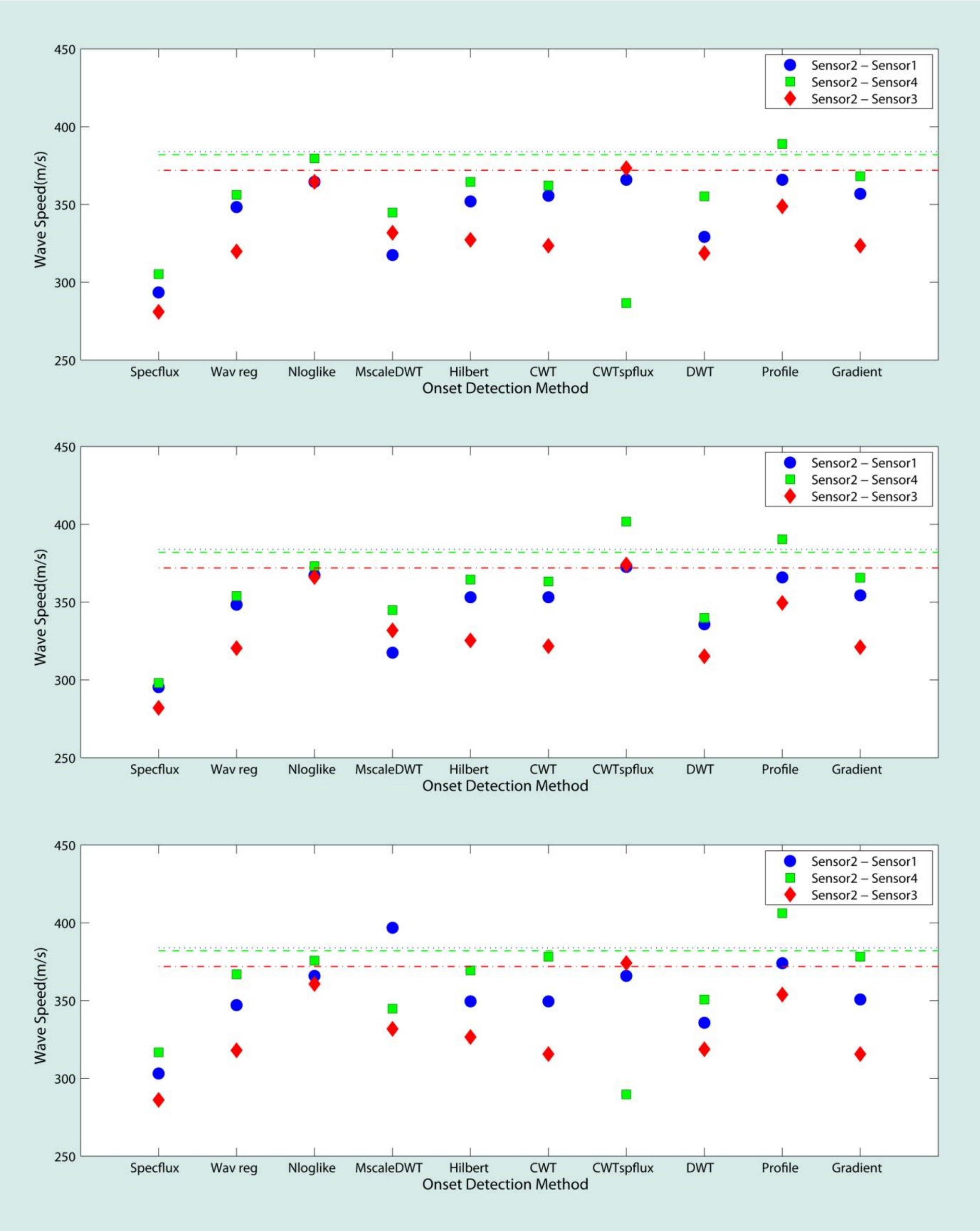


Figure 6-29 Wave speed estimation for three separate closures of valve 2 on the phase III pipe configuration 4 KHz data

Variation exists in the estimated wave speeds for each arrival detection method in Figure 6-29 and while the wave speed estimates in plots one and two are very similar those in plot three vary slightly. This is most likely due to slight variations in the manual operation of the valve. The wave speeds estimated as a result of the negative log-likelihood method appear to provide the strongest correlation with the predicted wave speeds, even for plot three when the other methods vary the most. The wave arrival detection methods were also applied to the 100 Hz data which is shown in Figure 6-30. More than half of the arrival methods failed to provide acceptable wave speed estimations on the 100 Hz data, of the successful methods the CWT and negative log-likelihood methods performed very well with estimates comparable to those using the 4KHz data.

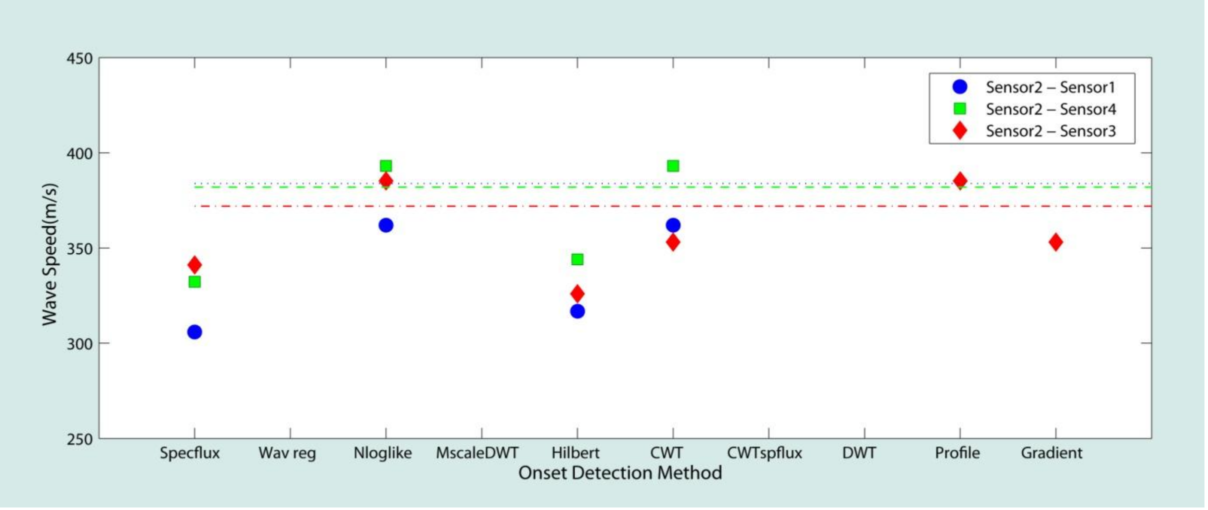


Figure 6-30 Wave speed estimation for three separate closures of valve 2 on the phase III pipe configuration, 100 Hz data

The indications are that from all the wave arrival detection methods evaluated, the methods which perform the most consistently are the same four that provide reasonable results in Figure 6-30. All of the methods show some variations and perform differently under different condition. The Spectral Flux method consistently provides lower than expected wave speed estimates which implies that this method may respond to dispersion or degradation of the primary wave front. The negative log-likelihood method consistently provides wave speeds very close to expected. The Hilbert and CWT methods both seem reasonably robust but show more variability than Negative log-likelihood method.

6.4.3.2 Source Localisation using Linear Wave Speed

Using wave arrival time estimates from the CWT wave arrival detection method the source localisation was applied to the phase III network. The CWT method was used because for these plots because if successful localisation can be achieved with the method then other methods should prove to be as effective if not more so.

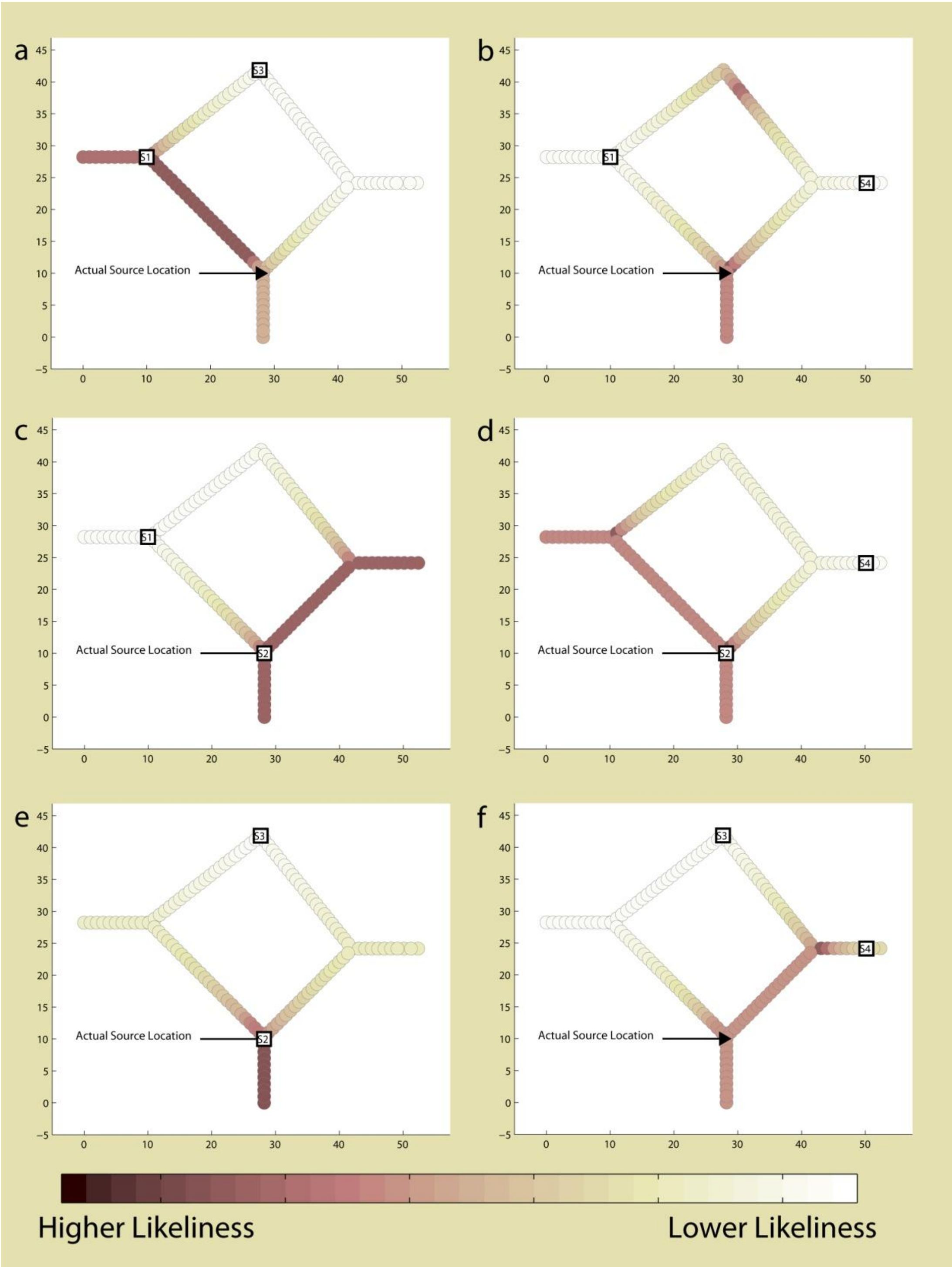


Figure 6-31 Source localisation results with all combinations of two sensors for the phase III network using wave arrival times from the CWT detection method on 4KHz data, with disctetisaiton interval at 1 m.

Figure 6-31 shows localisation results attained using all possible combinations of two sensors only Figure 6-31e provides a positive localisation result. All the other sensor combinations provide ambiguous or negative results. This agrees with the predictions from chapter 5 and shows that more sensors are required for successful source localisation.

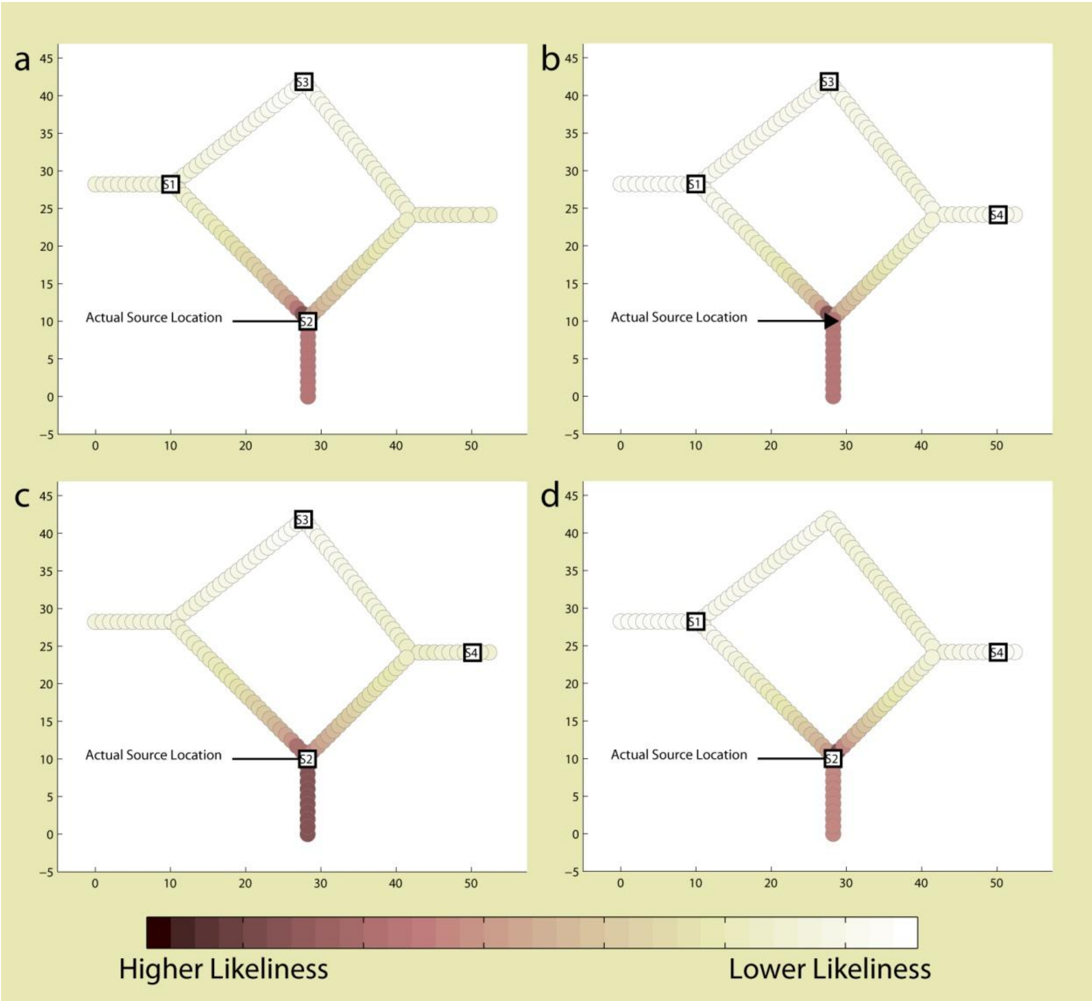


Figure 6-32 Source localisation using data from all combinations of three loggers at 4 KHz

Figure 6-32 shows localisation results using all possible combination of three sensors. A strong localisation result is provided with every sensor combination but a small error does exist which can be seen most clearly in Figure 6-32b. The pipe loop was well fastened to the steel armature, for the tests, movement of the pipe would be unlikely. The small errors could well be caused by ignoring wave speed retardation but they could equally be caused by wave arrival detection error. Either way for practicable purposes the localisation accuracy is suitable.

One objective was to verify the localisation procedure on lower sample frequency data and this was done by repeating the above analysis with the sampled 100 Hz data.

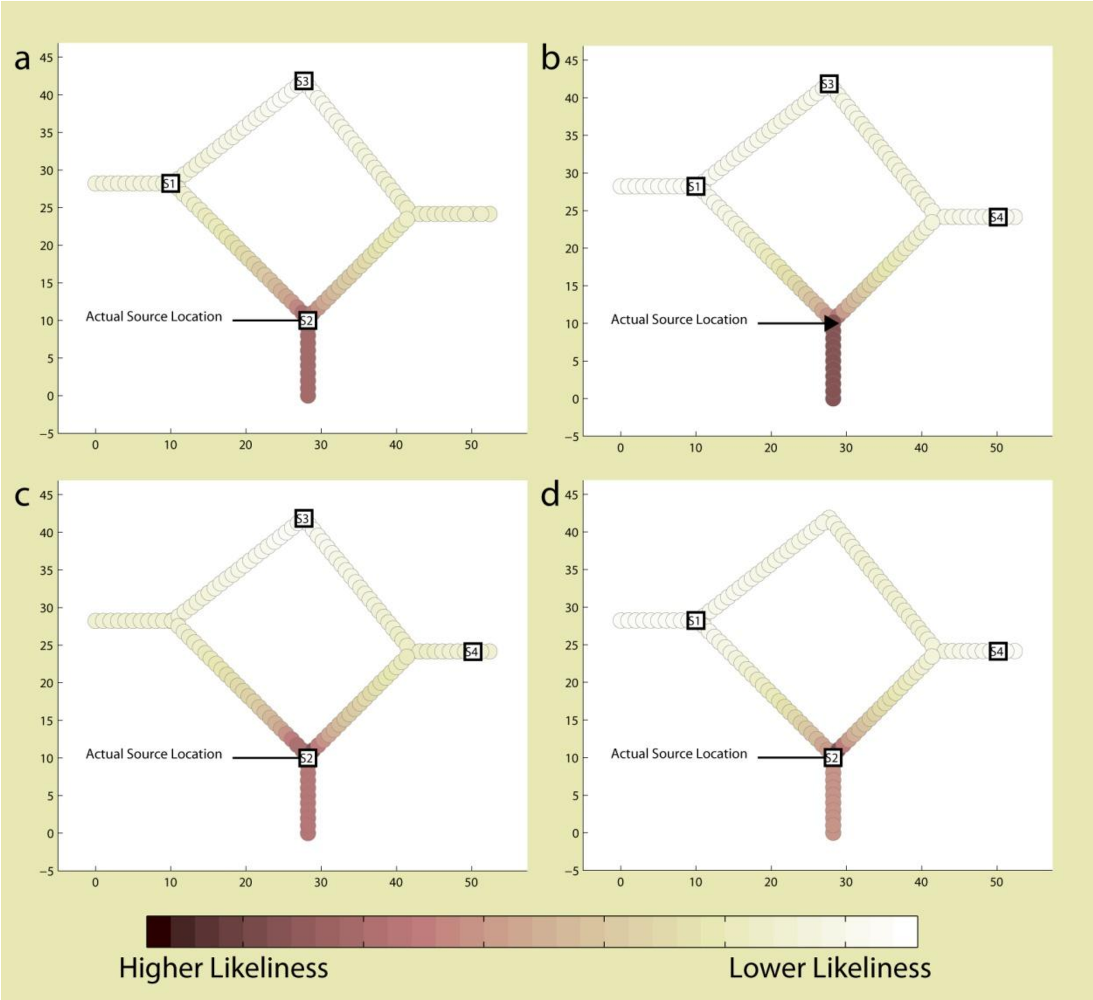


Figure 6-33 Source localisation using data from all combinations of three loggers at 100 Hz

Figure 6-33 shows the localisation results using threes sensors on the phase III pipe configuration. The results are comparable to using the higher frequency data and counter intuitively seem to show a more accurate localisation result using the lower frequency data. This verifies that the source localisation procedure is effective using 100 Hz sample frequency data and using the CWT wave arrival detection method.

6.4.3.3 Source Localisation non linear wave speed

Although the accuracy of the localisation results suggests that the procedure should be viable for application to real distribution system the uncertainties associated with wave speed variation had not been accounted for. The objective was to incorporate wave speed retardation into the graph theoretical model and a method was identified for achieving this. The prescribe localisation procedure as used up until now specifies the transit time for each pipe in the adjacency matrix prior to determining the shortest paths. This was to ensure that the shortest temporal path is accounted for and not the shortest path by distance, which is only of concern when pipe with different properties are being considered. Here, all the pipe is the same and therefore the shortest path by distance will also constitute the shortest temporal path, allowing the wave speed to be ignored at this stage. Instead, the shortest paths are calculated based on pipe lengths to provide the shortest distance between each node.

Using data for the fast valve closure, arrival time was plotted against the distance travelled and a polynomial trend line fitted. The arrival times used here were from the CWT method although other methods showed comparable results.

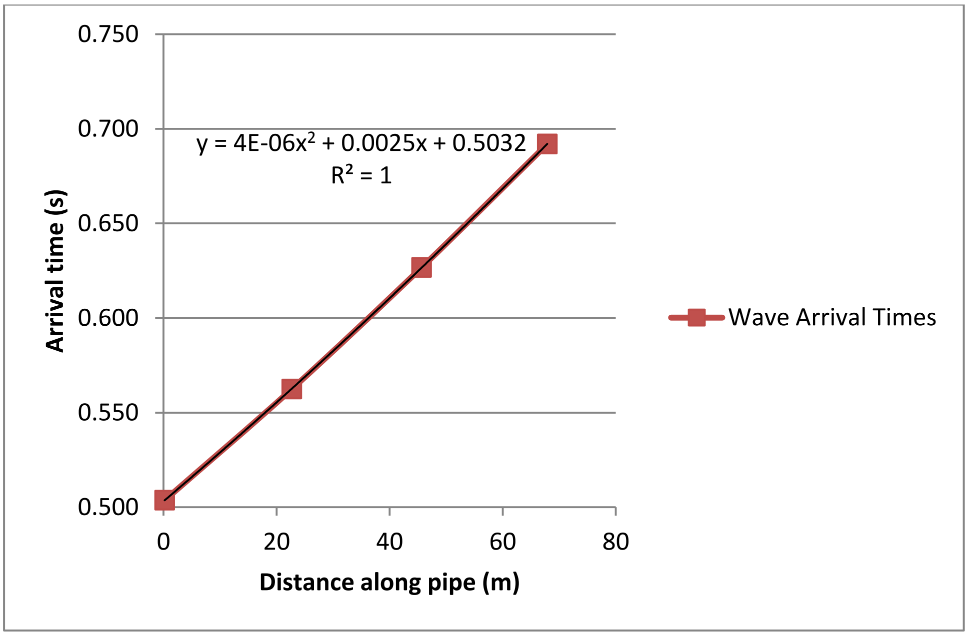


Figure 6-34 Expression derivation for non linear wave speed

Ignoring the final term from the equation of the trend line, to remove the offset, an equation for the travel time as a function of distance travelled is given in(4.33).

$$t = 4.0 \times 10^{-6} x^2 + 0.0025x \tag{4.33}$$

While this is not a definitive representation of the wave speed retardation it is a viable means of defining it to assess the theoretical approach and it provides a good approximation to the wave arrival time over the distances concerned and provides a means of incorporation wave speed retardation into the source localisation procedure. Equation (4.33) can then be use to provide the transit times base on the non linear wave speeds. This approach is only applicable where the system is made from a single pipe type but it provides a means of including wave speed retardation.

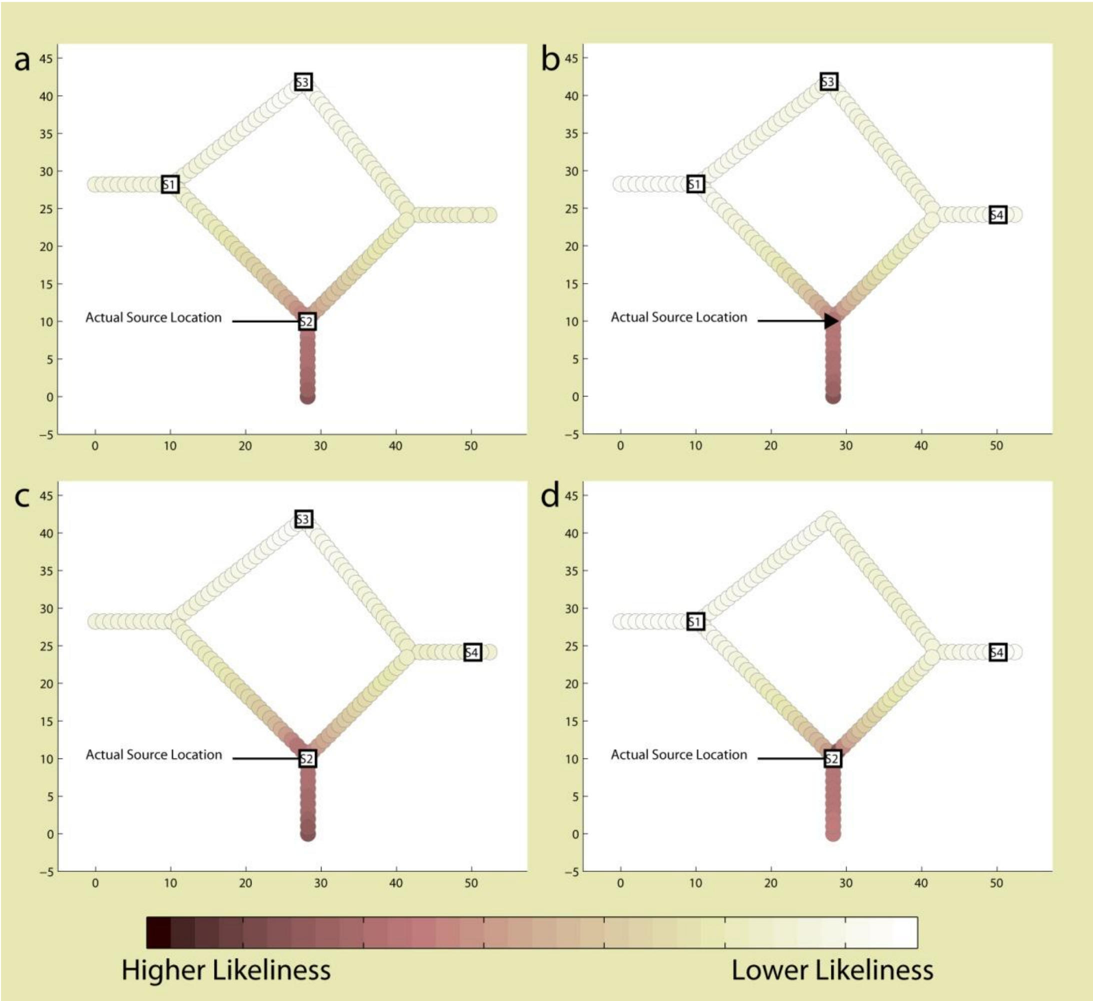


Figure 6-35 Source localisation using data from all combinations using non linear wave speeds of three loggers at 100 Hz

Figure 6-35 shows localisation results where a non linear wave speed is accounted for in the theoretical model. For all sensor combinations the accuracy of the result does appear to be improved. Of most significance are the results in Figure 6-35 where the highest Likeliness is towards the end of the branch. If a source is located along a branch, where linear wave speeds are used the method can only localise the connection node but with nonlinear wave speed the method is able to show that the source lies along the branch. While it does not indicate how far along a branch a source is, it could imply a potential for greater source localisation accuracy when nonlinearities are taken into account.

6.5 Discussion of Laboratory Verification

The wave speed in the test pipe was characterised using data from the phase I pipe configuration. Confirming that wave speed retardation did occur and providing higher wave speeds than would be predicted using the manufacturer values for Young's modulus.

A poignant finding from the characterisation of wave speeds was the implication that wave speeds did not continue to retard with time and distance travelled but advanced (increase in speed) as the reflected wave approached the generation source. This holds with the understanding that wave speeds are governed by the dynamic elastic modulus of the pipe material. Steeper gradient of the reflected wave closer to generation source should therefore incur a higher dynamic elastic modulus and faster wave speeds. Reflected wave speed advancement does not affect the proposed source localisation method, because only the primary wave front is considered. It does however reinforce the philosophy for ignoring the reflected waves.

Ten wave front arrival detection methods were evaluated. This was a challenging task because due to degradation of the primary wave front and retardation of the wave speed it is difficult to explicitly define the wave arrival time for comparison. The chosen approach to evaluate the detection methods was to compare their predicted wave speeds and to evaluate their ability to provide a valid source localisation result. This approach was valid because the objective was to find the wave arrival detection functions most suitable for source localisation. The findings were that from the ten methods the Spectral flux, Hilbert Transform, Negative Log-likelihood and Continuous Wavelet Transform methods were the most robust, to varying degrees. It is the judgement that all four methods be used for source localisation in real networks with the variability in results representing uncertainties which exist in defining the actual wave arrival time.

The results of the transient source localisation applications show that the method is robust and to within a certain margin of error can provide accurate localisation results. It should be reaffirmed here that the aim of the localisation method is to identify the location of system assets or customer devices which cause problematic transient pressures. With this in mind localisation to within tens of meters in a real distribution system could generally be seen as a successful localisation result for practicable purposes. Provided wave speeds can be accurately estimated or empirically measured and accurate data synchronisation can be achieved localisation results could potentially be better than this.

Considering wave speed estimation, the inclusion of wave speed retardation improves the success of the localisation results. The approach used to achieve this is a novel means of including viscoelastic behaviour into the model without the need for deterministic modelling.

Provided the four best wave arrival detection methods are used and provided they perform effectively on data from a real distribution system, using a sample frequency of 100 Hz is suitable for transient pressure source localisation in real distribution systems.

7 Field Validation

7.1 Introduction

Procedures for identifying the source location of transient pressure events in water distribution systems have been developed and verified in earlier chapters, through conceptual design and laboratory verification. The aim of this chapter was to perform final validation of these procedures on physically acquired data from a real distribution system. The adopted approach was to intentionally generate small controlled transient pressures at a number of known locations in a real water network, meanwhile synchronously acquiring pressure data at multiple locations in the system. For field validation to be successful the following objectives needed to be satisfied:

- Identify a suitable experimental field system with the following attributes:
    - is complex with multiple loops and branches,
    - is unlikely to experience adverse effects from artificially generated transient sources i.e. it was a relatively new system and is constructed from modern materials,
    - is isolated from a larger distribution system, to minimise the possibility of other transients occurring, to reduce the risk of adversely effecting the wider system, to minimise steady state flows hence minimise frictional damping of the pressure wave.
- Develop field equipment to acquire temporally synchronised 100 Hz pressure data at multiple locations in a water distribution system, in doing so acquiring all data from the equipment deployment without selectivity. 100 Hz is specified so that field equipment could potentially log data for up to a week to capture transients relating to routine operations occurring in the system.
- Develop a transient pressure generation device to create transients within permissible magnitudes.
- Establish whether transient pressures can be observed at the extremities of a complex network and be useful for source localisation, given that

degradation of the primary wave front will occur as a result of dispersion and attenuation.

- Transient pressures are generated and successfully observed by data loggers at multiple locations at the test site.
- Wave arrival time estimation methods are validated and it is shown that they are applicable for successful transient source localisation.
- Validate the source location procedures using estimated system characteristics and physically acquired pressure data.
- Evaluate optimal sensor placement methods.
- Identify any shortcomings of applying the source localisation procedure to a live distribution system and identify protocol to maximise the effectiveness of the procedure.

Initially in this chapter the selection criteria of an appropriate experimental field site is considered and a suitable site is successfully identified. Field equipment is then described, including data acquisition hardware and the transient generation device, followed by test methodology and sensor placement analysis. The results section analyses the acquired data, evaluates wave arrival time estimation methods and finally validates the source localisation procedure.

7.2 Site Selection

To facilitate the identification of a suitable experimental field site, a number of assessment criteria were defined. The criteria were based on the configuration requirements for successful validation and were also guided by the need to minimise disruption and risk. Assessment criteria and their reasons are provided in Table 7-1.

Table 7-1 Experimental field site assessment criteria

Criteria	Reason
Configuration: Looped Branched System	The configuration of the system needed to have an increase in complexity from the laboratory verification stage, meaning increased number of loops and branches. A looped system was preferential because of the known source localisation ambiguities which can occur in looped systems, thus providing a rigorous and thorough test of the localisation procedure. The clear advantage of field validation was the ability to specify an experimental site with far larger pipe lengths than would be practicable in a laboratory environment.

	A number of branches and connections across the loops were desirable because the site needed to have an adequate number of hydrants to provide multiple pressure logger deployment and transient generation locations. Understandably, it was a request of the water utility to minimise the magnitude of the transients generated, to help minimise the risk to their network and customers. This had implications on the site selection because of the attenuation, dispersion and dissipation experience by the generated pressure waves as they passed through multiple pipes and intersections. A balance therefore needed to be struck between maximising the complexity of the system while retaining a level of simplicity to help reduce the degradation of the primary wave fronts.
Material Type: New and predominantly plastic pipe.	As an extension of the laboratory based experiments which used 25 mm MDPE pipe it was desirable to find an experimental field system, which was predominantly constructed from plastic pipe for the following reasons; • Newly installed plastic pipe should have a low susceptibility to failure. • Records of newly laid pipes should be accurate and up to date providing reliable pipe properties needed for wave speed evaluation. There were potential disadvantages to using a plastic pipe system. Variable wave speeds encountered in the viscoelastic pipes may affect the ability to successfully apply the source localisation procedure, although should localisation still be successful it helps prove the robustness of the procedure. Increased damping of transients in plastic pipes could make it difficult to decisively identify the primary wave front at a distance from the transient source. The positive outcome from this is that if localisation is successful in a heavily damped system then arrival time estimation should be easier in systems constructed of stiffer pipe materials.
Location: Residential, quiet accessible area	A residential system was favoured as this reduced the chance of large transients and system noise being generated by high volume customers. Residential housing estates would also be likely to provide a variety of loops and branches required. A relatively quiet area was required because transient sources needed to be generated at hydrant locations and in the day time minimal disruption would be caused to pedestrians and road users.

Discussions with water utility staff identified a number of potential site locations, with this knowledge and the use of GIS database an experimental field site was identified which ideally suited the selection criteria.

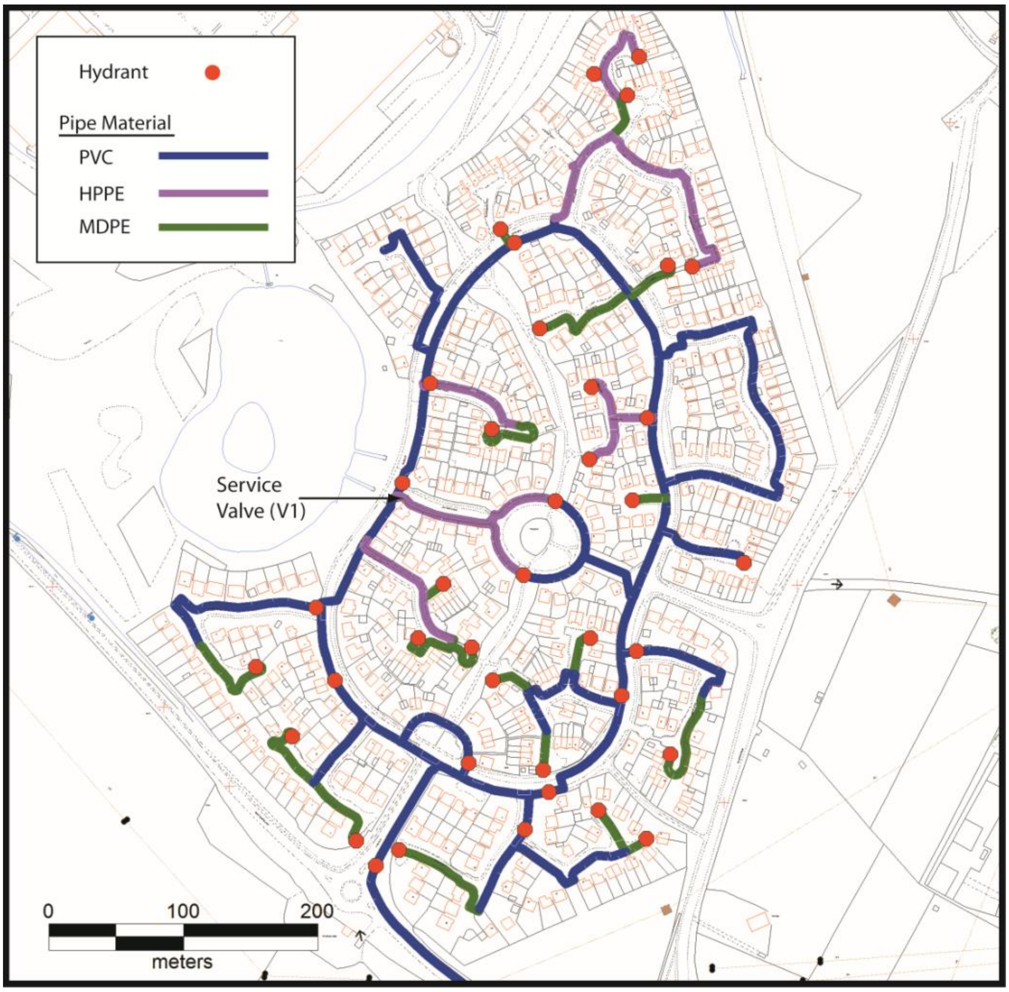


Figure 7-1 Experimental field site, pipe materials and hydrant locations

Figure 7-1 shows a map of the chosen experimental field site, which met all the relevant assessment criteria. The system had increased complexity from the laboratory based pipe configurations, with multiple loops and branches and with 33 hydrants specified. The site location was a modern residential housing estate. The system was constructed wholly from plastic pipes, using MDPE, HDPE and PVC of varying diameters. The longest reaches from extremity to extremity were approximately 800 m, it was considered that transients would be observable across the whole network and this was confirmed by making preliminary observation tests. Only one pipe fed the system which meant that if any significant transients did occur in the wider network only one location existed for them to enter the experimental field site. It also meant that no cross flow would occur in the system which would further dampen the generated transients. An advantage of the test site was the ability to change the system configuration. Operation of the service valve V1 could allow or stop cross flow across the system, hence allowing or restricting the propagation of transient by isolating the pipe which connects either side of the main loop. Test could be undertaken with V1 open and closed to generate a more comprehensive data set.

7.3 Field Equipment

It is relatively straight forward, using current data acquisition hardware, to achieve highly accurate data synchronisation when data is acquired in a laboratory situation. All the pressure transducers can be connected to one data acquisition board and instructed to acquire data simultaneously. Achieving successful synchronisation in a field situation becomes more complex as a result of temporal drift of acquisition hardware, and ensuring that the initial synchronisation of the devices is accurate. The data loggers need to be synchronised, deployed, work independently for a period of time, then collected and the data extracted and re-synchronised.

For extended observation periods the physical memory and data storage capacity of the data acquisition hardware becomes an issue. Previous research has ignored all data except significant events Stoianov et al., (2007). A prime concern for this project is that all pressure data is captured because the nature of a significant event is still not certain.

7.3.1 Data acquisition hardware

7.3.1.1 GPS Loggers with pulse synchronisation

The data loggers used were Race Technologies DL1 data loggers. The loggers were GPS compatible but due to their deployment locations, in hydrant chambers, they were unable to acquire signals while deployed. Instead each logger received a GPS timestamp prior to deployment from a master unit. To receive the timestamp the loggers were individually connected to the master unit via serial cable. An onboard chip quartz chip intended to retain accuracy to 10 ms while the loggers were deployed.

To validate the time synchronisation a voltage pulse was synchronously sent to a second channel on each logger. This was achieved by connecting the second channel on each logger using a wire harness then briefly connecting a 12 V battery for approximately three seconds. To verify time synchronisation post deployment, the process was repeated and a second voltage pulse was applied to channel two immediately prior to stopping data acquisition. As well as validating the time synchronisation, the pulse also provided a secondary means of correcting any synchronisation errors.

Figure 7-2 Ten DL1 data loggers connected with a wire harness for the application of the time synchronisation voltage pulse

7.3.2 Transient Generation Device

It has been previously stated that transient pressures have the potential to caused damage and cause other problems in water distribution systems. This imposed a limitation on the magnitude of transient that would be permissible for experimental purposes. Because small transients can occur regularly in distribution systems the intentionally generated, experimental transients, would have to be of significant magnitude to be observable at logger locations in the network but not too significant that they would adversely affect the system. A preliminary assessment was made to identify suitable apparatus and flow velocities for generating transients.

Figure 7-3 Transient generation devices

A picture of the transient generation devices is shown in Figure 7-3. A stand pipe with flow meter was fitted to the hydrant. An assembly was connected to the hydrant outlet which was fitted with a 20 mm manually operated ball valve for transient generation. A 2 m length of 25 mm MDPE pipe was connected to the ball valve, which had a gate valve at the other end for flow control. An upturned junction was fitted after the gate valve to ensure the pipe did not drain while the ball valve was closed. If the pipe was allowed to drain, the gate valve would not immediately control the flow rate once the ball valve was opened and downsurge magnitudes greater than permitted could therefore be generated. A T-junction was fitted at the pipe outlet to stop the pipe snaking.

The transient generation device enables flow to be regulated through the ball valve so that for varying system pressures flow could be limited to 2 l/s. The flow of 2 l/s was attained through experiments on a small test network at a test facility owned by the sponsoring water company. Transient pressures generated using this flow rate, were shown to stay within the permissible limits of 10 m water column.

7.4 Experimental Field Site Assessment

7.4.1 Preliminary Site Assessment

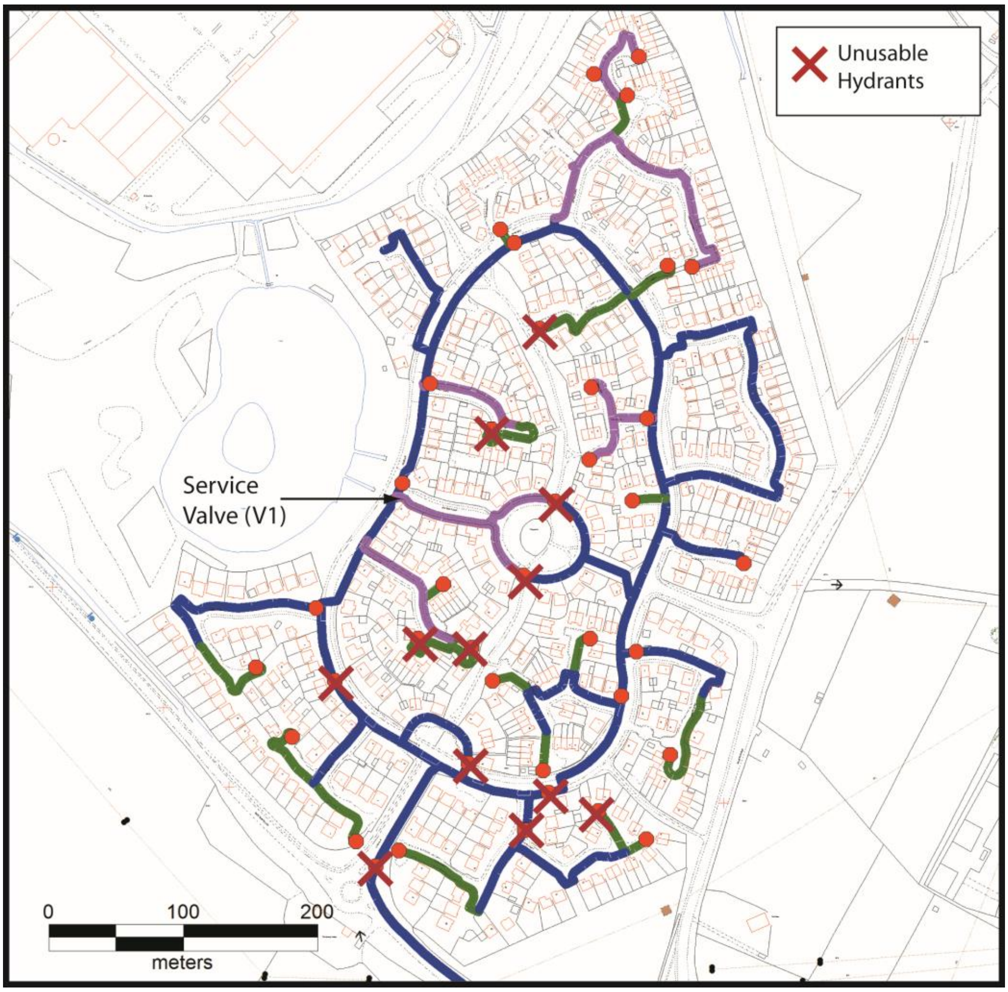


Figure 7-4 Field site - logger deployment locations, transient source locations and unusable hydrants.

The preliminary evaluation identified a number of hydrants at the field site that for various reasons were not suitable for either pressure monitoring or source generation. A map of the unsuitable hydrants at the field site is shown in Figure 7-4 and the reasons making them unsuitable are listed below.

- The stand pipe would not fit on the hydrant because the angle of the hydrant in relation to the chamber would not permit it.
- The screw thread on the hydrant was damaged.
- The frost valve had operated so the hydrant released water constantly when the cap was fitted and the valve was open.
- There was no key attachment on the top of the hydrant

- There was not enough space in the hydrant chamber to attach the logger, either not enough room for the box or not enough clearance to replace the cover once the transducer was attached.
- Inaccessible Hydrants
- In some cases a hydrant had been removed or had never existed at a location specified.

Having established that a number of hydrants were unusable at the field site this could indicate the need to identify an alternative site. Indeed another site was explored but the same issue of unusable hydrants was also present at that location. With an adequate number of usable locations still existing at the original site and well documented availability it was appropriate to still use the original location.

Observing that a considerable number of hydrants were not usable at the test site has implications for the source localisation procedure, in particular, for the desire to determine optimal locations for logger deployment. It will not always be possible to place loggers at desired locations and ideally the procedure needs to be adaptable to allow for logger placement at non optimal locations while still achieving valid localisation results.

7.4.2 Experimental Field Site Model Definition

A discretisation of the Experimental field site was generated using GIS pipe data as a reference. The graph representation was defined manually; using AutoCAD a simplified representation of the network was made using straight line sections. Node points were specified at each pipe intersection and hydrant locations, the node coordinates were extracted and placed in a coordinates array. The pipes array was populated manually by specifying the start and end node of each pipe. Some pipe properties needed to calculate theoretical wave speed were stored in the water utilities GIS database; these were the nominal diameter and the pipe material. The specific parameters, internal diameter, wall thickness and Young's modulus were not available so needed to be inferred from manufactures data and stored against each pipe in the pipes array.

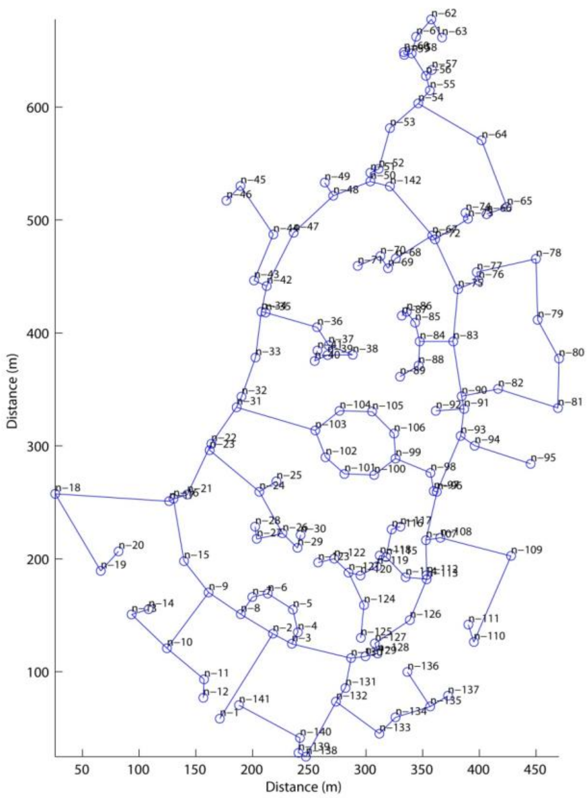


Figure 7-5 Field site discretisation – sparsely populated

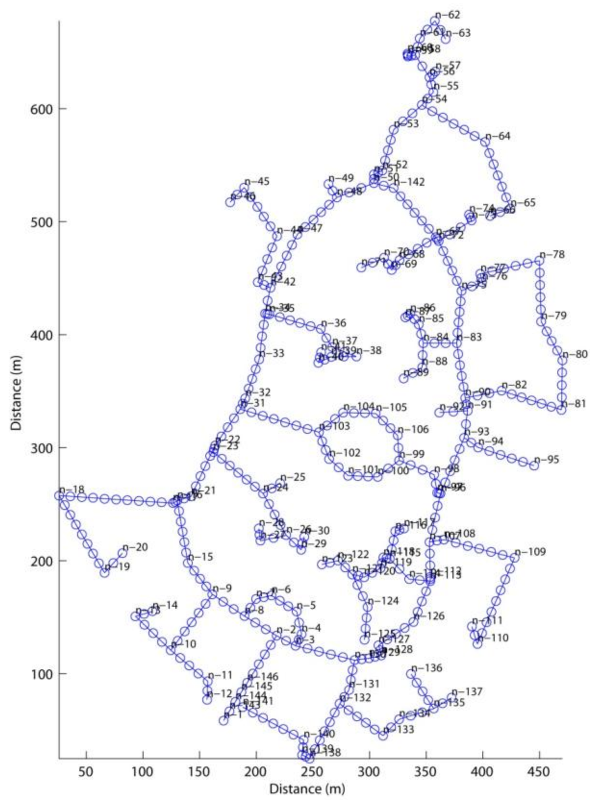


Figure 7-6 Field site discretisation – Max imum10 m pipe

The defined discretisation of the experimental field site is shown in Figure 7-5. Figure 7-6 shows discretisation with increase resolution with 10 m maximum pipe lengths.

7.4.3 Logger Placement Optimisation

All three optimal logger placement methods, the unique path method, the entropy method and the composite method, were applied to the experimental site. Optimal placement was performed for both system configurations, with the service valve V1 open and closed

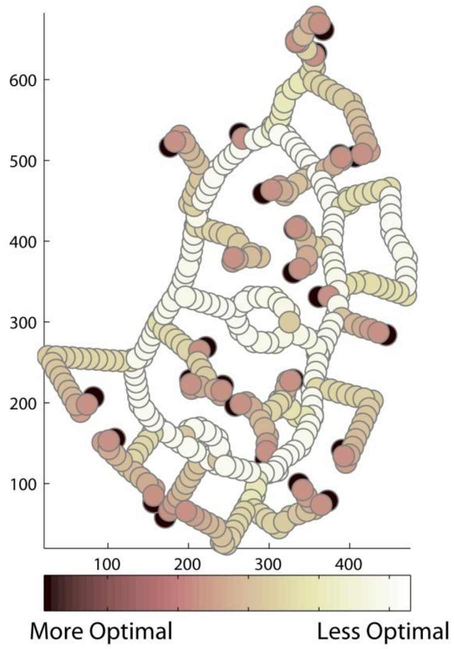


Figure 7-7 Optimal sensor placement locations using the unique paths method with V1 open.

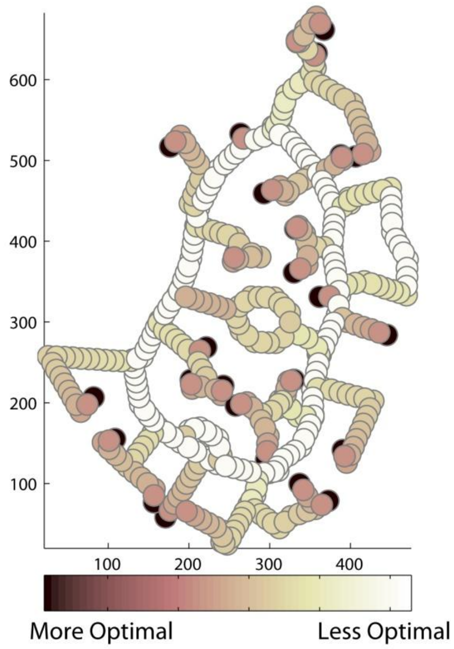


Figure 7-8 Optimal sensor placement locations using the unique paths method with V1 closed.

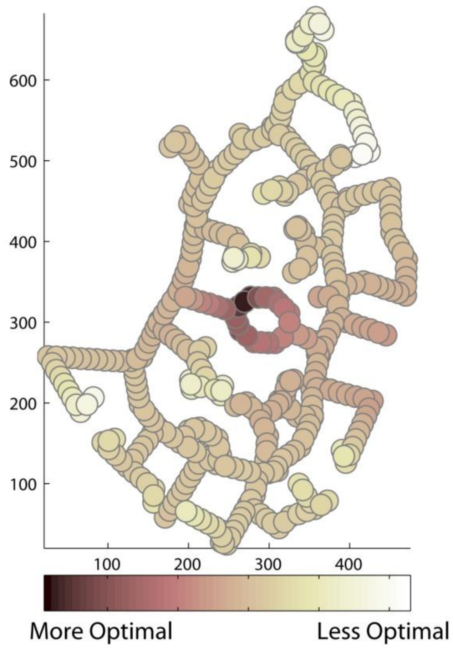


Figure 7-9 Optimal sensor placement locations using the entropy method V1 open

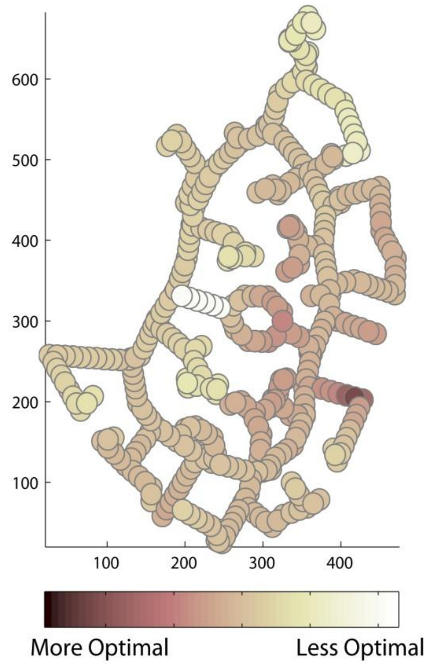


Figure 7-10 Optimal sensor placement locations using the entropy method V1 closed

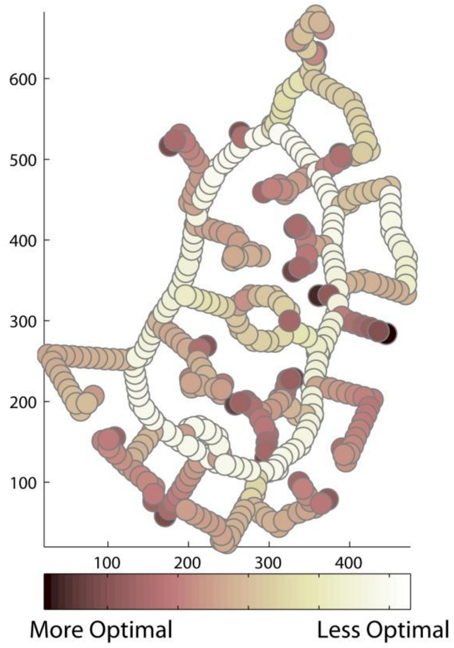


Figure 7-11 Optimal sensor placement locations using the composite of the unique path and the entropy method V1 open

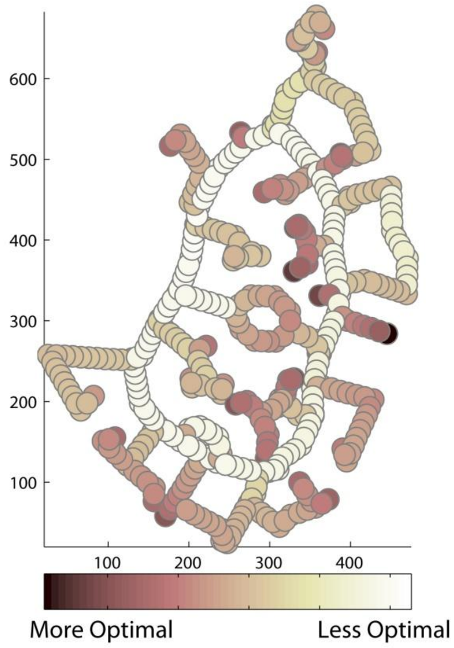


Figure 7-12 Optimal sensor placement locations using the composite of the unique path and the entropy method V1 open

Using the composite optimal sensor placement vector, with V1 open, the sensor placement procedure discussed in 4.5.4 was applied to the experimental test network. Locations were chosen with V1 open because the intention was to leave the loggers in the same locations for all tests.

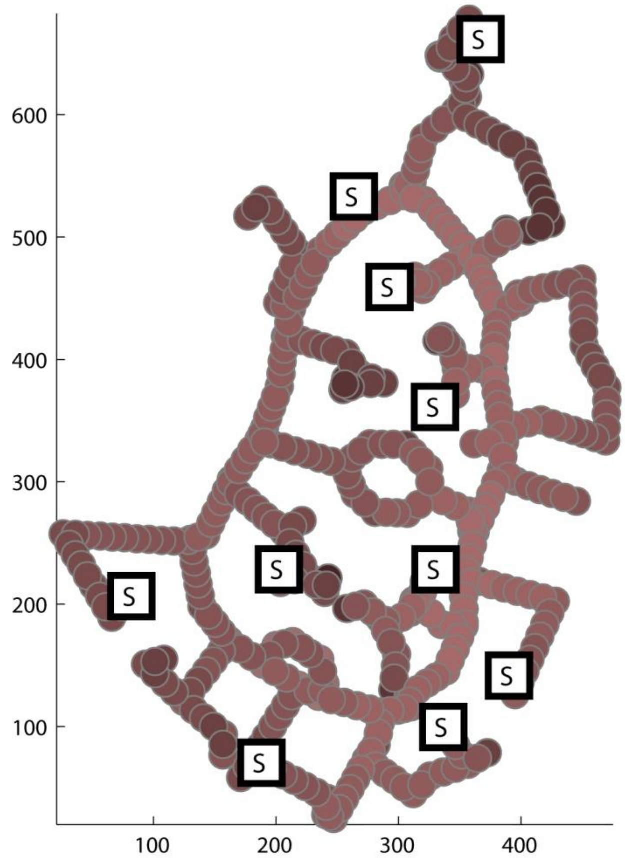


Figure 7-13 Deployment locations for nine logger defined by the optimal logger placement procedure

While it is possible to make theoretical assessment as to the optimal placement of pressure loggers, to achieve maximal source localisation results, in live distribution systems numerous factors may exist which limit the possible locations available for logger deployment. Therefore a slight modification had to be made to the logger placement procedure, to account for the fact that some hydrant locations were known to be unusable. The modification involved adding a weighting factor to the corresponding nodes in the optimal placement vector. The weighting factor ensured that the unusable locations could not become minima and could therefore not be selected. The placement result from the procedure is shown in Figure 7-13

Each time a new logger location was added using the logger placement procedure, theoretical analysis was performed using a series of source locations and the 5th 10th and 15th percentiles of the location Likeliness vector was stored. The average of these percentiles was plotted to assess the quantity of data loggers required as shown in Figure 7-14.

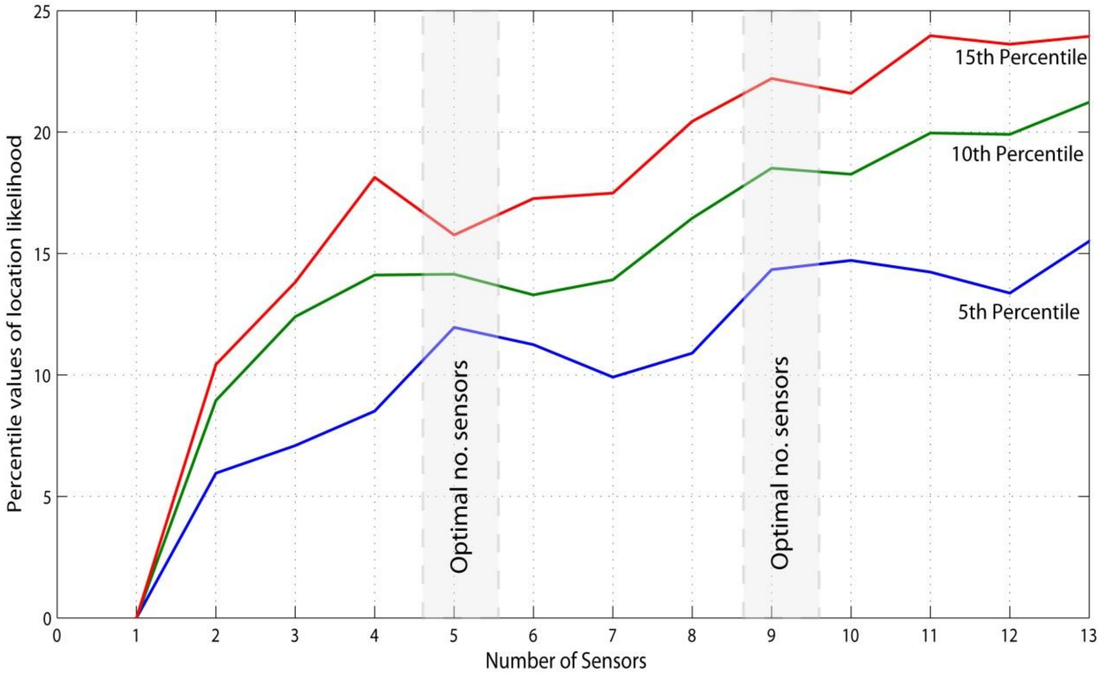


Figure 7-14 Plots showing the average of the 5th, 10th and 15th percentiles of the location Likeliness vector from multiple simulations with different quantities of data loggers

Figure 7-14 appears to show two steps defining the optimal number of loggers required. The percentile plots first level at around five to six loggers but then increase and level again at around eight to ten loggers. This outcome could be explained by considering the configuration of the system. Initially with very few loggers, a larger number of ambiguities will exist on the looped part of the system. As the number of loggers increases, the ambiguities will decrease. The second step could be explained by considering the second factor which reduces the number of nodes with high Likeliness, this being the values along branches, which do not have loggers at their extremities. As new loggers are added from six and upwards, this should tend not to considerably reduce ambiguities on the main loop but will reduce ambiguities along branches. Therefore if a logger is placed along a short branch this should change the percentiles less than if it were placed along a long branch. If it is accepted that it is not possible to determine the exact location of a transient source, which is situated along a branch then five to six would appear to be the optimal number of loggers required.

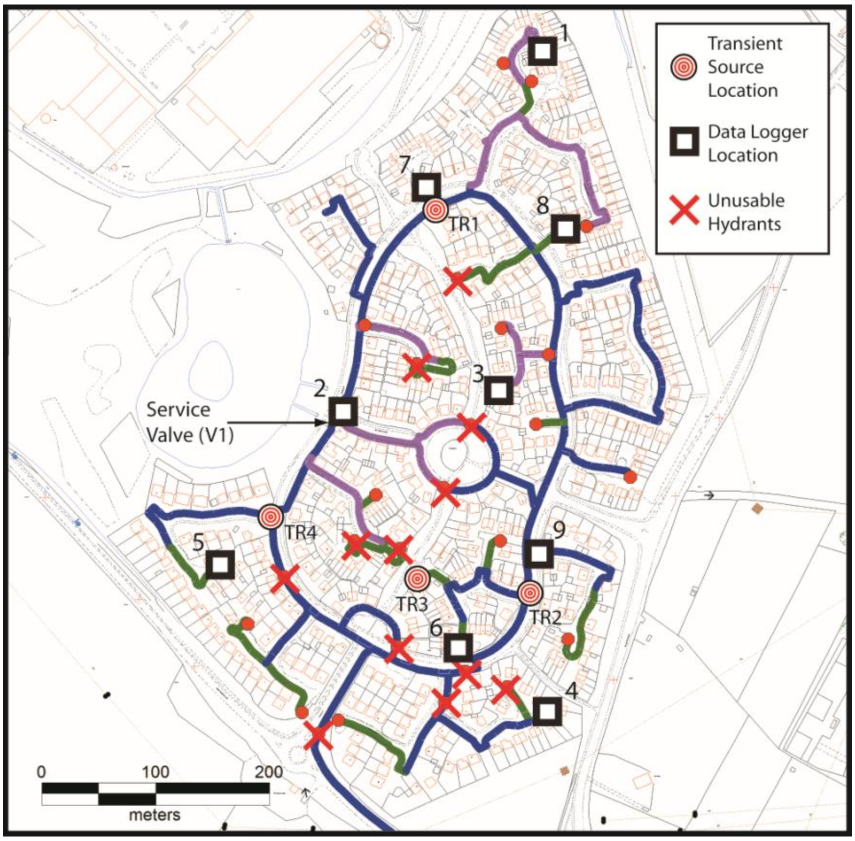


Figure 7-15 Data logger and transient generation source location at the experimental field test site.

The actual logger deployment locations are shown in Figure 7-15. On the day of the tests further locations were found to be unsuitable for use for either transient generation or as logger deployment locations and they are indicated as such.

7.5 Test Methodology

In broad terms the test methodology involved the deployment of multiple synchronised data loggers at hydrant locations in the experimental field site. Once all the loggers were deployed transient pressures were successively generated at a number of other hydrant locations at the site. The system configuration was changed by operating a service valve in the system then further transients were generated at the same locations previously used. The data loggers were then collected with the data being subsequently used for validation of the source localisation procedure.

Prior to undertaking the experiments discussed a preliminary assessment of the site was performed to verify that the generated transients could be observed.

Table 7-2 Experimental test schedule

Task	Details
Time Stamp Loggers	All data loggers had formatted memory cards installed and their power turned on. Each logger was then connected in turn to the master unit at the University of Sheffield to acquire a time stamp and set the clock.
Apply First Synchronisation Voltage Pulse	Analogue channel 2 for all ten data loggers was connected to a wire harness. Logging was started for each logger then a 12 V battery was simultaneously applied to channel 2 on each logger via the wire harness. The harness was disconnected and the loggers were sealed.
Logger Deployment	Nine pressure loggers were deployed at the experimental field site at the predetermined locations. If locations were unusable for any reason then loggers were deployed at either the closest or other optimal locations. A degree of flexibility should always need to be allowed for logger deployment locations to account for scenarios where it is not possible to use a particular hydrant location.
Generate Transients	Transients were generated in turn at four different locations by performing three rapid valve closures and rapid valve openings. At least one minute was allowed between each valve operation to allow system pressures to stabilise. A logger was connected to the stand pipe at the transient generation source to record the generated transients and as a validation of the generated transient times.
Service Valve Operation	To change the system configurations and therefore provide a more comprehensive data set a service valve was opened in the in the system.
Generate Transients	The previous transient generation procedure at four locations was repeated at the same four locations. This was to provide comparable results using the same logger locations but with a different system configuration.
Collect loggers	All nine data loggers were collected
Apply Second Synchronisation Voltage Pulse	The ten loggers were opened and channel 2 was connected to the wire harness. The 12 V battery was again synchronously connected to channel 2 on all loggers for approximately three seconds. The second pulse was not needed to achieve synchronisation but was required to validate logger synchronisation.
Stop Loggers	Data acquisition was stopped for all loggers, the data cards were removed and data was stored on a hard drive.

Table 7-3 Schedule of tests performed

Source Location	Operation-Time	Flow Rate Ball Valve open (l/s)
TR1 V1 closed	Valve closure-10:16 am Valve opening-10:18 am Valve closure-10:19 am Valve opening-10:20 am Valve closure-10:21 am	2 l/s
TR2 V1 closed	Valve closure-10:51 am Valve opening-10:52 am Valve closure-10:53 am Valve opening-10:54 am Valve closure-10:55 am	2 l/s
TR3 V1 closed	Valve closure-11:05 am Valve opening-11:06 am Valve closure-11:08 am Valve opening-11:09 am Valve closure-11:10 am	2 l/s
TR4 V1 closed	Valve closure-11:30 am Valve opening-11:31 am Valve closure-11:32 am Valve opening-11:33 am Valve closure-11:34 am	2 l/s
TR1 V1 open	Valve closure-11:52 am Valve opening-11:53 am Valve closure-11:54 am Valve opening-11:55 am Valve closure-11:57 am	2 l/s
TR2 V1 open	Valve closure-12:12 pm Valve opening-12:13 pm Valve closure-12:14 pm Valve opening-12:15 pm Valve closure-12:16 pm	2 l/s
TR3 V1 open	Valve closure-12:34 pm Valve opening-12:35 pm Valve closure-12:37 pm Valve opening-12:38 pm Valve closure-12:40 pm	2 l/s
TR4 V1 open	Valve closure-12:48 pm Valve opening-12:49 pm Valve closure-12:51 pm Valve opening-12:52 pm Valve closure-12:53 pm	2 l/s

7.6 Results

In this section the data from the experimental field site is analysed. Temporal synchronisation is validated using the pre and post deployment voltage pulses. Individual trigger events are identified. Primary wave front arrival estimation is applied to the pressure signals from all data loggers and the source localisation procedure is applied using linear wave speed estimations.

7.6.1 Temporal Synchronisation and Validation

The reason for simultaneously applying a voltage pulse to all ten loggers pre and post deployment was to validate the temporal synchronisation across all the acquired data. The pulse also served as means of correcting any synchronisation errors.

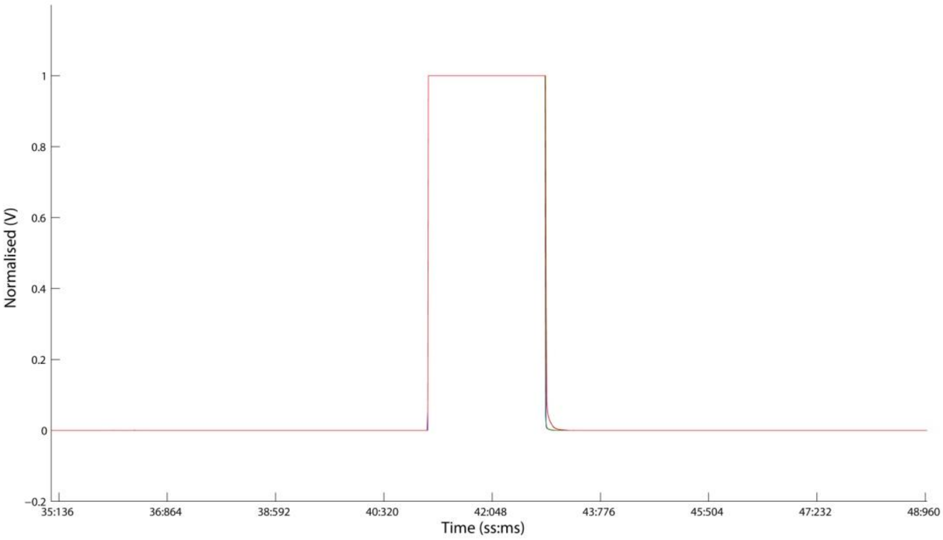


Figure 7-16 Synchronised pre-deployment voltage pulse for all ten data loggers

The master unit from which all loggers were synchronised only records a GPS time stamp at a frequency of 20 Hz. When loggers were connected to the master unit to acquire a time stamp the time could therefore only be accurate to 0.2 second. The start time of the first voltage pulse could easily be identified in the data from one logger and this was used as a bench mark to correct the synchronisation errors in data from all other loggers. The pulse initiation time was identified in the data for each logger, the time difference between this and the bench mark was calculated, then applied as a correction factor to each set of data, to ensure the times were synchronised to the time of the pulse. To validate the synchronisation over time and to check for temporal drift the second pulse was compared for all loggers.

The pre deployment synchronisation pulse for all ten loggers is shown in Figure 7-16 and the post deployment pulse is shown in Figure 7-17. It is clear in these two figures that all ten loggers were successfully synchronised and that minimal drift occurred over the logging period.

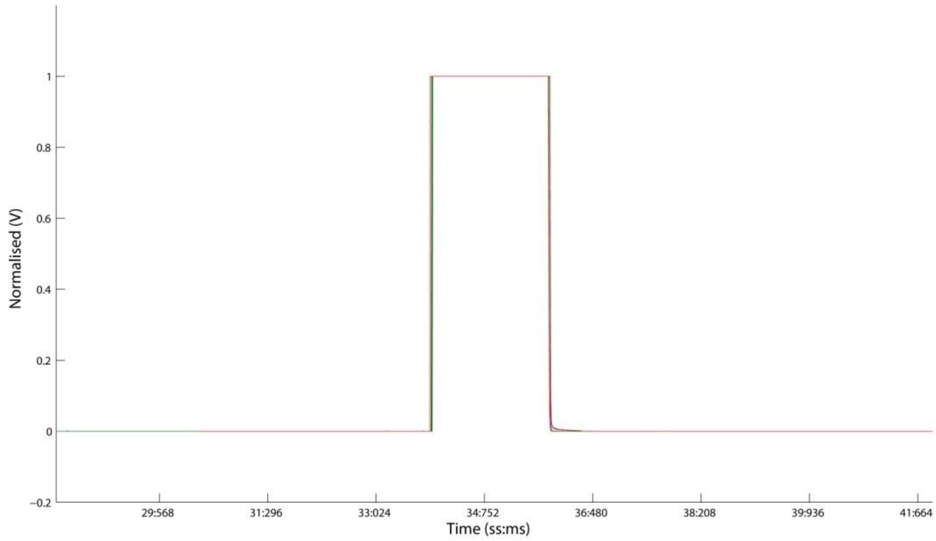


Figure 7-17 Synchronised post-deployment voltage pulse for all ten data loggers

7.6.2 Experimental Field Data

This section shows plots from a selection of the experimental field data. Figure 7-18 shows a pressure plot of the data from all ten pressure loggers where the purple line, H is the hydrant logger. The eight separate deployments of the transient generation equipment are highlighted showing the first four deployments with service valve V1 closed then the next four deployments with V1 open.

7.6.2.1 Full Data Set

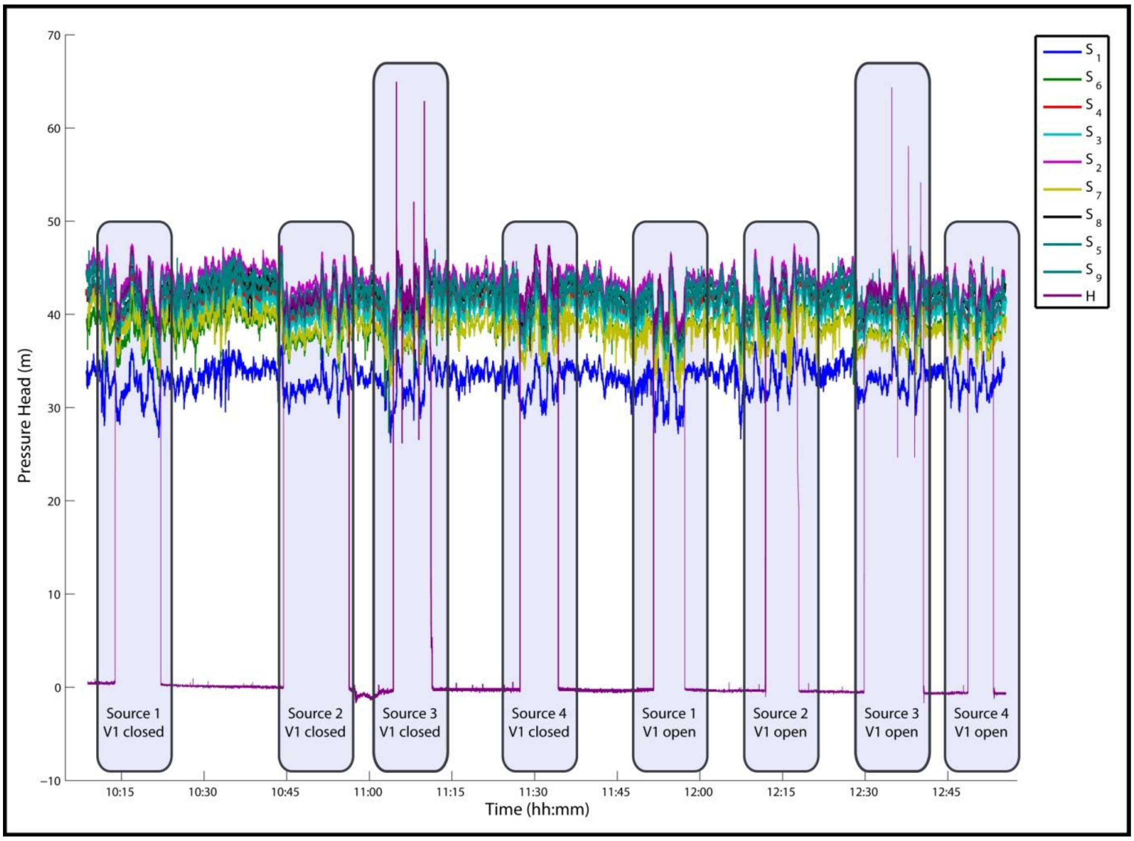


Figure 7-18 Pressure/Time plots of data from all ten pressure loggers showing the eight separate transient generation events

For both the deployments of the transient generation equipment at the source 3 location (tr3) the pressures observed at the hydrant are noticeably larger than at the other three location. This could be due to the fact that tr3 is at the end of a branch of a 63 mm pipe were as the other locations are all situated along larger pipes. Higher pressures should therefore be observed due to the smaller pipe diameter at this location and the resultant greater change in flow velocity.

7.6.2.2 Transient Source - Location 1

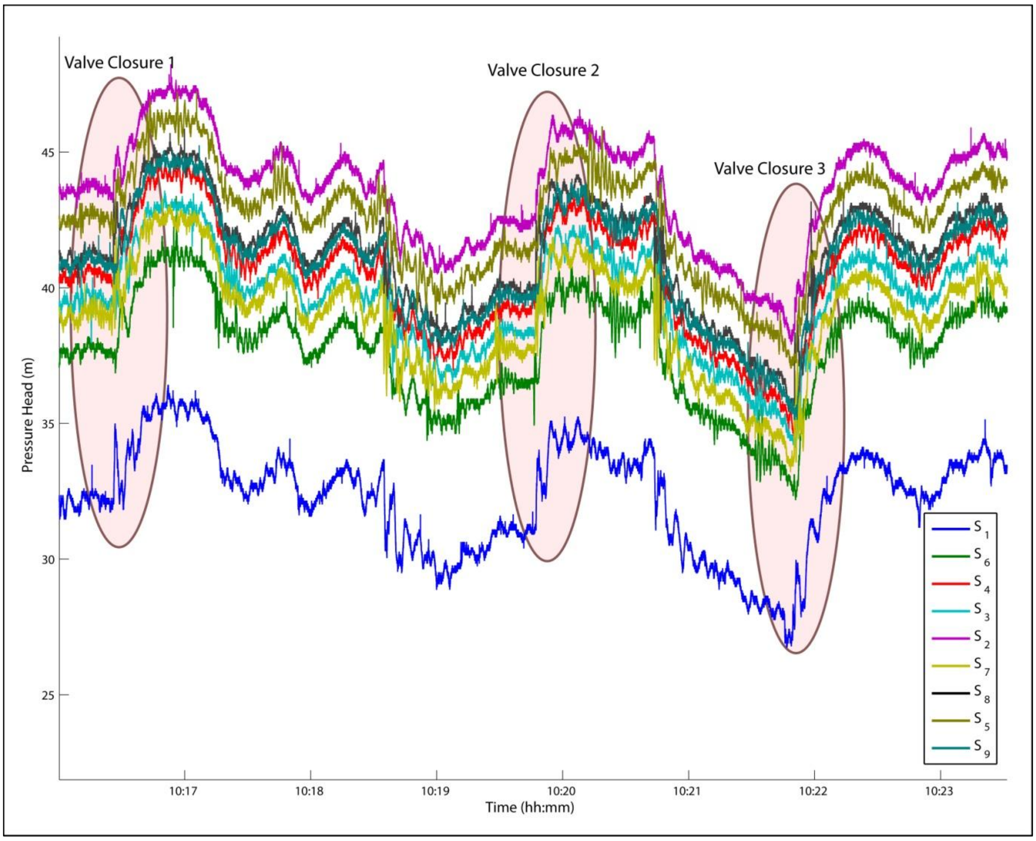


Figure 7-19 Generation Source Location 1 valve 2 closed

A closer observation of the data from Generation source 1 with V1 closed is shown in Figure 7-19, where pressure plots are shown for all nine logger locations. The three valve closure events are highlighted. The pressure variations associated with the closure of the ball valve at source location 1 can be observed at all nine logger locations.

A more detailed plot of the data associated with valve closure 1 is shown in Figure 7-20 which plots the voltage signal for each of the nine loggers deployed in the system.

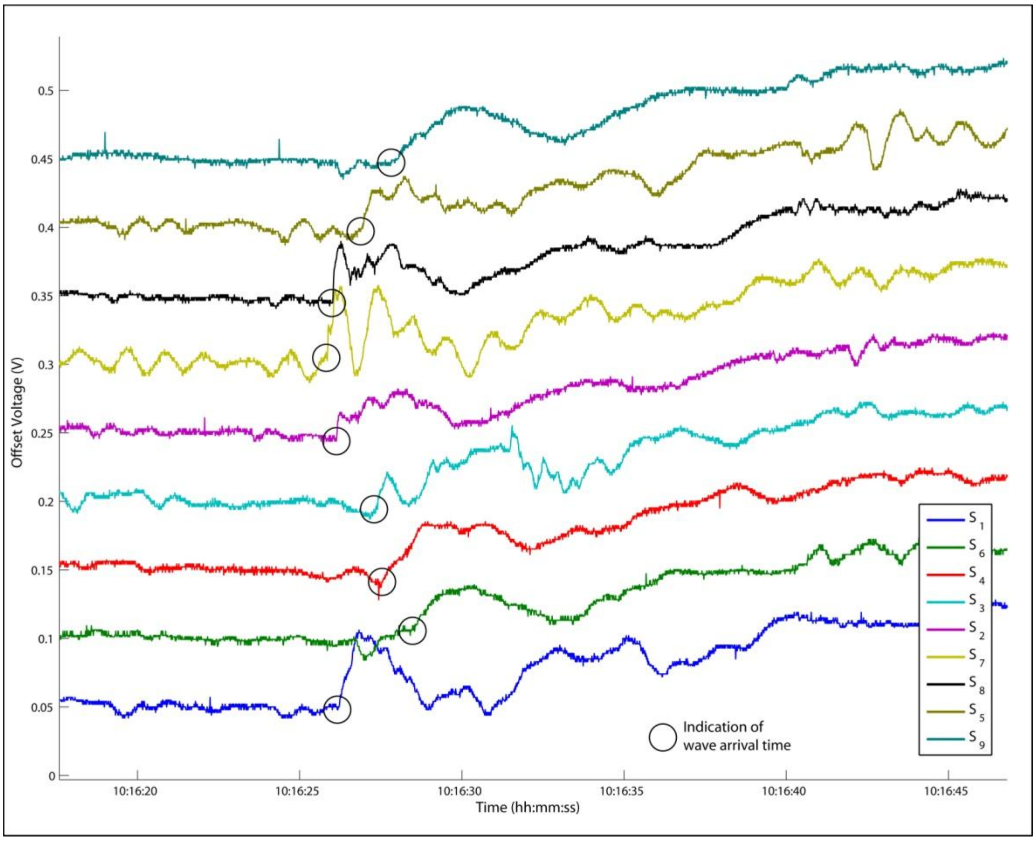


Figure 7-20 Source location 1 Closure 1

The y-axis in Figure 7-20 is in volts and to aid clearer observation of the independent signals, each signal was given a zero mean then offset by an increasing increment. It is not necessary to use calibrated pressures for the source localisation procedure because only the arrival time of the pressure wave and the relative changes in the signal profile are important. Characteristic transient pressure oscillations can be observed in the signal at S_7, which is closest the source location, at many of the other locations particularly those furthest from the source, the transient overpressures cannot be seen and the pressure follows a more gradual gradient as it changes to the new steady state pressure.

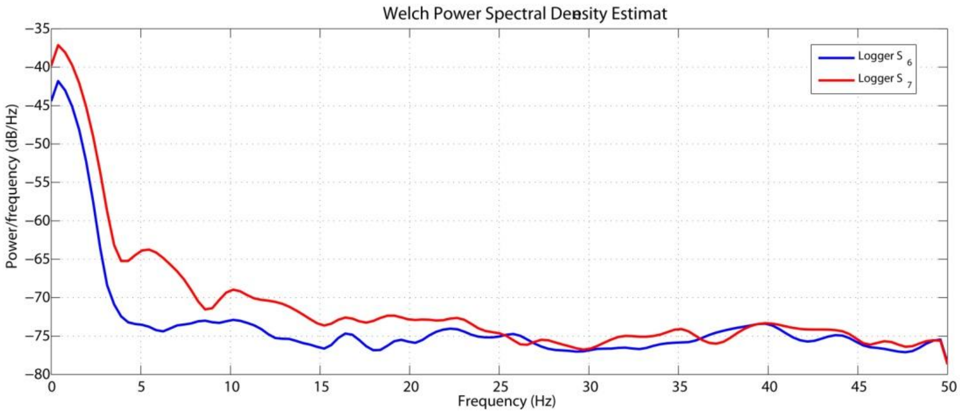


Figure 7-21 Power Spectral Density plot of signal at location 1 for valve closure 1

A power spectral density estimation of the signal at logger locations 7 and 6 is shown in Figure 7-21 confirming that frequencies in the range 0 to 25 Hz have been attenuated from the signal at location six 6. The strong primary wave fronts observed in the laboratory data are not therefore present in the pressure profiles for logger locations at distances away from the source. Even at logger location 2, the initial step in pressure is well defined but very little over pressure is observed. Even with the considerable attenuation, dissipation and dispersion of the transient signal it is still relatively clear to observe the arrival times of the pressure wave at all logger locations. Arrival times determined by visual inspection are indicated in Figure 7-20.

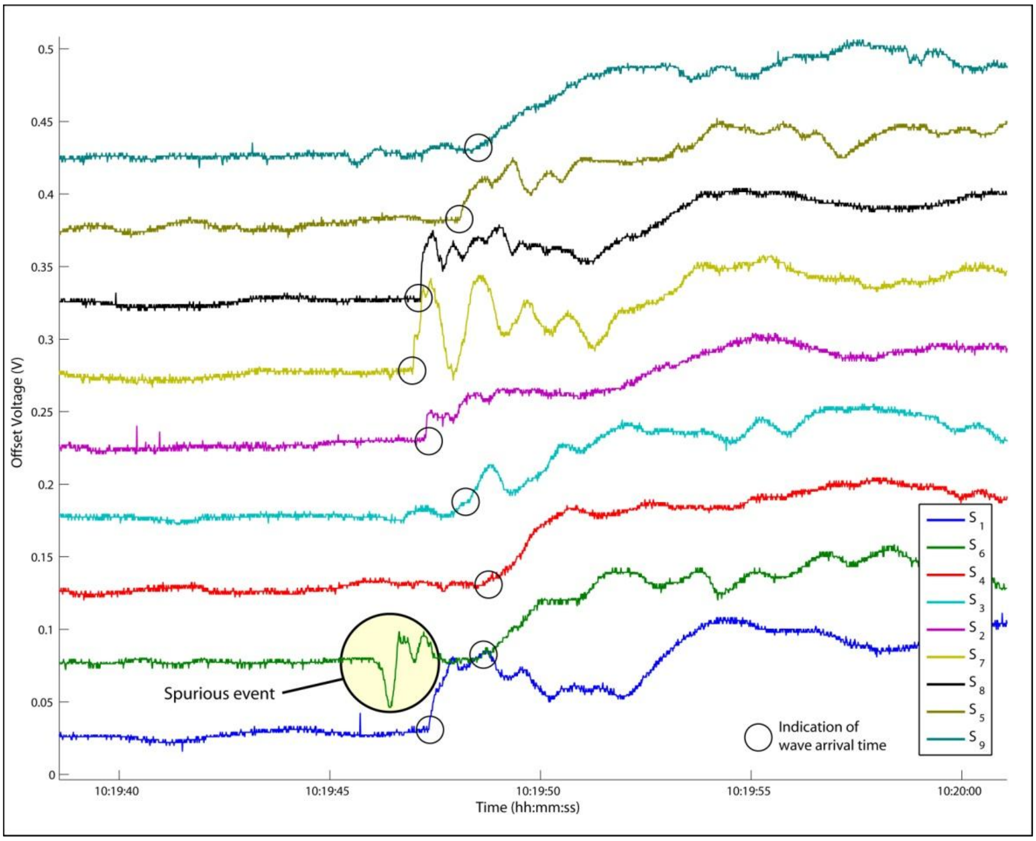


Figure 7-22 Source location 1 closure 2

Valve closure 2 at source location 1 with service valve V1 closed is shown in Figure 7-22. The signal profiles at all logger locations are very similar to those for closure 1 but it is apparent that a transient from an alternate source occurs at location S6. The spurious event is barely noticeable at other locations in the system implying that the relatively small event is dissipated as it enters the larger pipes in the system. The significance of the spurious event, is that it is likely to affect the output of the wave arrival time estimation methods. In this instance, it is therefore more useful to use the data associated with closure 1 for source localisation, in the grander scheme it highlights a need to check the data visually or otherwise before it is used for localisation. On balance, the generated transient events were intentionally small and in practice would probably not constitute a significant event.

7.6.2.3 Transient Source - Location 2 valve V1 open

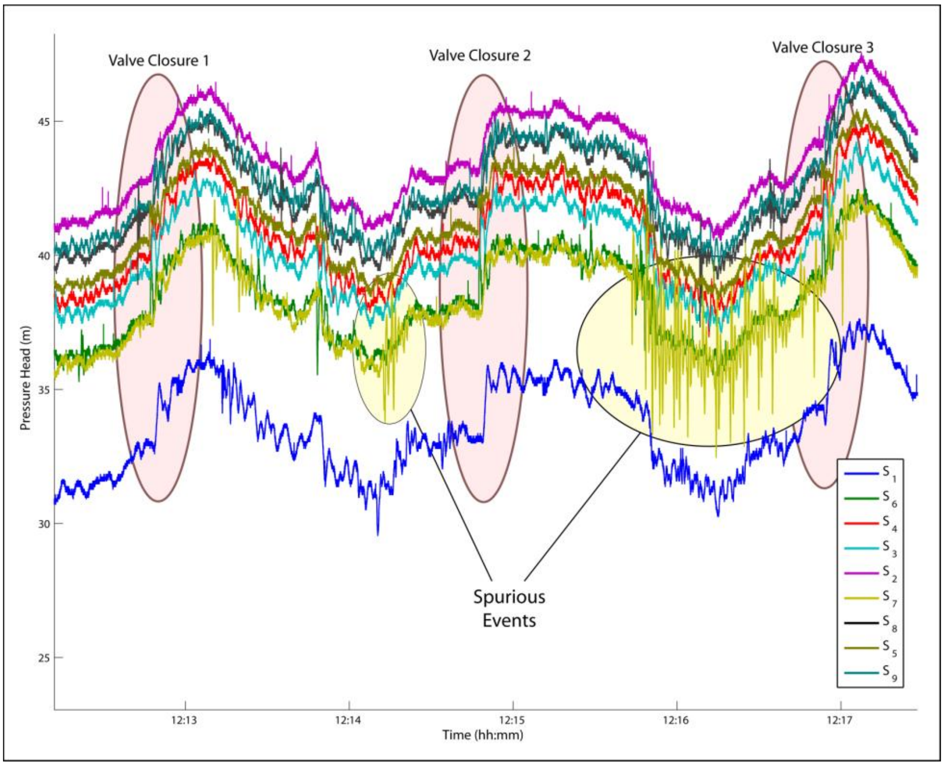


Figure 7-23 Source location 2 Valve 1 open

A plot of the pressures, associated with the generation device operating at location 2 is shown in Figure 7-23. More instances of spurious events occurring in the system can be observed. The relatively small magnitude of the spurious events means they can only be clearly observed close to where they are generated. Because the location being a residential area the events are most likely to be caused by house hold appliances, with fast closing valves. in Figure 7-24 a regularly occurring transient can clearly be seen at logger S_7. The occurrence of these small transient events has two main implications for source localisation:

- They invalidate the data obtained at logger sites where the small transients have been observed, because it is difficult decisively identify the primary wave front.
- Fortunately the small transients do not greatly influence the pressure profiles at other logger locations. This means that these could still be valid for source localisation.

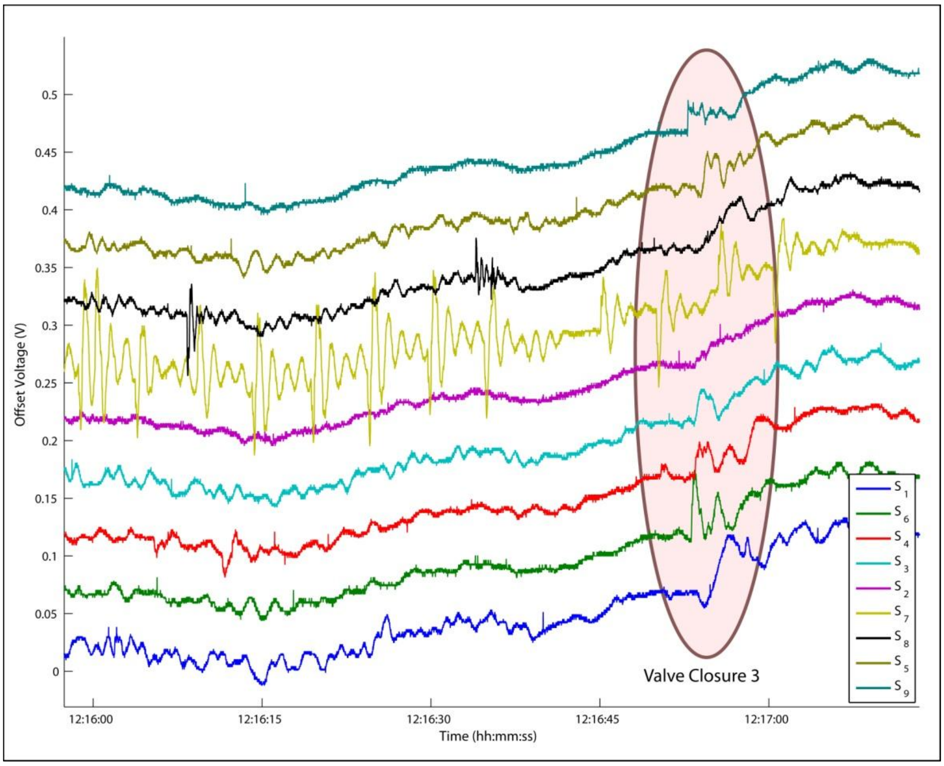


Figure 7-24 Source location 2 Valve 1 open valve closure three

7.7 Wave Front Arrival Time Estimation

The four most successful wave arrival time estimation methods on 100 Hz data identified in the laboratory experiments were the:

- Spectral Flux method,
- Negative Log-Likelihood method,
- Continuous Wavelet Transform method,
- Hilbert Transform method,

All four methods were applied to the data for each valve closure of the transient generation device, to assess their ability it identify the arrival time of the primary wave front. By observing the estimated times for each method and visual inspection of the pressures at each logger location, the Hilbert Transform method was the only method which consistently, successfully identified a location coinciding with the wave front arrival. Considering the relatively small magnitude of the transients generate this is a strong result. The other methods were susceptible to noise in the system so although they appear to identify the wave arrival at some locations they failed at other.

7.8 Source Localisation - Validation

In this section, the procedure for determining the locality of transient sources is applied to data relating to each of the eight transient generation device deployments, at the experimental field site. The objectives were; to validate that source locations could be successfully identified, to an acceptable degree of accuracy by using the graph theoretical model, to show that this could be achieved by using estimated wave speeds and the successful wave arrival time estimation methods, to confirm that the derived optimal logger placement locations could effectively obtain a successful result.

From the four wave arrival time estimation methods listed in 7.7, provided that no significant spurious events were present in data close to the time of the transient generation events, the Hilbert Transform method consistently provide valid arrival times and successful localisation results. All of the other three arrival time estimation method failed to provide valid localisation results for some if not all of the generated transient events. This was probably, in part, due to the relatively small magnitude of the generated transients, compared to system noise, For that reason results are only shown using the Hilbert Transform method and manual wave arrival time estimation.

7.8.1 Validation of method - Source 1 V1 closed

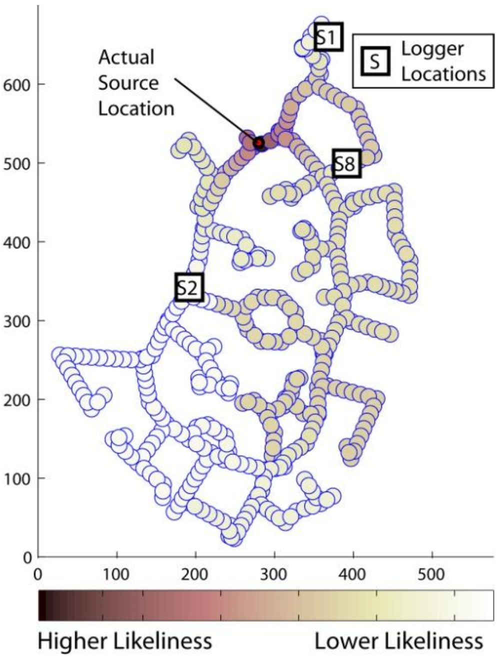


Figure 7-25 Source localisation using three loggers for transient source 1 with V1 closed, Hilbert Transform wave arrival estimation was used

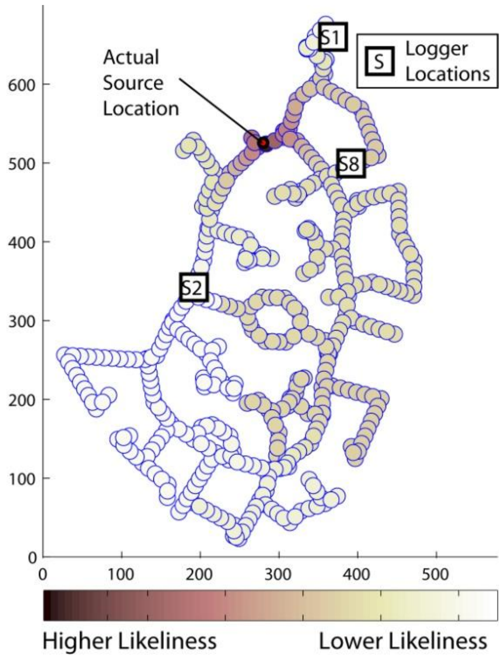


Figure 7-26 Source localisation using three loggers for transient source 1 with V1 closed, Manual wave arrival estimation was used

To verify that a valid localisation result could be achieved and that model parameters were appropriate, a source was chosen with three loggers surrounding it and arrival time estimates were made using the Hilbert Transform method and manual estimation. Plots of the localisation result are shown in figures Figure 7-25 and Figure 7-26. Both results show a very strong positive localisation coinciding with the same node as the actual generation source. Ignoring the logger which was closest to the source so not to trivialise the results a strong positive result is seen in Figure 7-27 when all the other eight loggers were used.

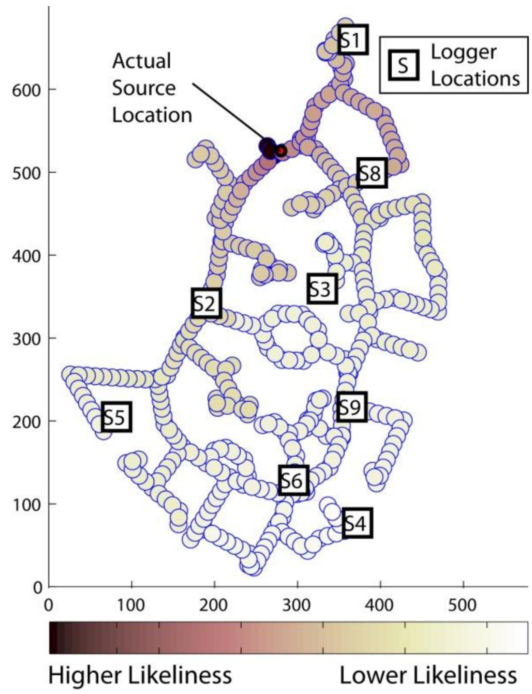


Figure 7-27 Source localisation using eight loggers for transient source 1 with V1 closed, Hilbert Transform wave arrival estimation was used

7.8.2 Source Localisation Validation - Source 1 V1 closed

Application of the source localisation procedure using the data acquired from the field experiments showed that using logger locations furthest from the source could have an adverse effect on the accuracy of the localisation result. For this reason a two stage approach was devised to analyse the data.

The initial step was to perform localisation using the data acquired from the two loggers. The location of the first two loggers can be determined using the logger placement procedure but the objective was to place the loggers at extremities of the system. To determine the wave arrival time the Hilbert Transform method was used. Figure 7-28 shows the results from the preliminarily assessment where the chosen logger locations were S5 and S8.

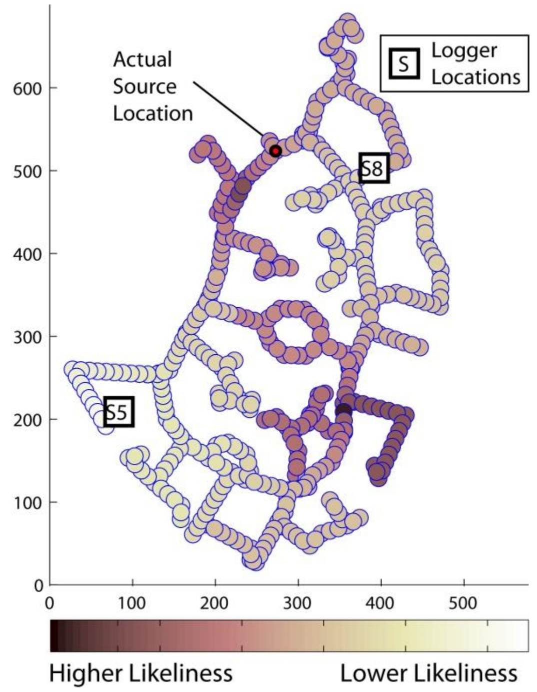


Figure 7-28 Source localisation using two loggers for transient source 1 with V1 closed, Hilbert Transform wave arrival estimation was used

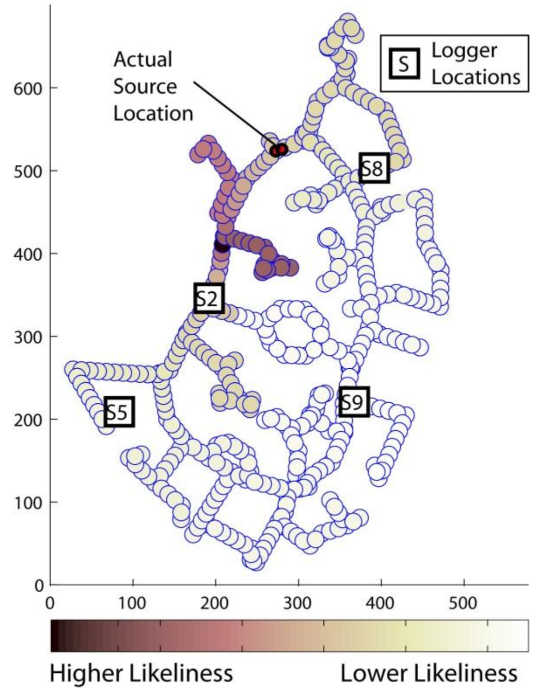


Figure 7-29 Source localisation using four loggers for transient source 1 with V1 closed, Hilbert Transform wave arrival estimation was used

Two possible source locations are indicated in the results from the preliminary assessment in Figure 7-28. Informed by the areas of highest Likeliness two further logger locations are used in the analysis, shown in Figure 7-29. Data exists for logger location S7 which was directly next to the source location but the close proximity of S7 to the source would trivialise the result so instead data for S2 was used. S9 was used as the other location, being very close to the other area of high Likeliness. Source localisation was performed using the two original logger locations and the two new locations. Results from this second phase show that the ambiguity close to S9 no longer exists and one area of highest Likeliness is apparent. Although an unambiguous result is achieved after the second phase the source location prediction defined by the area of highest Likeliness has a considerable error. Fortunately the error appears to be caused by arrival time estimation errors at the logger locations furthest from the source. Greater arrival time estimation errors are could be expected further away from the source location due to wave front degradation and wave fronts arriving from multiple paths. Due to the longer travel distance, the primary wave front travelling anticlockwise around the main loop would arrive at S9 very slightly after the wave travelling clockwise, which may slightly affect the wave arrival time estimate.

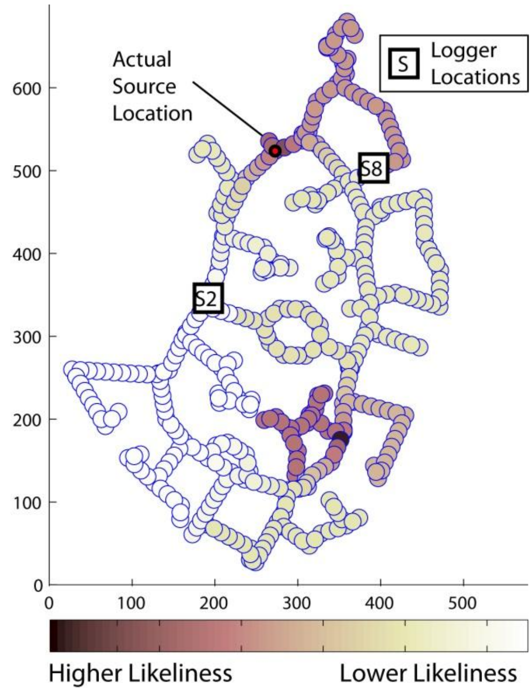


Figure 7-30 Source localisation using two loggers for transient source 1 with V1 closed, manual wave arrival estimation was used

Fortunately a third localisation result (Figure 7-30) can be attained, using data from the two loggers closest to the source location prediction in stage two. This third stage provides a very strong positive result at the true source location. An ambiguity also occurs but this can be ignored because it was already eliminated as potential source in stage two.

It is a valuable concept, that to maximise location estimation, the pressure loggers furthest from the predicted source location can be ignored once ambiguities have been identified.

7.8.3 Source Localisation Validation - Source 2 V1 closed

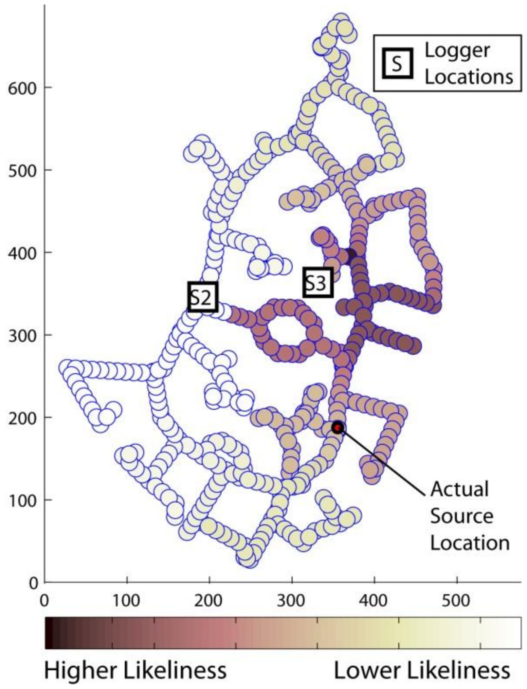


Figure 7-31 Source localisation using two loggers for transient source 2 with V1 closed, Hilbert Transform wave arrival estimation was used

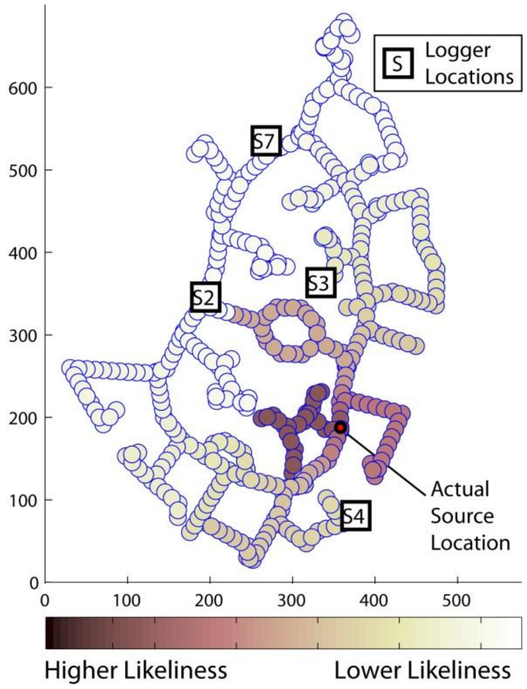


Figure 7-32 Source localisation using four loggers for transient source 2 with V1 closed, Hilbert Transform wave arrival estimation was used

To show that loggers at other locations and at network extremities can be used for this first stage in the analysis, logger 2 and 3 were used. In Figure 7-31 the highest Likeliness does not suggest an ambiguous source location and at face value it would appear to indicate that the source is located at or close to location 3. This is a misleading result and it should therefore be taken into account that S2 is at the opposite side of the loop from the source location where multiple wave arrivals could influence the arrival time estimates.

In the absence of multiple areas of highest Likeliness as shown for source location 1, an alternative procedure needs to be applied to decide the locations of the other sensor locations. The first assessment identifies that the source is somewhere down the right hand side of the loop. If the extra loggers are incorporated in the analysis the location S3 and the source then S2 would still need to be relied on for source localisation. Relying on S2 is undesirable as it is sited the furthest distance from the source. The desired outcome, is that once the extra loggers are deployed for stage two, then either of the new logger locations should lie to the opposite side of the source to S3. The chance of achieving this is increased if the new sensor locations are not too close to S3 and a useful guide is towards the extents of the area of highest Likeliness from the assessment stage. Using this guidance the most appropriate sensor locations were S4 and S7. Analysis of stage two results in Figure 7-32 provides a strong positive result.

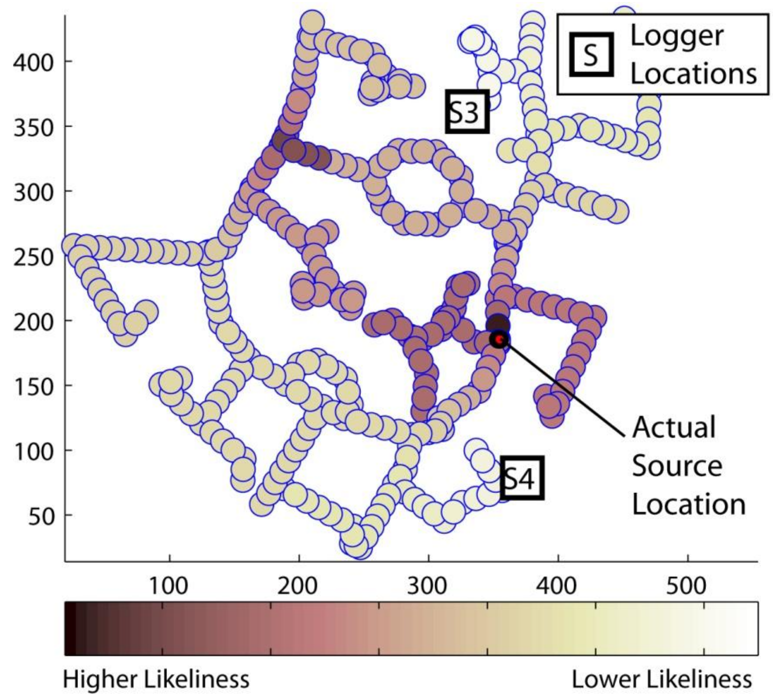


Figure 7-33 Source localisation using two loggers for transient source 2 with V1 closed, manual wave arrival estimation was used

Moving to stage three and performing the analysis with the furthest loggers removed confirms the strong positive result in Figure 7-33. The ambiguity near to the location of S2 can be ignored as it was ruled out in the second stage assessment.

7.8.4 Source Localisation Validation - Source 3 V1 closed

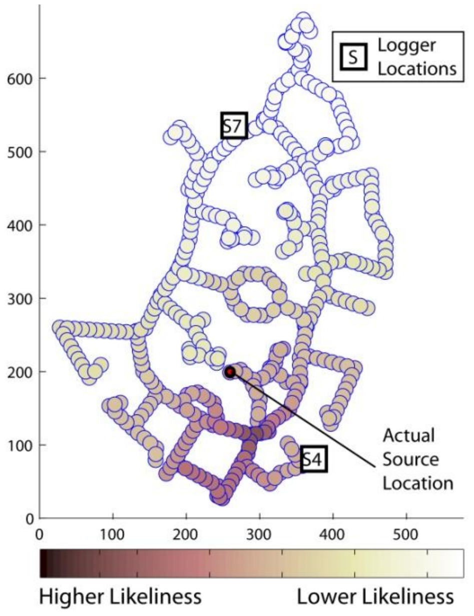


Figure 7-34 Source localisation using two loggers for transient source 3 with V1 closed, Hilbert Transform wave arrival estimation was used

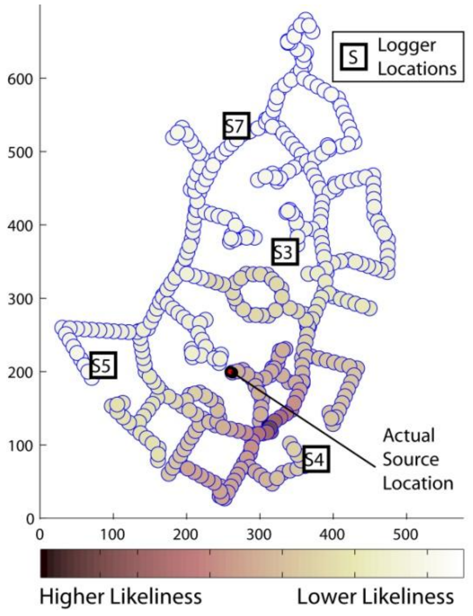


Figure 7-35 Source localisation using four loggers for transient source 3 with V1 closed, Hilbert Transform wave arrival estimation was used

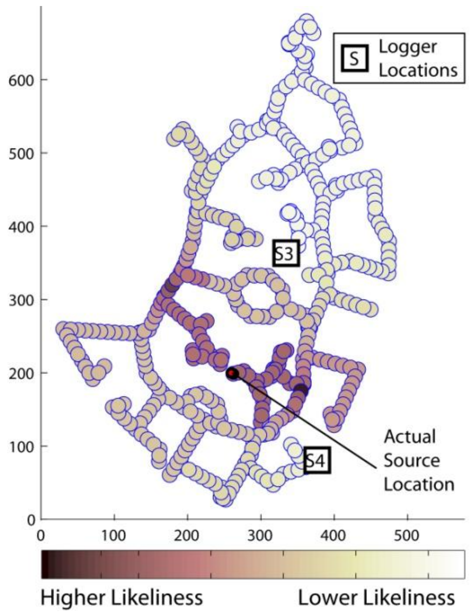


Figure 7-36 Source localisation using two loggers for transient source 1 with V1 closed, Hilbert Transform wave arrival estimation was used

For source location 3, the first assessment suggests that the source is close to S4, Figure 7-34. Using two extra loggers in the analysis at the extremities of the area of highest Likeliness shown in Figure 7-34, removes the ambiguity. Finally removing the two furthest locations provides a strong result.

7.8.5 Source Localisation Validation - Source 4 V1 closed

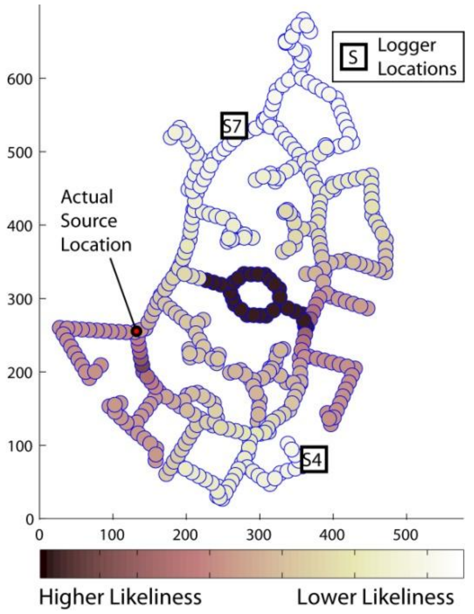


Figure 7-37 Source localisation using two loggers for transient source 4 with V1 closed, manual wave arrival estimation was used

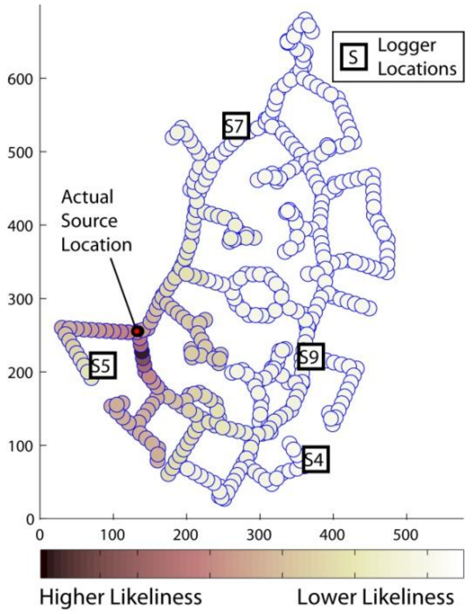


Figure 7-38 Source localisation using two loggers for transient source 3 with V1 closed, manual wave arrival estimation was used

For source location 4, the first assessment shows ambiguities in Figure 7-37. Extra loggers are therefore used at locations S5 and S9.

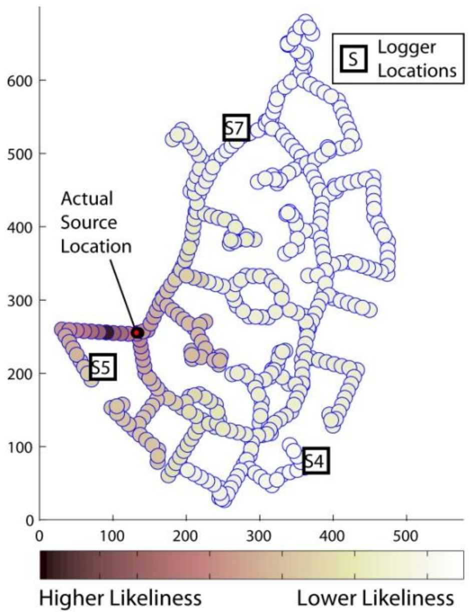


Figure 7-39 Source localisation using two loggers for transient source 4 with V1 closed, manual wave arrival estimation was used

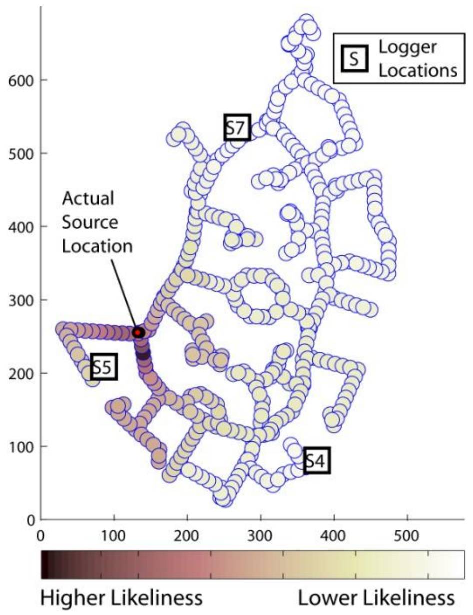


Figure 7-40 Source localisation using two loggers for transient source 4 with V1 closed, manual wave arrival estimation was used

Only S9 is removed for the third stage of analysis because S4 and S7 are a similar distance from the estimated source location. Shown in Figure 7-39 a localisation error of approximately 30-40 m exists using the Hilbert Transform wave arrival time estimation method. For comparison, wave arrival times were estimated manually these results are shown in Figure 7-39. A slight error still exists but in a different direction. Using both methods provides a guide as to the variability in results but both are within in acceptable degree of accuracy.

7.8.6 Source Localisation validation - Source 1 V1 open

The following results shown are all from data generated with valve V1 open

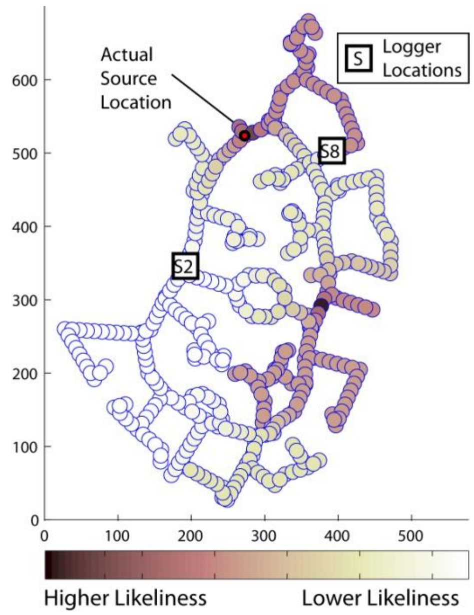


Figure 7-41 Source localisation using two loggers for transient source 1 with V1 open, Hilbert Transform wave arrival estimation was used

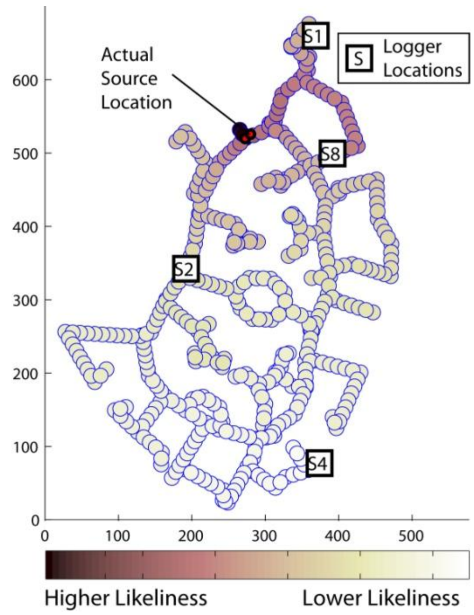


Figure 7-42 Source localisation using four loggers for transient source 1 with V1 open, Hilbert Transform wave arrival estimation was used

Using the two phase analysis approach it is always possible to identify an approximate source location and make an informed decision as where to place other loggers in the system with Figure 7-41 and Figure 7-42 confirming this approach and the positive result.

7.8.7 Source Localisation validation - Source 2 V1 open

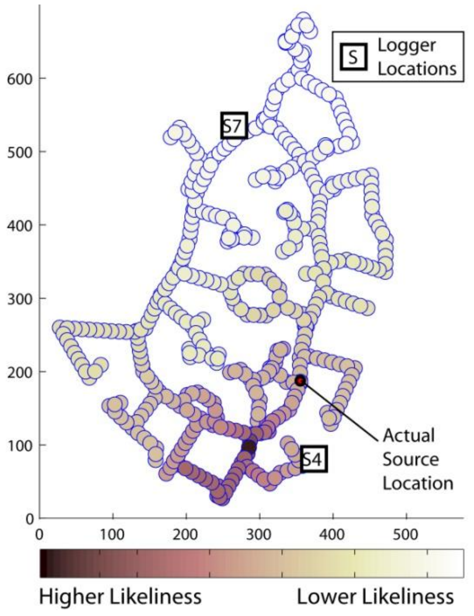


Figure 7-43 Source localisation using two loggers for transient source 2 with V1 open, Hilbert Transform wave arrival estimation was used

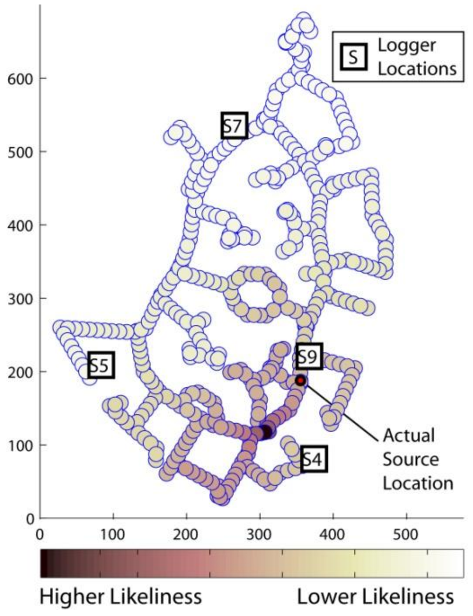


Figure 7-44 Source localisation using four loggers for transient source 2 with V1 open, Hilbert Transform wave arrival estimation was used

Figure 7-43 confirms that if one of the two loggers used in the first assessment is a considerable distance from the source, in particular, at the opposite side of a loop, then the localisation result is affected and only those two loggers cannot be relied on for localisation. Adding extra loggers removes the ambiguities as in Figure 7-44 and although not shown here, removal of the furthest two loggers improved the result.

7.8.8 Source Localisation validation - Source 3 V1 open

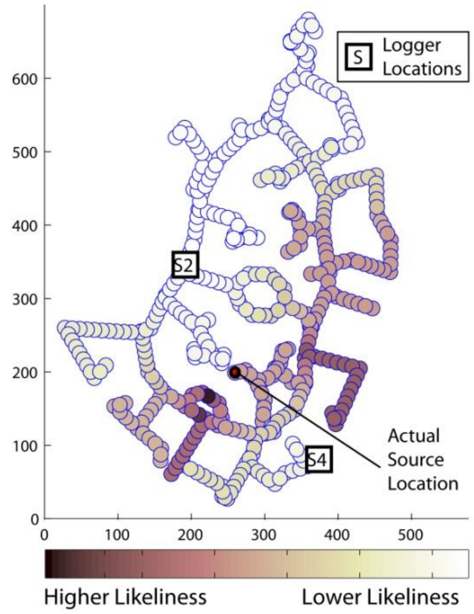


Figure 7-45 Source localisation using two loggers for transient source 3 with V1 open, Hilbert Transform wave arrival estimation was used

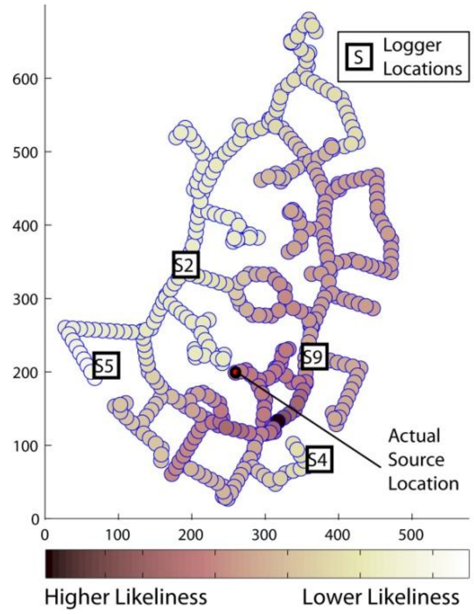


Figure 7-46 Source localisation using four loggers for transient source 3 with V1 open, Hilbert Transform wave arrival estimation was used

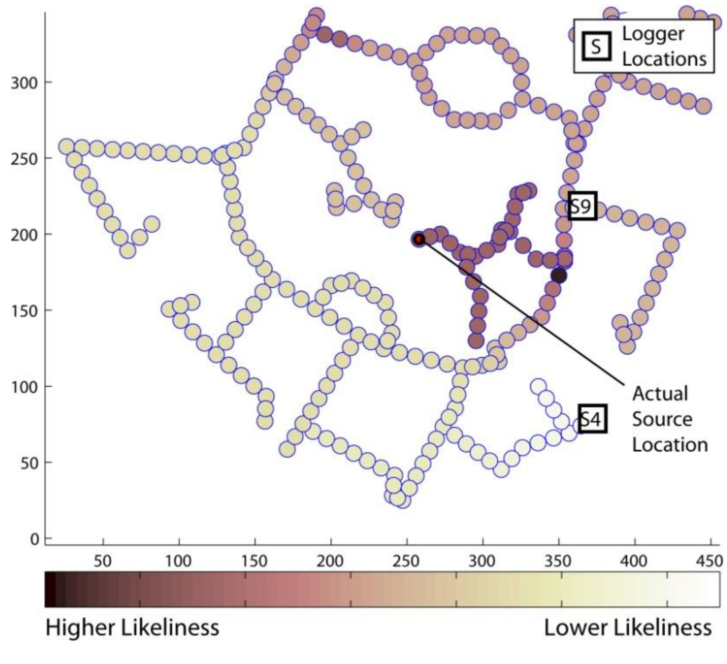


Figure 7-47 Source localisation using two loggers for transient source 3 with V1 open, Hilbert Transform wave arrival estimation was used

Figure 7-47 further highlights that having loggers placed close to the source location can provide a very strong result to within one discretisation interval of 10 m.

7.8.9 Source Localisation Validation - Source 4 V1 open

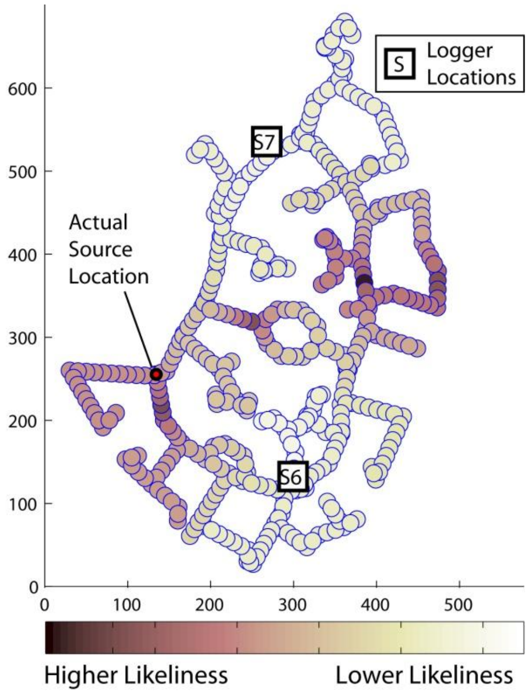


Figure 7-48 Source localisation using two loggers for transient source 4 with V1 open, Hilbert Transform wave arrival estimation was used

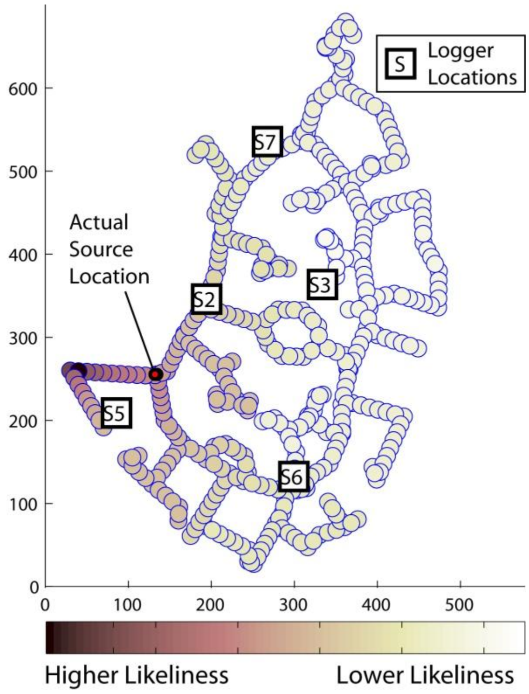


Figure 7-49 Source localisation using five loggers for transient source 4 with V1 open, Hilbert Transform wave arrival estimation was used

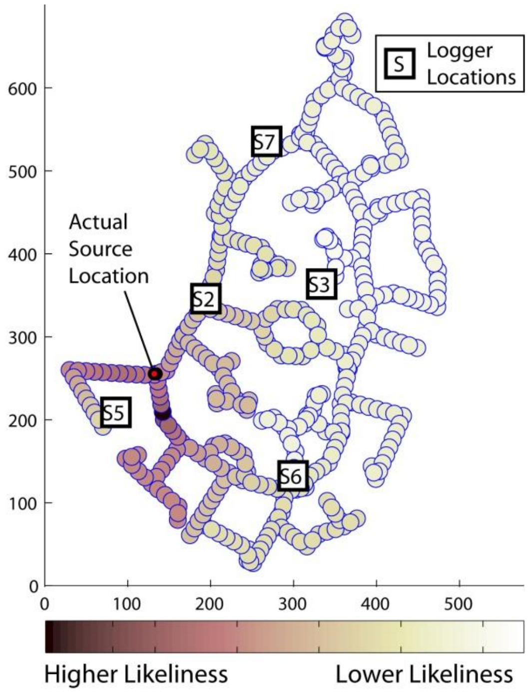


Figure 7-50 Source localisation using five loggers for transient source 4 with V1 open, manual wave arrival estimation was used

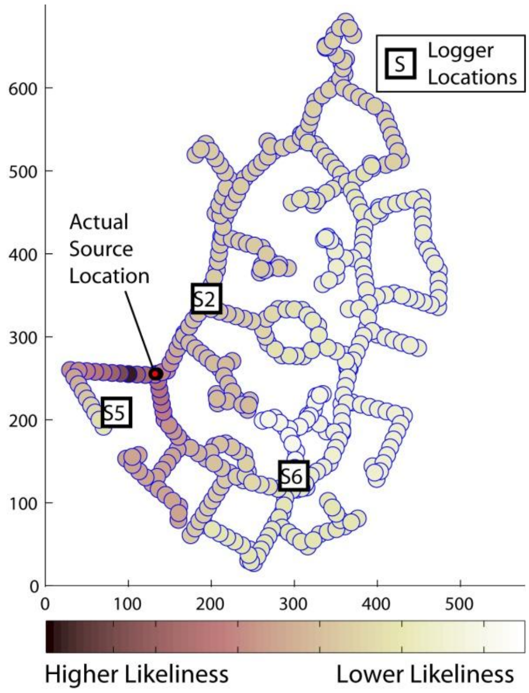


Figure 7-51 Source localisation using three loggers for transient source 4 with V1 open, Hilbert Transform wave arrival estimation was used

Figure 7-48 identifies an issue associated with having valve V1 open because three possible source locations are shown. In this case, three extra loggers are used in the second stage of analysis and they are placed close to the areas of ambiguity. Utilising these three extra loggers in Figure 7-49 and Figure 7-50, which respectively use the Hilbert Transform and manual wave arrival time estimation methods, it is show that the ambiguity is removed. Using the three loggers closet to the specified source location, Figure 7-51 shows that the accuracy of the result is improved.

7.8.10 Localisation Error

Although every effort is made to minimise uncertainties and errors, to ensure that accurate source locations can be identified, uncertainties are inevitable with the following factors being potentially significant contributors.

- Synchronisation Error
- Wave Arrival detection error
- Wave speed estimation error

Data Synchronisation errors should generally be mitigated and it has been shown that checks can be imposed to verify temporal synchronisation. The main uncertainties therefore arise from unknown wave speeds and arrival time detection errors.

Assuming records of pipe material and approximate dimensions are available, approximations to the wave speeds can be ascertained. For most linearly elastic pipe material, a suitable value for Young's modulus can be assumed, with relatively small variability in the values. For visco elastic pipes however the variability in wave speeds can be considerable. The major contributing factor to wave speed variation is uncertainty in the Young's modulus, although approximations to upper and lower values for the Young's modulus can be established. Considering a 1000m long pipe with a sensor at each end and a source situated ¾ of the distance along the pipe. If the actual wave speed is 400 ms^{-1} , a 20% variation in wave speed could produce a 50 m error in localisation. An error of this magnitude could still provide a practicable solution but in reality uncertainties in wave speeds should be considerably smaller than 20%. Further work to provide greater understanding as to the wave speeds in visco elastic pipes could help to further minimise errors, where considerable uncertainties still exist, empirical measurements could be made in a real distribution system. Based on empirical data from Covas et al., (2004), A K Soares et al., (2008) and work published in this thesis, reasonable approximations to wave speeds to within 10% error should be achievable. If faster wave speeds are consider for the same 1000 m pipe the location error associated with a 20% wave speed error is still 50 m but for linearly elastic materials estimated wave speeds should be more accurate due to more reliable values for the Young's modulus.

Errors are evident in source likeliness of the field validation results, which are largely attributable to errors in wave arrival time detection. Increased degradation of the primary wave front with increased distance from the transient source location reduces the certainty in arrival time detection. These effects can be partially mitigated by ignoring the results from the furthest sensor location once ambiguities have been eliminated. Small errors in wave arrival time detection are still very likely but the errors observed in the field validation results are still permissible. For more rigid pipe materials with lower damping and less wave front degradation it is conceivable that wave arrival time detection errors could be reduced, hence improving the localisation results.

In summary, uncertainties are inevitable but valid results can be achieved based on estimated pipe characteristics. Where higher levels of accuracy are required improvements can be made, for instance, by empirically determining wave speeds or increasing the density of the logger placement. The latter could be implemented after an initial approximate solution had been obtained.

7.8.11 Discussion of Source Localisation

Using the Hilbert Transform wave arrival time estimation method provided positive source localisation results for all source generation locations, provided there were no spurious events in the results. Some localisation errors did occur, but the maximum error was 40 m and generally much smaller which would generally be acceptable for practicable purposes.

From all nine loggers deployed it possible to achieve a strong positive result using appropriate combinations of just six of the loggers these being logger locations S1 S2 S4 S5 S8 and S9 which is in agreement with quantity suggested using the optimal placement procedure. Admittedly due to location restrictions it was not possible to generate transients at every location in the system but the results strongly validate the source localisation procedure

Application of the source localisation procedure using the data acquired from the field experiments showed that using logger locations furthest from the source could have an adverse effect on the accuracy of the localisation result. For this reason a two stage approach was devised to analyse the data. The approach validates the source localisation procedure and the successful placement of the loggers. It also forms the basis of a framework for routine proactive monitoring of water distribution Systems.

Considering the localisation framework represented by Figure 4-1, an element of the background assessment was to verify the existence of a transient event through pressure monitoring and data acquisition. If two synchronised loggers are used for this verification step and an event is identified then a preliminary assessment can be performed to establish an approximate source location based on these results.

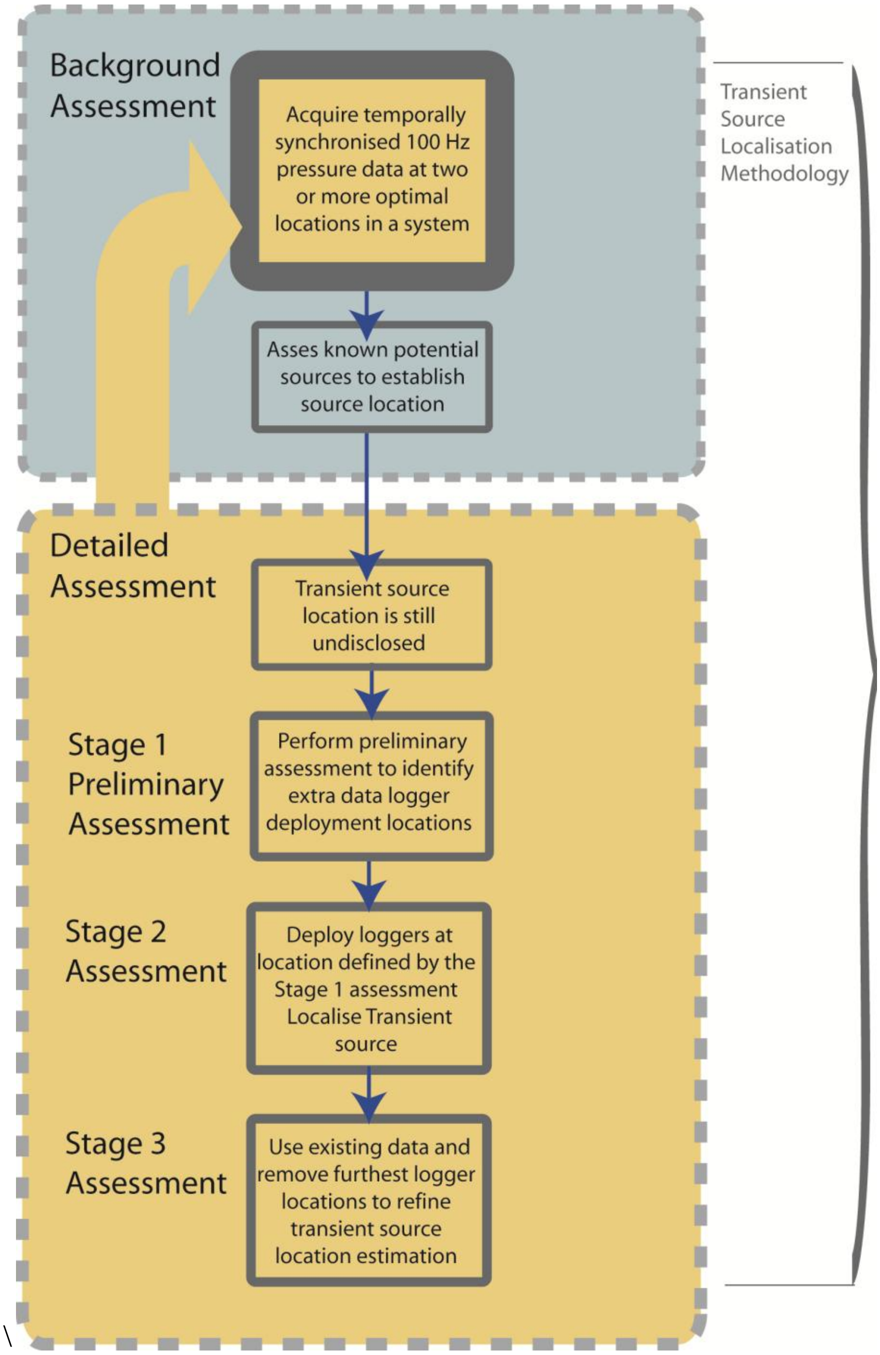
The information gained from the preliminary assessment can be used to deploy more pressure loggers in more optimal locations. A minimal number of loggers can be deployed because the user is already informed as to the approximate location of the source. Conversely, a greater number of loggers can be deployed in smaller parts of the system to improve the accuracy of localisation.

Following this procedure for logger deployment, two loggers need to be deployed at the same locations that were used in the preliminary assessment, the reason being, that the objective of deploying further loggers is to eliminate the ambiguities identified in the preliminary assessment. Using the original two logger locations should ensure that localisation result from the preliminary assessment is repeated and that the ambiguities are removed. The advantage of a two stage analysis approach is that proactive assessment of multiple systems can be performed by only deploying two data loggers in each system. If significant events are located then further loggers can be deployed to perform a more robust analysis.

At all stages the optimal logger placement procedure can be used to determine logger locations. Should a two stage approach not be desired, the logger placement procedure could be used to define placement and quantities of multiple pressure loggers in a system.

7.8.12 Source Localisation Procedure Schematic

Informed by the development process from Conceptual Design, to Laboratory Verification and finally to Field Validation the following schematic represents a procedure for proactive assessment to successfully identify the locations of transient pressure sources in water distribution networks.



7-52 Source localisation procedure schematic

7.9 Discussion of Field Validation

It was shown that it is feasible to acquire synchronised pressure data from multiple data loggers at multiple locations in a live distribution system at relatively high sample frequency of 100Hz. From this data, wave arrival times can be successfully estimated and used for source localisation. The Hilbert Transform wave arrival time estimation method provides reliable arrival time estimates for source localisation on small transient pressures. Validation of the arrival time estimates by visual inspection would generally be recommended.

The observation made from the data in Figure 7-20 and Figure 7-21 help to validate some of the decisions made and the adopted approach. Using 100 Hz data is clearly applicable, at least in highly damped systems. It is relatively easy to establish the arrival time of the initial wave but degradation of the wave front at distances from the source seem to imply, that at least for this system, the consideration of secondary and tertiary wave arrival times could be prohibitive, and may not improve the localisation procedure.

The deployment of data loggers at locations consistent with using the placement optimisation procedure can provide a valid localisation result to within a practicable level of accuracy required. The results imply that greater errors in estimated wave arrival times at logger locations further from the source location can affect the accuracy of the result. These effects can be mitigated; once an approximate source location has been identified, the furthest loggers can be omitted from the analysis to improve the accuracy of the result at a local level. Ambiguities arising from the omission of the furthest loggers can be ignored. The results therefore show that using fewer loggers than were deployed, four or five, can still provide positive localisation results, forming the basis from two possible procedural approaches.

- Option one is to deploy loggers in the quantities and locations specified using the optimal placement procedure. Subsequent analysis can then use this data informatively to optimise the accuracy of the solution with the gradual omission of logger location.
- Option two is to deploy two loggers for an initial site evaluation. Analysis of the data provides guidance as to the estimated position of the transient location. The user is then informed as to other optimal logger placement

locations required for successful source localisation, with the deployment of a minimal quantity of loggers.

Large quantities of novel data have been generated in this chapter with up to ten synchronised logger locations and various known transient source locations. Aside from direct application to the source localisation procedure the data could be used to improve understanding of transient propagation in live complex pipe networks.

8 Discussion, Conclusions and Further Work

A number of drivers contributed to the concepts developed throughout this thesis. The primary driver was the realisation that on occasion, problematic transient pressure events can be regularly occurring in water distribution systems, where the generation source is undisclosed and difficult to identify. The concept of determining analytical procedures to identify generic transient pressure sources had not been widely discussed in the literature, although evidence existed to suggest that the problem of unidentifiable events could occur. Secondly, state of the art high frequency data acquisition hardware was available, which could be adapted to observe pressures in water distribution systems.

8.1 Locating Transient Sources Using Graph Theory

A graph theory methodology was considered as a theoretical means of identifying the generation source location of a generic transient pressure in a water distribution system, based on observations at multiple points in the system. The adopted approach relied on the comparison of measured and estimated arrival time differences of primary wave fronts at multiple pressure data acquisition locations. The advantage of only considering the primary wave front was that uncertainties in system configurations, hence the uncertainty of subsequent wave front arrivals need not be accounted for, minimising the requirements for system characterisation. Theoretical evaluation of the methodology implied that if uncertainties still existed in the wave speed, hence transit time, a suitable level of accuracy could be achieved, provided accurate wave arrival time estimations could be made. If significant uncertainties in the pipe wave speed did exist these could be determined through empirical measurement. The graph theory methodology was verified and validated using novel laboratory and field validation experiments.

As well as providing a method for transient source localisation the graph theoretical approach provided novel solutions for determining optimal sensor placement locations. The locations determined by using these methods were verified by the successful localisation of transient sources at an experimental field site.

The success of the source localisation methodology relied on an ability to acquire temporally synchronised high frequency pressure data at multiple locations in a water distribution system, then subsequently estimating accurate arrival times of the pressure primary wave fronts at all locations. Field validation showed that logger locations further from the source had greater errors in wave arrival time estimation but the effects could be mitigated by removing the furthest loggers from the analysis once ambiguities had been eliminated.

8.2 Data Acquisition

High sample rate pressure data acquisition is now routinely available to identify the occurrence of transient events but the literature showed that while 20 Hz data acquisition and upwards of 500 Hz has been used to identify transient pressures, the use of sample frequencies in between these values had generally been ignored. It was considered that developing a method to identify source locations using pressure data sampled in the range 20:500 Hz could have a number of advantages because frequencies outside that range had a number of disadvantages these being:

- Pressure wave speeds in pipes can travel up to 1500 m/s. Using sample frequencies of 20 Hz or lower would not provide sufficient temporal accuracy to determine the arrival times of wave fronts for meaningful analysis.
- Sampling above 500 Hz has limitation associated with increased power requirements and dealing with very large datasets. The generally adopted approach to deal with higher frequency data acquisition is to use selective data capture so that only significant events are recorded therefore limiting the data storage requirements and ignore potentially valuable information.
- When high frequency data was analysed some of the adopted approaches provided temporal resolution far lower than the sample rates employed.

The problem of locating sources of transient pressures is in itself transient; new occurrences could arise in a system, which once mitigated needed no further observation. The solution therefore required re-deployable data acquisition hardware, which could be installed for periods of a week or longer with a sample rate high enough for the required temporal accuracy but low enough to minimise power and data storage requirements.

100 Hz data loggers were sourced from the race car industry, which were adapted to log pressures in water distribution systems. The memory capability of the loggers

would allow up to a month of continuous data acquisition and with less than 60 mA current requirement could feasibly be battery powered for up to two weeks. Ten data loggers were successfully synchronised to less than 0.01s over approximately a 7 hour period, deployed in a live distribution system and synchronously acquired data. To verify the application of 100 Hz data to source localisation a suitable and robust means of estimating the arrival times of primary wave fronts in real distributions systems was established.

8.3 Wave Arrival Time Estimation

A novel dataset was generated using a modular laboratory test pipe assembly. Ten different wave arrival time estimation methods were evaluated; among them were established methods, new methods, and some existing methods, which were newly applied to transient pressure wave fronts. All ten methods were shown to be effective to varying degrees on a single pipe but when applied to the novel data from the looped laboratory network showed greater variations in results. When applied to 100 Hz data only four of the methods were successful at estimating wave arrival times. The four successful methods were applied to 100 Hz pressure data, which was acquired from a real water distribution system and one of them, the Hilbert Transform method, was shown to be successful in estimating wave arrival times to achieve a valid source localisation result. The magnitude of the transients generated in the real system for validation purposes, were intentionally relatively small, highlighting the robustness of the successful method.

Using the Hilbert Transform method to estimate wave arrival times with 100 Hz data provided greater temporal resolution for wave arrival time estimation than other methods for example using multi scale discrete wavelet decomposition.

8.4 Non Linear Wave Speed

The pipe material used for the laboratory test pipe was MDPE, a viscoelastic pipe material, in which the wave speed was known to slow down or retard as it travelled along a pipe. This phenomenon has been previously measured empirically under laboratory conditions. Analysing data from the modular test pipe to verify the wave arrival time estimation methods it was observed that the reflected wave appeared to advance as it neared the generation source. Unfortunately the phenomenon was not investigated further because only the arrival of the primary wave front is considered for source localisation procedure.

8.5 Conclusions

The need to develop a novel approach for localising the source of transient pressures in water distribution systems was identified. The concept was not widely discussed in the literature so the aim was to devise, verify and validate a solution to the problem through conceptual and experimental verification and validation.

A solution was devised based on graph theory, where theoretical arrival time differences of a transient pressure primary wave fronts could be compared to measured arrival time differences from physically acquired pressure data from a real distribution system.

The source localisation procedure was conceptually verified by achieving the following objective:

- The graph theory approach was verified through theoretical simulations on different network configurations using variable quantities of sensor locations
- Bespoke solutions for defining sensor placement were identified and theoretically verified.
- Assessments were made of the variability in source location prediction due to errors in wave speed and wave arrival time estimation.

Using a laboratory based physical model further verification of the source localisation procedure was achieved by:

- Adapting and developing methods for estimating the arrival times of transient pressure primary wave fronts on data acquired at 4 KHz and data down sampled to 100 Hz.
- Proving the effectiveness of the localisation procedure on data acquired from the novel modular test pipe network with 100 Hz data on pipe material known to have variable wave speeds.

Full scale field experiments validated the source localisation procedure by successfully identifying the location of transient pressures generated at four locations at an experimental field sites showing that:

- 100 Hz pressure data could be synchronously acquired at multiple locations in a system and successfully used in the transient source localisation procedure.
- The Hilbert Transform successfully identified appropriate primary wave front arrival times at all sensor locations in the test system for all the generated transients.

8.6 Future Work

It has been verified that the approximate location of transient pressure sources can be identified in relatively complex pipe networks using temporally synchronised pressure data from multiple data loggers and a graph theory based source localisation procedure. Considering all stages of the work presented in this thesis, from conceptualisation to validation, a number of opportunities have arisen which could require further research and development. Taking into account the success of the source localisation procedure a number of other possibilities for future developments also exist.

8.6.1 Further Field Deployment

A primary task and logical progression following on from the work covered in this thesis would be to apply the successful source localisation procedure to multiple real problems occurring in water distribution systems. Hence, providing further validation of the procedure and providing novel data sets for future developments of the localisation procedure. At first, this could be achieved by using the models developed to prove the concepts in this thesis. To further develop the practicability of the localisation procedure, it would ideally be integrated with existing water utility infrastructure, which could be achieved by satisfying the following objectives:

- Novel software development, to integrate with existing water utility infrastructure and provide usability to end users.
- Automated model generation based on existing Geographic Information System (GIS) asset database.
- Bespoke hardware development, to maximise the reliability, efficiency and effectiveness of hardware deployment and to better integrate with software systems. In achieving this objective, further advancements could potentially be made in state of the art water pressure monitoring devices.

- Refine and streamline hardware deployment and data analysis procedures.

8.6.2 Increased Understanding of Transient Activity

Further deployments of the source localisation hardware and subsequent data analysis would provide further insights to the prevalence and propagation of transient pressures in real distribution systems. With readily deployable equipment, that can be reactively installed in any part of a water network, which has adequate installation locations, the significant instigators of transient pressure events can be greater understood and categorised. It is accepted that large transient events have the potential to damage infrastructure. With further development of the localisation procedure and greater automation of data analysis software, the source of small to medium transient events could be localised and their regularities and magnitudes evaluated. This would provide critical insight into the impact that these ‘less significant’ events have on distribution systems.

8.6.3 Improved Source Location Accuracy

It has been accepted through the development of the transient source localisation procedure, that the method is unable to evaluate how far along a branch a transient is located. For practicable purposes, this can provide a suitable level of accuracy. Future work could consider adapting the procedure by adopting alternative methodologies, to identify how far along a branch a source is located. The efficient graph theory approach could pave the way to adopt more computationally intensive methods on localised parts of a system. For instance, having localised a source to a small area of a network, a deterministic solution could be adopted and/or coupled with other signal processing procedures.

8.6.4 Viscoelastic Pipe Behaviour

Considerable gaps still exists in the understanding of transient pressure wave propagation in viscoelastic pipe materials. Valuable work has been undertaken in this area Covas et al., (2004) and Alexandre Kepler Soares et al., (2008) but analysis has only been performed on data from a limited number of experimental test rigs and a limited number of specific pipe materials. Wave speeds have only been measured empirically in well controlled conditions. With a large array of different viscoelastic materials currently in use with many uncertainties as to the specific properties of buried pipes, greater understanding is required. This could potentially be achieved through comprehensive empirical experimentation, which could in turn lead to the development of better theoretical wave speed predictions based on known or assumed pipe and material characteristics.

While characterising the wave speed in the experimental test pipe in 6.4.1.1 an apparent wave speed advancement was observed as the reflected wave front approached the initial transient source, as a reversal of the wave speed retardation observed in the initial transit of the primary wave front. This phenomenon does not seem widely discussed in the literature. Further investigation was not directly consistent with the progression of the research discussed in this thesis but further understanding from future work may help to strengthen the understanding of wave propagation in viscoelastic pipe materials.

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