VIBRATION SENSORS: LISTENING FOR NETWORK LEAKS

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ABSTRACT

Sotto® is a key innovation in South East Water's (SEW) critical work to reduce non-revenue water losses due to hidden leaks on SEW's network.

SEW's Sotto® program involves the development of high-performance vibration sensors that are small enough and cost effective enough to be packaged within a digital water meter installed on commercial and residential properties. While digital meters will identify leaks on the consumer's property Sotto® is instead tuned to detect water leaks on SEW's infrastructure before the leak reaches the surface where it invariably is reported by the public or potentially develops into a mains burst emergency.

The Sotto® sensor has been in development and testing for over three years and is currently at a commercial level quality and undergoing trials installed within digital water meters. The trials are on actual in-field leaks and are focused on determining Sotto®'s ability to detect and report those leaks. In addition, the trials are studying the impact of pipe materials, understanding the likely sensor distribution density of any large-scale network deployment and interpreting the generated data and how it may be used to increase Sotto®'s effectiveness.

The Sotto® device takes multiple vibration readings during the quietest part of the night and assesses them against a pre-determined threshold before sending alerts to operations teams via the digital meter's reporting payload. Various actions and algorithms are applied to mitigate against false positive signals. Leak vibration signals depend on several variables including distance, pipe material and leak size among others.

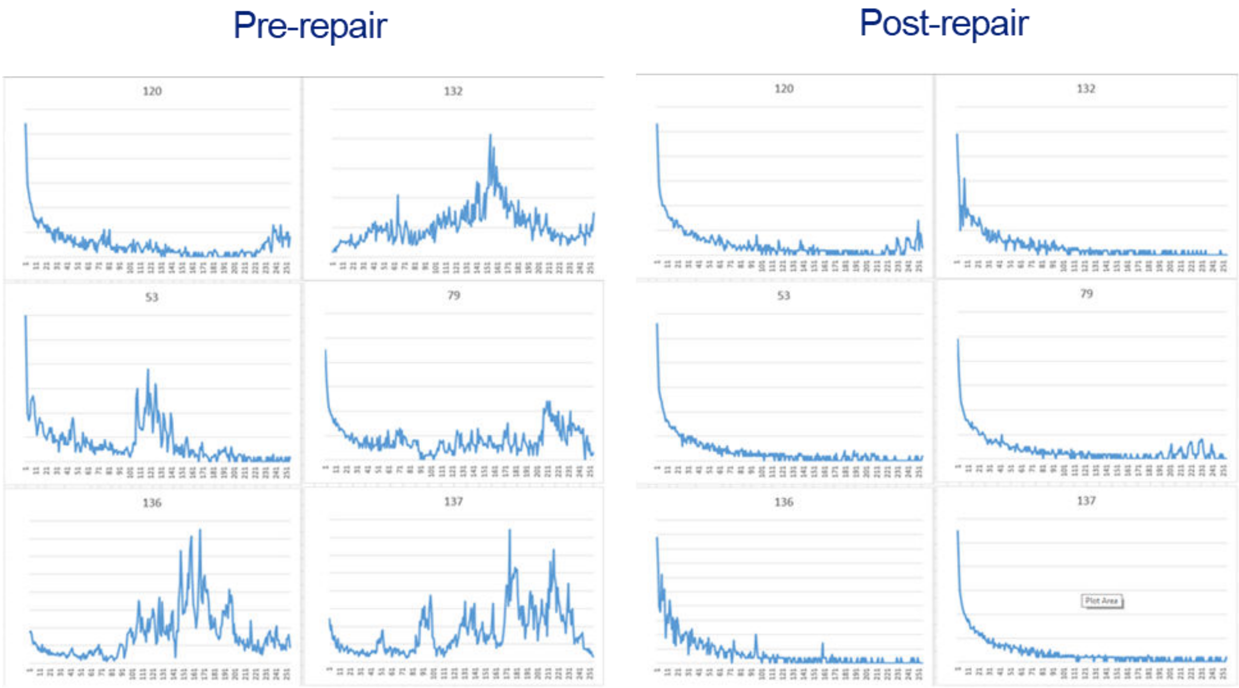
Sotto® has detected vibration signals at 80m and, when leaks are detected on multiple sensors simultaneously, can support triangulation to approximate the leak location. Where there is no leak a very low noise floor on the sensor ensures a leak signal is not lost within the noise and minimizes the chance for false positives.

Trials to date have exceeded expectations with Sotto®'s performance similar to or better than benchmark commercial leak detection 'listening sticks'. Sotto® has shown the capability to detect a majority of SEW's network leaks. Further development work is underway to improve Sotto®'s sensitivity on challenging small leaks and pipe materials such as UPVC that attenuates vibrations

A patent has been submitted and is pending.

The program is now approaching final trials with the deployment of 1,000 Sotto® embedded digital meters in mid-2020 and another 4,500 in late 2020.

Figure 1: Examples of multiple Sotto® vibration signals pre (left) and post (right) repair of network leak



KEYWORDS

vibration sensors, leak detection, non-revenue water

PRESENTER PROFILE

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1.0 INTRODUCTION

Like most water utilities around the world SEW is working hard to reduce water losses in their system. Not long after a 10+ year drought wracked the Australian continent the efforts to minimize the drain on a limited resource continues. A large but hidden source of those losses are from SEW's water network. It is difficult to define exactly the size of these losses as they are often hidden underground and are only apparent when they come to the surface if they do.

SEW estimates the non-revenue water losses during 2018/19 were 21.6 GL which equates to about 13.3% of the total volume of bulk water purchased by SEW. Leakage is estimated as 14.3 GL but includes more than just the network leaks.

In addition to the water losses there is reputational damage that naturally derives from relying on the public to report water leaks once water is already running down the street. If repair crews are unable to get to the job or repair the leak after a few days this only exacerbates the reputational damage.

Finally, the rare but serious issue of mains pipe bursts, particularly when in high density zones, are difficult to predict. Detecting and organizing preventative repairs well in advance of these bursts would minimize disruption to the public.

Water leaks on SEW's infrastructure are either on the water main, the service line connection, the service line itself or the stop tap and meter assembly. Most leaks at SEW occur on service lines and their connections to the main. In trying to detect these leaks, SEW also deploys a small group of leak detection operators using Fuji leak detection 'listening sticks' to detect hidden leaks. These operators walk SEW's network of one million meters reporting leaks as they hear them through their sensor equipment to address these leaks prior to them becoming apparent to the public.

In 2016 SEW was in the process of investigating the development of digital water meters to replace their 1 million mechanical meters. These digital meters communicate via an NBIoT network reporting in payloads of data each day. It was recognized that an opportunity existed for SEW to procure or, failing that, develop themselves a leak vibration detection sensor that was compact enough to fit inside a digital meter, cost effective enough to deploy in every digital water meter and had a similar performance to 'listening sticks'. If this sensor could be successfully developed SEW would effectively have a listening stick on every water meter reporting in data every day for 10+ years with a target cost of a few dollars per meter. The business case was clearly highly desirable.

Consequently, after SEW ascertained no commercial product existed that could fulfil this purpose the process of formal product development was begun. The program was managed under SEW's Product Development Stage/Gate system to manage risk and resources with the project held accountable to management stakeholders.

Figure 2 (left): Service line leak at the connection to the main. Figure 3 (right): Leak on PVC main

2.0 SENSOR DEVELOPMENT AND TESTING

2.1 PRELIMINARY PROTOTYPING

Preliminary feasibility and proof-of-principle work conducted in-house by SEW engineers demonstrated the project had potential. SEW decided to employ Planet Innovation, a Melbourne product developer who had the depth and breadth of engineering knowledge and experience to add the necessary weight to optimize the project's chance for success.

The initial work was conducted to document product requirements, understand the vibration sensor's working environment and profile the leak signals to detect. Various prototypes were designed and manufactured with different seismic masses, spring rate suspension and vibration pick up to permit preliminary testing.

Figure 4: Three examples of the sensor prototypes and mounting methods

The prototypes are an attempt to understand whether the concept could work under ideal conditions. As such the designs incorporated only limited consideration of likely final product packaging, weight and cost constraints.

A test rig was designed and built at SEW's Mt Martha Water Recycling Plant that would replicate the real-world environment of buried water mains with different materials. This would allow SEW to conduct testing in a controlled manner. Different leaks could be generated on the various pipe materials and the resultant leak vibrations detected with the prototype sensors and their respective performance compared. A reference sensor was installed to act as a datum to compare the performance of the prototypes.

Figure 5 (left): test rig instruments and prototypes. Figure 6 (right): installing mount pipe for prototypes

The results of the test rig trials verified it is possible to detect the small vibrations present in the water mains due to leaks and confirmed the value of moving the project forward to continue to assess technical feasibility. The information captured from the multiple prototype variations allowable optimization of the design for the next Alpha prototype phase in which the sensor would be deployed and tested in the real-world environment.

It had not, at this stage, been determined if it was feasible to reduce the sensor size to be compatible with SEW's expectations for packaging into a water meter enclosure.

Figure 7 (left): exposed pipes where leaks were created by drilling. Figure 8 (right): prototype sensor and Meggitt Mems sensor used as a reference mounted to the test pipe

A summary of results and learnings from the Mt Martha trials include:

- Identified optimal vibration sensor pick-up technology
- An increase in seismic mass increased amplitude response
- Changes in seismic mass shifted the frequency response
- Able to detect most leaks with only the smallest being challenging
- Reference Mems sensor detected even the smallest leaks but with a very low amplitude response
- Increased leak size increased both response amplitude and bandwidth
- Increasing the seismic mass decreased the frequency of max amplitude
- Poly pipe amplitudes were smaller than copper pipe which also suggests vibrations travel through pipe material and not the water
- Increasing the size of the leak did not change significantly the frequency of maximum amplitude
- The closer the sensor was to the leak the higher the frequency components appeared

2.2 ALPHA SENSOR DEVELOPMENT AND TESTING

After the initial success of the early proof-of-concept prototypes management decided to commit significant resources to developing an Alpha prototype. The Alpha prototype design process would take into serious consideration the design constraints that would be necessary for a successful final product. The initial prototype did not account for these constraints as they were solely intended to prove whether the concept could work with a minimal outlay of investment. If the project had failed these initial trials, losses would have been minimized and the project halted or taken in a new direction.

Planet Innovation were contracted by SEW to conduct the development of the Alpha prototypes.

The additional design constraints that this prototype would have to meet included:

- Performance
- Unit price
- Packaging

In parallel with the engineering of the electronics and understanding of the vibration signals, significant effort during Alpha development was on the sensor's mechanical components. The mechanical package design must fit within a generic meter envelope while the material and component selection along with design complexity all contributed to the final product's unit cost. Several mechanical design options were produced from which a most likely successful candidate was chosen that could meet all SEW's requirements.

A lab-based test rig was designed and built that could produce a repeatable range of vibrations to test the various Alpha prototypes responses across a wide spectrum. Again, a Mems sensor was used as a reference. For the first time these prototypes were mounted onto a flow tube typical of flow tubes found in water meters. This opportunity was leveraged to design a mounting method that would ensure complete transfer of vibrations from the flow tube to the sensor while also meeting manufacturing and assembly requirements.

Tests indicated the Alpha prototype had extraordinary sensitivity with distant vibrations in the building necessitating extreme efforts to isolate the test rig from these background noise sources.

For the first time tests were conducted in-the-field on actual SEW network leaks where mechanical residential water meters were replaced with flow tubes with mounted vibration sensors and the response signals captured. The data from these real-world tests were used to develop the best method of using and interpreting data received from the vibration sensors. Parameters such as frequency, amplitude, etc. were studied with the results of this work to be incorporated into the final Beta level prototype.

Results from this Alpha design and the subsequent tests indicated that not only was the concept of detecting leak vibrations in real world scenarios possible but also, and very importantly, that we could build a sensor that met the key product requirements indicated above. These results gave the management team confidence to commit resources to the design and manufacture of Beta prototypes. The Beta prototype would be designed for manufacture and meet all product requirements effectively being the final commercial level design barring any unforeseen problems necessitating significant design changes.

Figure 9: generic digital meter layout provided for Alpha prototype packaging envelope design

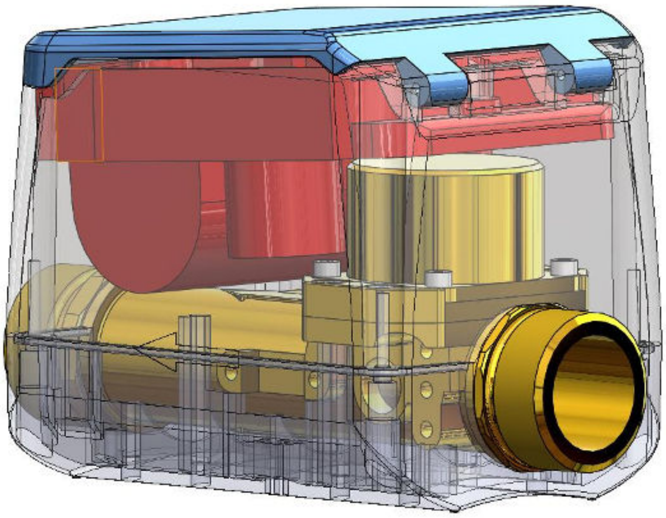
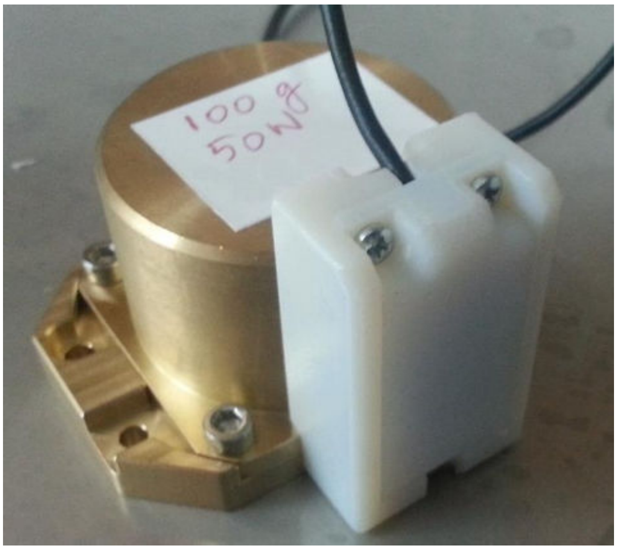


Figure 10 (left): one of various Alpha prototypes shown with external electronics. Figure 11 (right): lab test arrangement showing flow tube mounting and Mems reference sensor



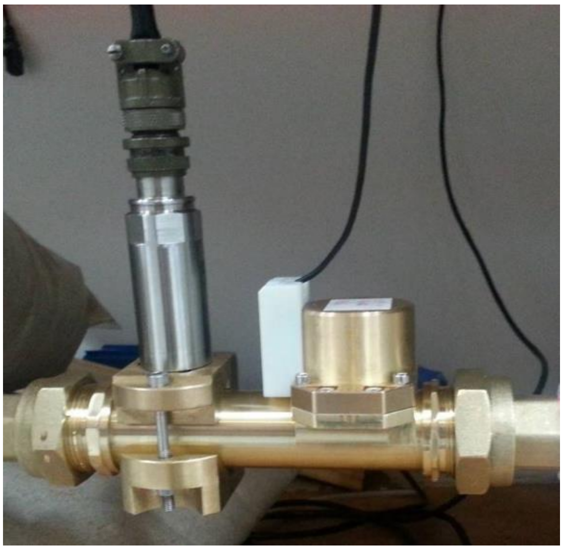
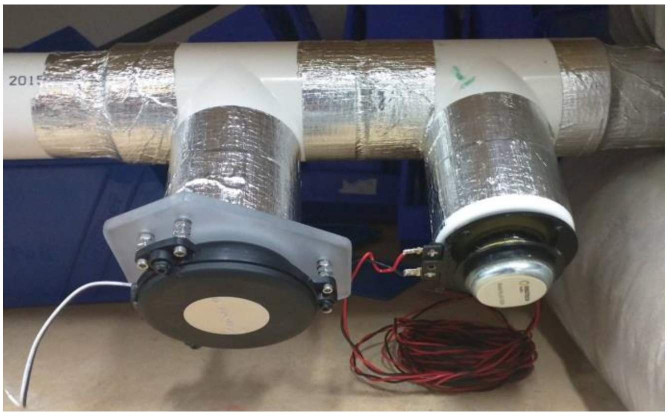


Figure 12 (left): background noise floor testing. Figure 13 (right): lab vibration test rig excitation diaphragms



2.3 BETA SENSOR DEVELOPMENT AND TESTING

After the success of the Alpha trials Planet Innovation were contracted to conduct the development of the Beta level unit. The Beta phase is the final significant design development step in preparation for full manufacture. Considering the Beta prototype is intended to carry over into a commercial product, its design constraints are as per the Alpha prototype with the addition of long term and commercial focused requirements:

- Performance
- Unit price
- Packaging
- Durability
- Reliability
- Environmental
- Purchasing
- Operational performance

- Flow tube mounting
- Design for volume manufacture
- Compliance and certification
- Branding and marketing

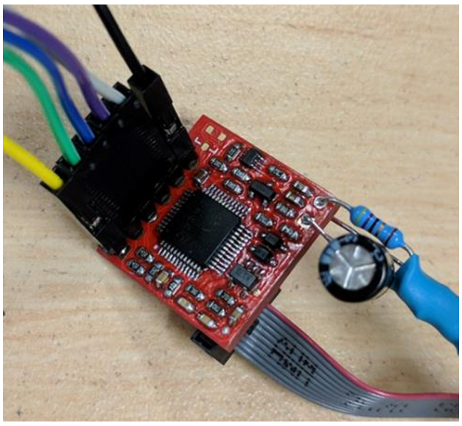
After engineering to meet the above full suite of constraints, multiple Beta units were manufactured and for the first time embedded within functional digital water meters supplied by a meter manufacturer. The meter manufacturer engineers worked to incorporate the power supply and data transfer needs of the vibration sensor into the digital water meter's code.

With this complete, testing was conducted for the first time on the complete digital water meter and vibration sensor system. Lab tests confirming successful delivery of the digital meter payload including the vibration sensor data were performed. The impact of the vibration sensor on the digital water meter was evaluated including packaging, power drain and data payload.

Multiple in-field targeted leak trials were conducted around existing SEW network leaks before their repair. Mechanical residential water meters were wholly replaced with digital meters containing the vibration sensors. Data was captured before and after the leaks were repaired enabling SEW to trial different data analytics methods for identifying leaks.

These real-world tests were the final, 'make or break' test of the vibration sensor's performance. Because of their success, management agreed to manufacture two batches of vibration sensors; 1000 and 4500, to be embedded in digital meters and deployed for large scale operation within SEW's network.

Figure 14 (left): PCB Beta development optimization. Figure 15 (right): PCB testing



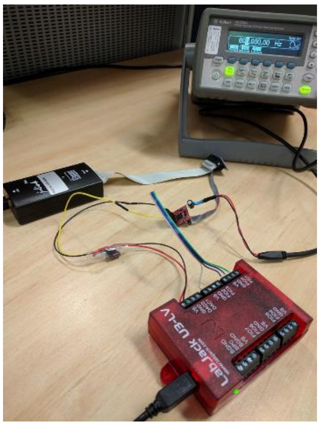


Figure 16: final Beta design packaging.

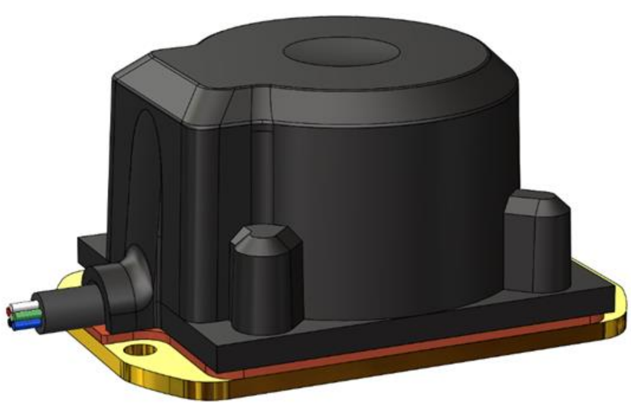


Figure 17 & 18: Beta design mock-up.

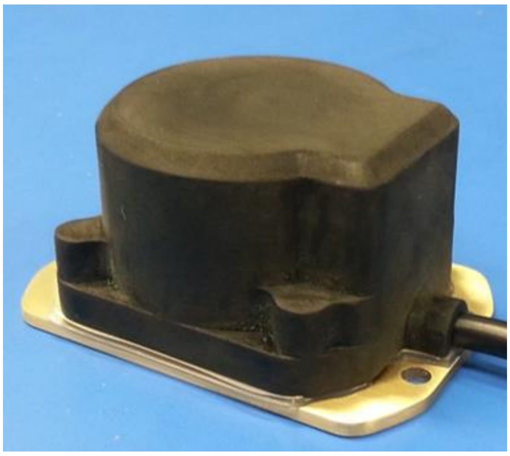


Figure 19 (left): manufacturing end-of-line tester design. Figure 20 (right): end-of-line tester in operation.

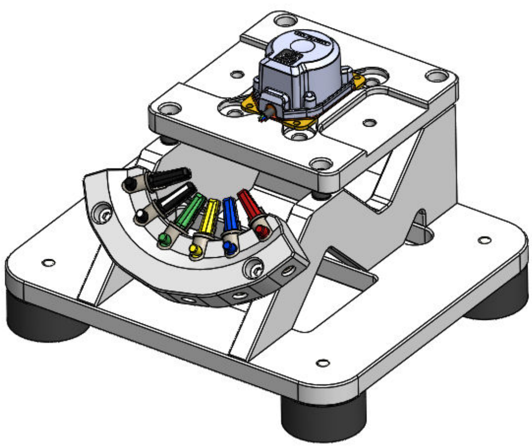
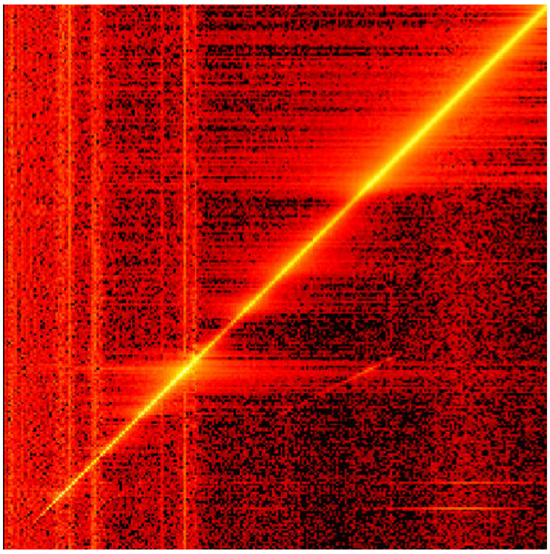


Figure 21 & 22: vibration response harmonics testing samples.



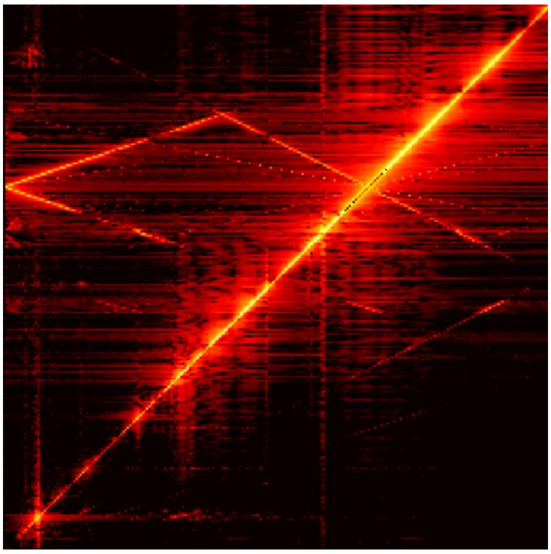
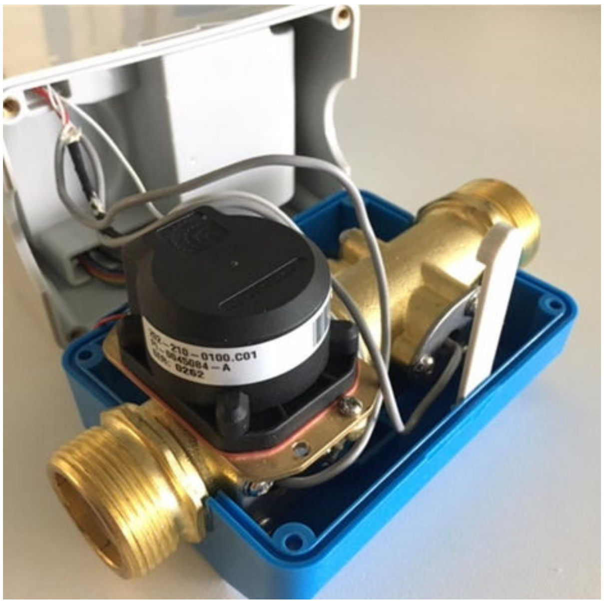


Figure 23 (left): vibration sensor mounted on flow tube and packaged within a digital water meter.



3.0 BETA UNIT TARGETTED IN-FIELD TRIALS

Lab trials confirmed the Beta unit's performance and their successful incorporation into the digital water meter. Multiple units were manufactured and embedded within digital meters that could be deployed on actual network leaks to test detection of the vibration signals before and after the leaks were repaired. These trials were to be the final evidence that the system could produce successful results in a scenario that matched the expected operational deployment.

Figure 24: Digital water meter containing the vibration sensor deployed on a residential property.

To conduct these real-world trials leaks were identified on SEW's network and the repair crew were asked to delay repair for several days. Digital meters were then swapped out for mechanical meters on multiple houses around the assumed leak location. Data from the vibration sensor was analysed for each daily reported payload. The digital meters were removed from site only after the leak was repaired so that the change in signal could be studied.

The in-field trial goals were to:

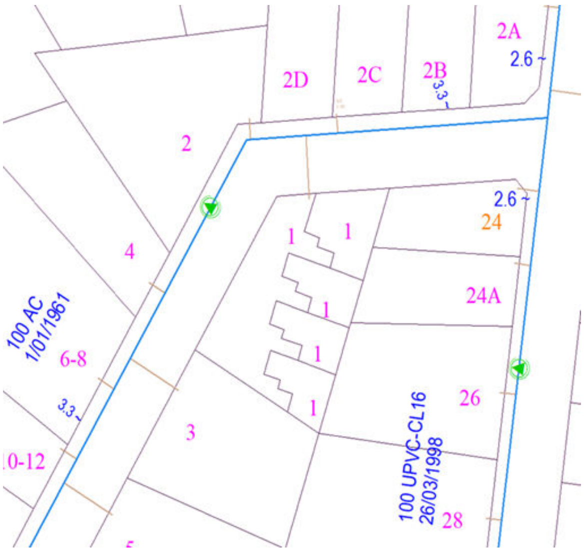
- Investigate the ability to detect and report leaks
- Understand the typical background vibration noise
- Study the impact of different pipe materials
- Understand likely necessary sensor distribution density
- Learn what data can be generated and how it can be used effectively
- Observe for failures
- Observe for environmental exposure concerns
- Acquire design improvements for the next phase

The vibration data was analysed by capturing multiple vibration signals during the night when the system is at its quietest. Leaks were detected by comparing the vibration signals against a defined threshold. Algorithms are deployed to avoid false positives such as checking for water consumption at the time a signal was taken that could interfere with vibration data.

3.1 TRIAL #1

Water was heard flowing in a stormwater drain where none was expected and was assumed to be sourced from an underground mains water leak that had not yet come to the surface. Digital meters containing the vibration sensors were deployed on residential properties around the presumed leak area by swapping them with the existing mechanical meters. Challenges were encountered during deployment with access to properties and different water meter sizes forcing the digital meters to be deployed further away from the source than preferred.

Figure 25 (left): water main and property GIS diagram. Figure 26 (right): location of digital meters relative to suspected water leak (red X)



All sensors on the AC water main detected the leak including to the meter installed 80 meters away. However, as expected and as would be the case in other trials, the vibration signals did not transfer through the T junction to two of the sensors (#123 and #126 in Figure above) installed on the PVC main. On the AC main there was a clear correlation between the proximity of the sensor to the leak and the strength of the signal received.

Several days after the sensors were attached to the network the water main burst with flooding of the street occurring. It was learned that the strength of the signals received could be an indicator of the threat of an imminent burst. This trial suggested that had vibration sensors been deployed on a network in similar circumstances the rising strength of a leak signal could have alarmed a potential coming burst raising the priority placed on repairing the leak.

The opportunity was taken to investigate the use of heat maps developed by the sensor data to identify leaks.

Figure 27: heat maps before and after leak repair

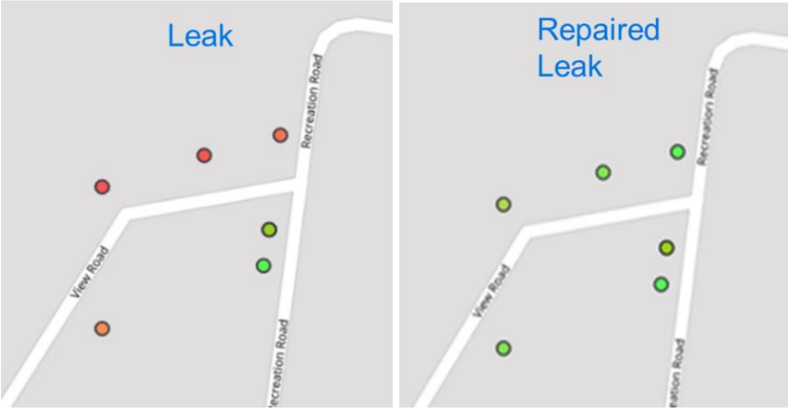
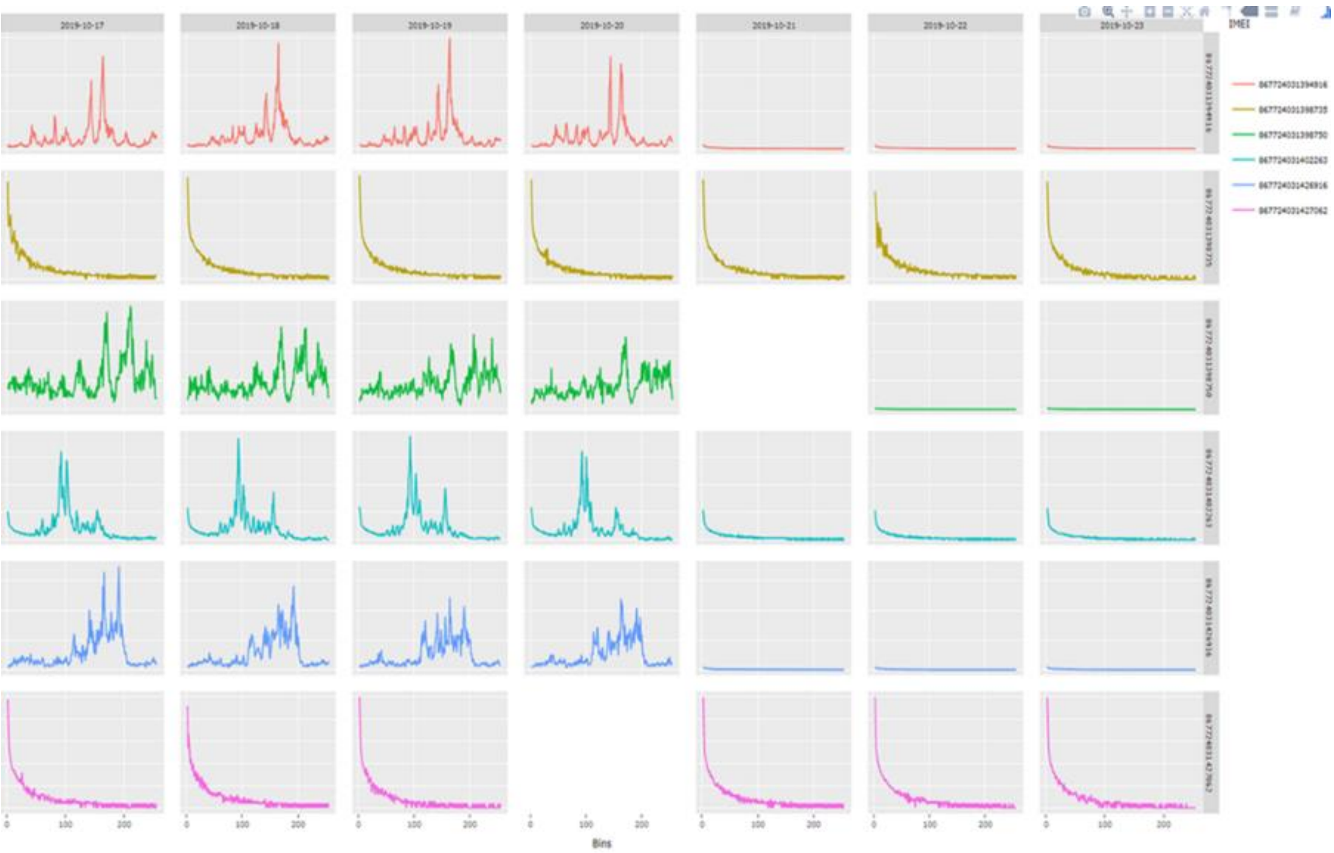


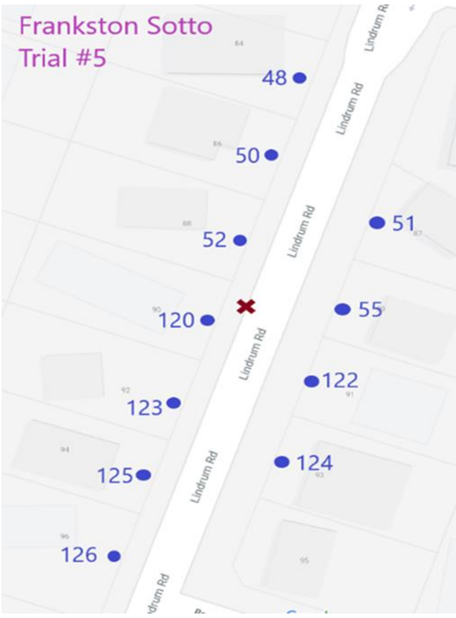
Figure 28: daily vibration results of six sensors (each in a different colour). Shown are four days of vibrations caused by the leak (left-hand side) followed by three days post-repair.



3.2 TRIAL #2

Again, water was heard flowing in a stormwater drain where none was expected and was assumed to be sourced from an underground mains water leak that had not yet come to the surface. It was later discovered, however, that in this case the water heard in the drain was not from a leak. Digital meters containing the vibration sensors were deployed on residential properties around the presumed leak area by swapping them with the existing mechanical meters.

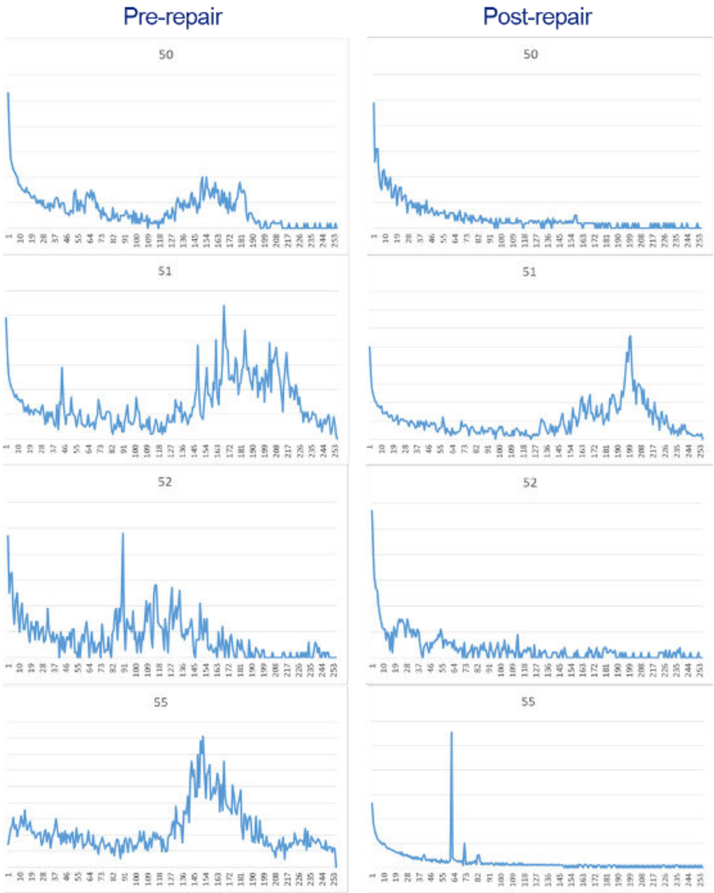
Figure 29 (left): water main and property GIS diagram. Figure 30 (right): location of digital meters relative to suspected water leak (red X)



Vibrations were detected on several sensors however only one sensor (#55) was consistently above the pre-defined leak alarm threshold. Not surprisingly the leak was discovered on the service line to the house with that sensor and was characterised as quite small.

Figure 31 (left): leak at service line connection to water main. Figure 32 (right): heat maps before leak repair

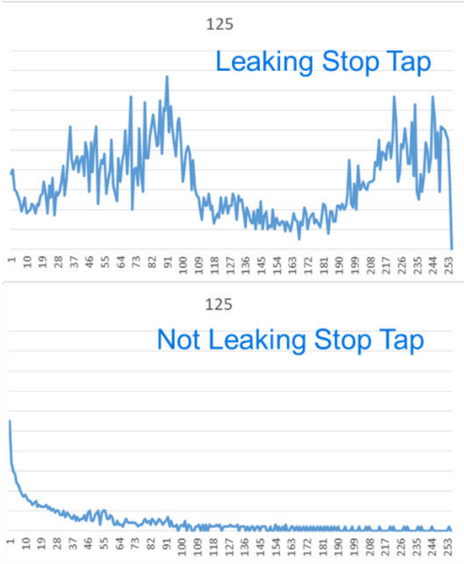
Figure 33: vibration signals before and after leak repair



Sensor #55 clearly indicated a leak vibration which disappeared after repair. However, an artefact spike remained that was assumed to have an electrical source. This spike is within a region ignored by the algorithm as it is where noise is typically observed. Other sensors also indicated a vibration but were not strong enough to breach the set thresholds. Of note was sensor #51 which after repair still carried a significant vibration. It was determined that the source of the vibration was a leak on the property.

This trial also revealed how the sensor could detect the smallest of seeping stop-tap leaks. Sensor #125 showed a strong vibration signal and after some searching it was discovered to be correlated to a seeping stop tap.

Figure 34 (left): seeping stop-tap. Figure 35 (right): stop-tap vibration plots



3.3. TRIAL #3

This trial revealed sensor performance features that hadn't been expected. A leak on a water main was repaired by contractors but the sensor appeared to indicate otherwise. Over a period of 5 days the sensor revealed vibrations that could be seen growing steadily in size. The contractors were asked to go back out to site and discovered the clamp bolts were not tightened enough.

Figure 36: five days of vibration data after leak repair illustrating growing leak

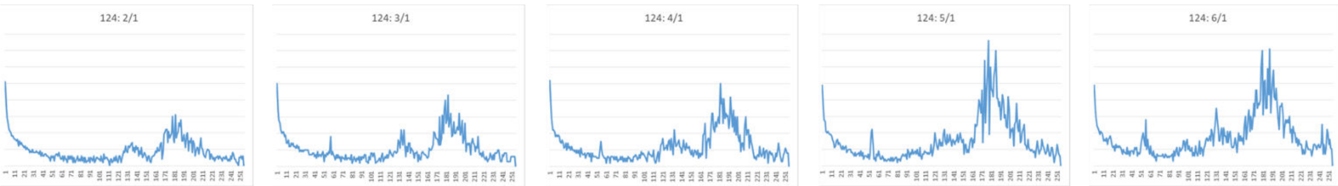
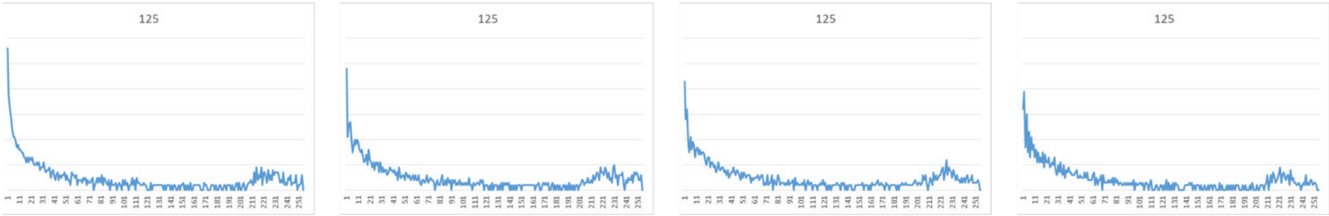


Figure 37: five days after leak was repaired the main was dug up revealing the failed repair.

On another sensor a consistent high frequency vibration could be detected. It was too weak to trigger a leak alarm but clearly indicated something was going on. A check of the meter flow suggested there was no leak on the property causing the signal. However, when a high-performance digital meter was swapped onto the property a very small leak was detected – too small to be registered on a normal digital water meter but still able to be detected by the vibration sensor.

Figure 38: daily consistent high frequency signal revealed to be caused by an extremely small property leak.



3.4 TRIAL #4

A leak had come to the surface on this street and 5 sensors were deployed around the leak location. All sensors detected the leak. However, after the leak was repaired a strong signal continued to be detected on one of the sensors which turned out to be a leaking meter tail connection.

Figure 39 (left): water main and sensor GIS diagram. Figure 40 (middle): leaking service line connection. Figure 41 (right): leaking tail connection

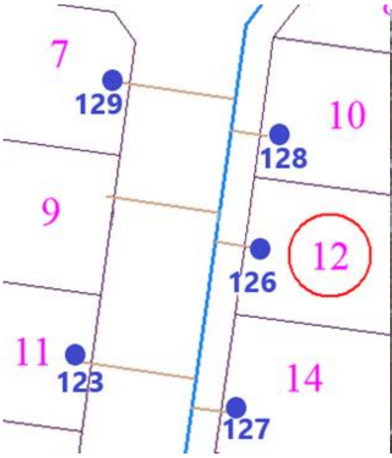
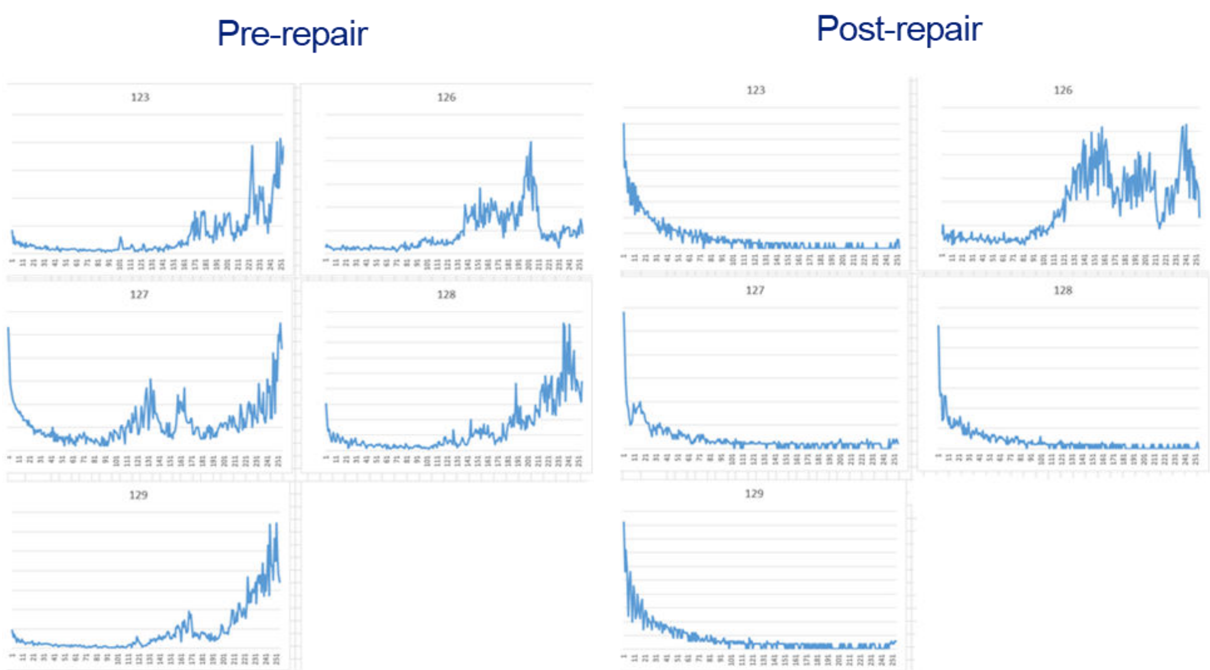



Figure 42: five sensors before and after leak was repaired.



3.5 TRIAL #5

A leak had come to the surface at this site and the contract repair crew were unable to locate it. Deploying 6 sensors around the street, the sensors immediately and clearly indicated the leak source was 50m away from where the leak had surfaced. All 6 sensors detected the leak including from a distance of 80m.

Figure 43 (left): water main and sensor GIS diagram - the leak was under the road on the service line to property #31 (sensor #132) while the water initially came to the surface outside property #42. Figure 44 (centre): first location of leak appearance 50m down the street from the leak source with unsuccessful repair visible. Figure 45 (right): vibration heat map.

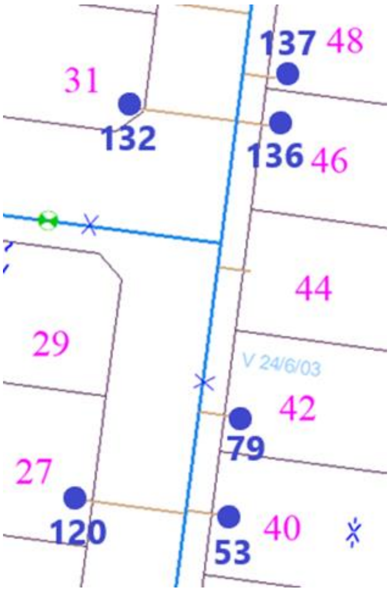
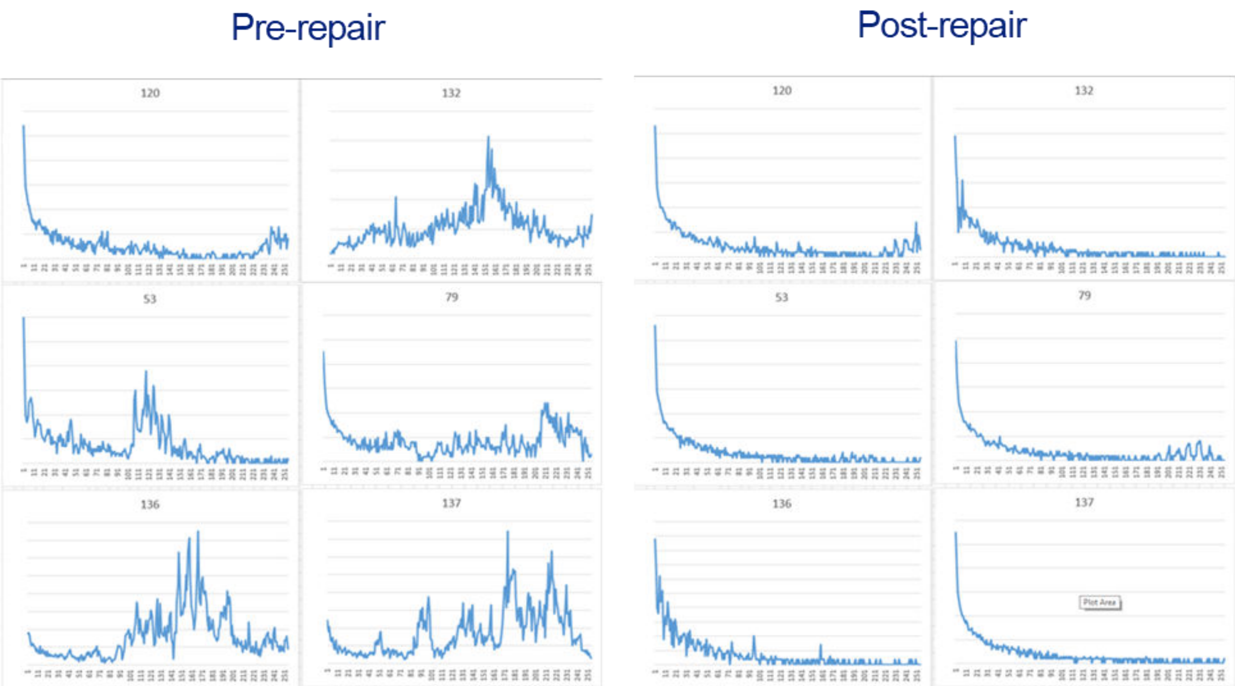


Figure 46: six sensors before and after leak was repaired.



4.0 CONCLUSION AND FUTURE WORK

The vibration sensor has met and, to some extent, exceeded SEW's expectations. The potential for a low-cost sensor to be deployed on every water meter in SEW's system that could detect network leaks has exceptional value in non-revenue water savings and strengthened reputation.

After the success of the in-field targeted trials further trials are to take place over 2020 to add to the growing knowledge base of the sensor's performance capability. Information to be gathered includes:

- Performance on UPVC water main with 'typical' sized leak
- Other information potential from the sensor data
- Noisy location impact on baseline signal
- Environmental factors impact such as ground material, pipe fittings, etc.
- Correlation between signal strength and leak size, materials and location
- Other digital water meters with an embedded sensor under development
- Long term durability and stability
- Understand variation of sensitivity between sensors

While the sensor has proven capable of detecting all leaks on service lines, the main challenge continues to be leaks on PVC or Poly water mains. These materials attenuate leak vibration signals. Consequently, SEW has contracted Planet Innovation to conduct a small development project to try increase the sensitivity of the sensors without swamping the signal with increased noise. The development of prototype designs has been successful in lab-based testing and SEW ordered ten prototypes to be manufactured. These high sensitivity sensors are due to begin in-field trials in the coming months.

The trials' success has reinforced the decision to manufacture large numbers of the sensors to be deployed in large scale trials. In these trials existing mechanical residential water meters will be swapped with digital water meters containing the leak detection sensors. The large volume of data produced will be managed on SEW's IoT platform. The first batch of 1000 units are manufactured and will be deployed in SEW's region in three suburbs in mid-2020. The second batch of 4500 sensors are currently under construction and will be deployed in late 2020 through early 2021. These scaled up tests will provide information needed to decide if and how these digital meters with vibration sensors will be deployed across SEW's network.