Smart Urban Water Supply Systems (Smart UWSS)

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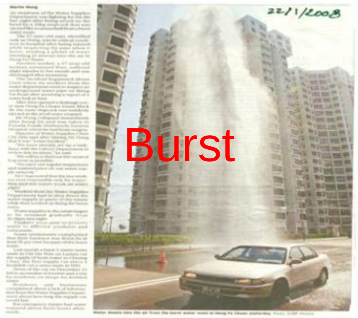
2015 CE Policy address -HKSAR

- Water Intelligent Network
  - Study and progressively establish Water Intelligent Network that utilizes sensors and related technologies to continuously monitor the health condition of the underground water supply networks.

Current state of UWSS

Water supply systems

- **Lifeline of 3 billion people; facilitator of economy; pillar of civilization**



..but, fraught with inefficiencies & deficiencies:

- **> 30% of water and energy lost!**
  - **Leaks, Bursts, Blockages (wall growth + air)**
  - **Deteriorated/weakened pipes**
  - **Malfunctioning devices (poorly performing pumps, immobilized or inadvertently set valves,…)**

- **Paralyze businesses; induce devastating floods; large financial losses!**
  - **"Burst water main paralyses business in busy districts"**

- **GHGs ~ about 5% (UWSS are one of the largest energy users in HK)**

..and challenged by:

- **Complexity, scale, inaccessibility, lack of information**
  - **HK: ~ 7,000 Km of pipes; ~200 pump stations; 1000s of valves and controls;**
  - **US: ~1.5 million Km of pipes; 100s of thousands of controls and devices**
  - **Buried under ground; most cities have poor knowledge of their system**
- **Limitation in current diagnostic systems**
  - **Intrusive, short range (200m or less!), costly: require closely spaced insertion and extraction points, disruptive,**
  - **None provides detailed, real-time, system-wide diagnosis & monitoring**
  - **Laborious, time consuming (walking pace);**
  - **Only targets limited range of specific faults**
  - **Unable to anticipate problems/respond promptly**
- **Urbanization + climate change + pollution**
  - **>200 million in China in 15 years; ~120million in HK+SZ+GZ & 6 billion in cities by 2040**
  - **20,000 km of pipelines are installed each year around the world**
  - **Water stress and need for conservation**

Typical Response

- ❑ **HK: over HK$20B; US, China > 300 B US$ needed**
  - **RR: Replace & Rehabilitate (HK ~3000 Km of pipes),**
  - **Manage Pressure —** Install devices to destroy energy(!), reduce pressure and hope to reduce leaks and bursts
  - **Ramp up the use of available technology**

- ❑ **Benefits are marginal and problems re-emerge!!!**
- ❑ **Disruptive/dangerous/costly failures remain**

Time is ripe: there is universal agreement that the problems are real and solving them is "*a most pressing, challenging and urgent strategic endeavor*"

- 2015 Policy address by CE –HKSAR

- The "**No. 1 document**" issued in January 2011 by the ***State Council of the Chinese Central Government*** exclusively highlights water and water infrastructure as the most pressing, challenging and urgent strategic issue facing China.

- The "**Green Quality Living in Greater Pearl River Delta**" document released in September 2011 puts water resources conservation and urban infrastructure development as a pressing core mission of the ***governments of Guangdong, Hong Kong, and Macao (PRD)***.

- In 2005, the Chief Executive of ***Hong Kong*** announced a **Total Water Management (TWM)** policy to address problems and challenges in local UWS.

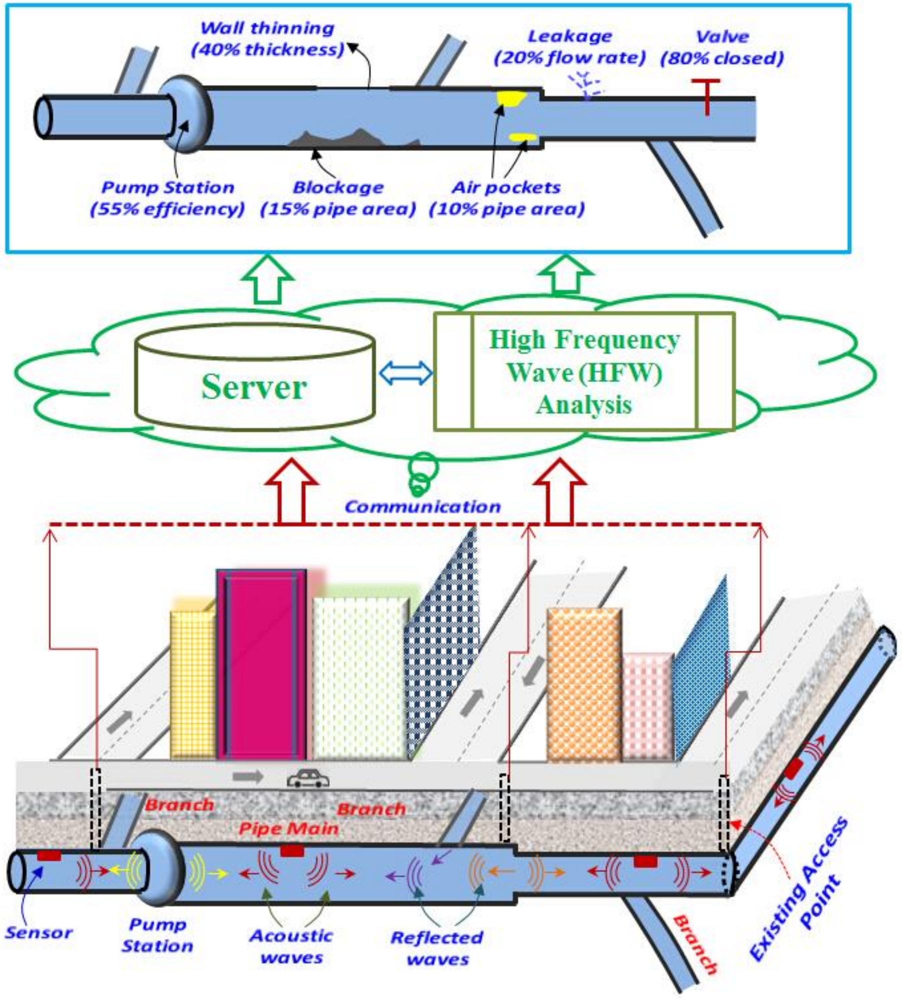
- The Report of the **President's Commission**, ***USA***, "There is no more urgent priority than assuring the security, continuity, and availability of our critical infrastructures."

- **US NAE** "Engineers of the 21st century face the formidable challenge of modernizing the fundamental structures that support civilization."

But, how and who?

Waves as diagnostic tools for UWSS!

- Waves proved instrumental in other fields: nondestructive testing, medical ultrasonics, ocean acoustics etc
- Goal: Use waves to diagnose ("image") pipelines; thus, save water, energy and other resources and minimize risk to human health!
- ***Principle**: Actively/passively generated waves carry information about a minimally accessible, poorly known, complex medium. Measurements of the waves and ingenious processing techniques are used to construct an image of the unknown system.*



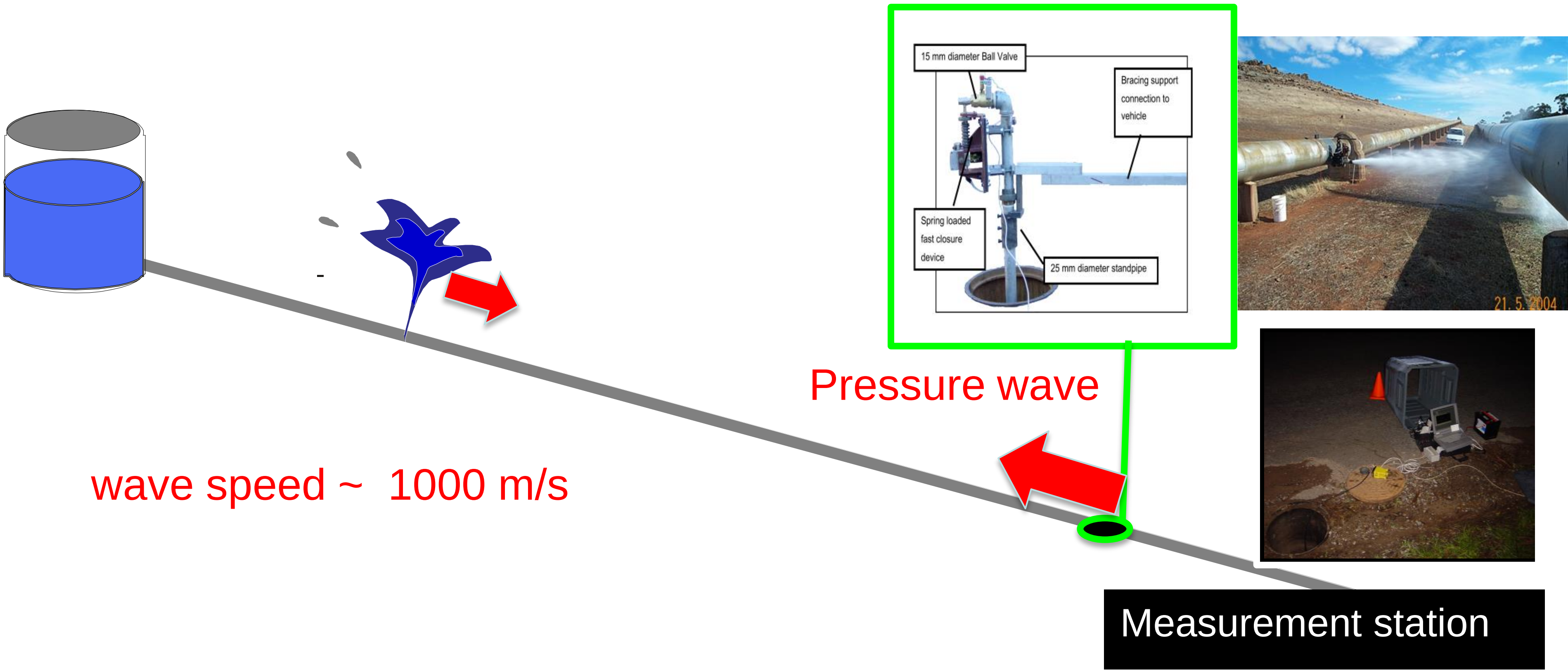
How Does it Work?

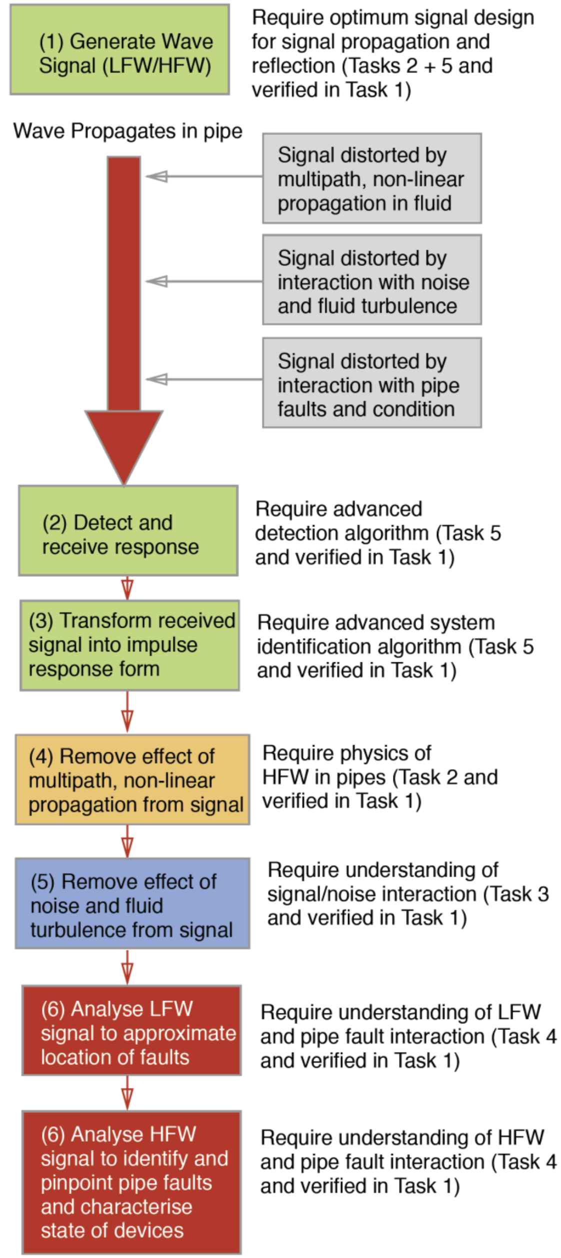
$$\frac{\partial H}{\partial t} + \frac{Q}{A}\frac{\partial H}{\partial x} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} + \frac{a^2}{gA} Q_L \delta(x - x_L) = 0$$

$$\frac{\partial}{\partial t}(\rho A V) + \frac{\partial}{\partial x}(\rho A V^2) + A\frac{\partial p}{\partial x} + \frac{\rho A f V^2}{2D} = 0$$

BC: devices (e.g., tanks, valves, pumps) etc); discontinuities (e.g., junctions)

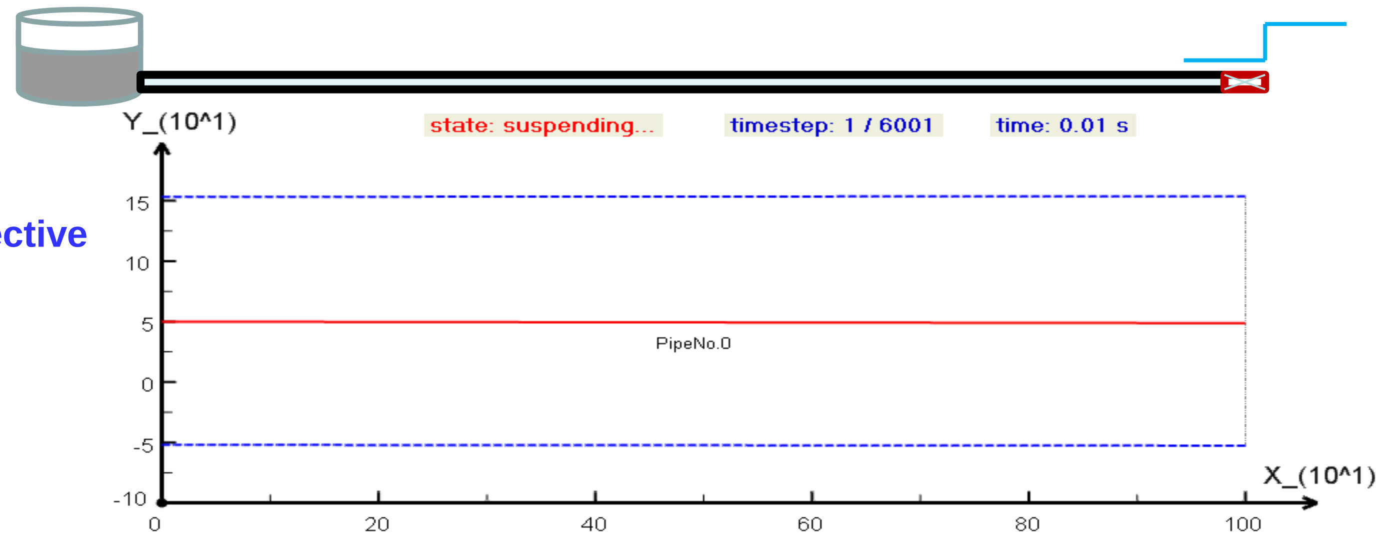
Wave generator



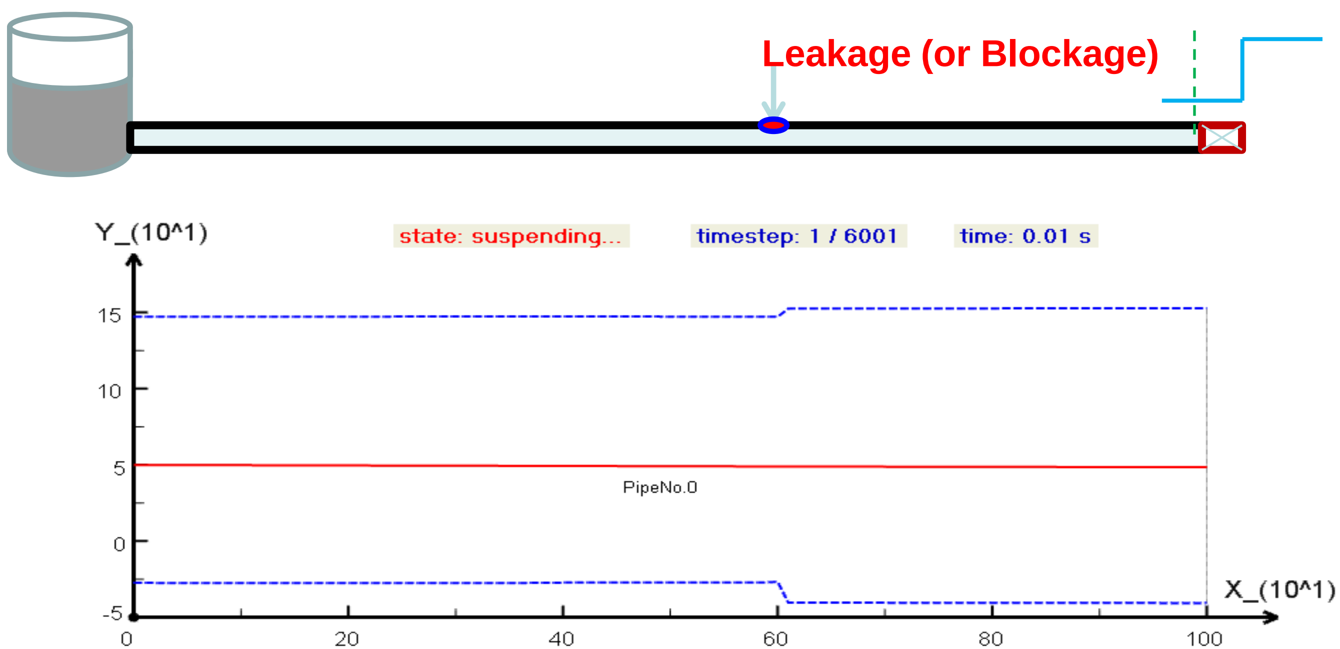

(1) Generate Wave Signal (LFW/HFW)
Require optimum signal design for signal propagation and reflection (Tasks 2 + 5 and verified in Task 1)
Wave Propagates in pipe
Signal distorted by multipath, non-linear propagation in fluid
Signal distorted by interaction with noise and fluid turbulence
Signal distorted by interaction with pipe faults and condition
(2) Detect and receive response
Require advanced detection algorithm (Task 5 and verified in Task 1)
(3) Transform received signal into impulse response form
Require advanced system identification algorithm (Task 5 and verified in Task 1)
(4) Remove effect of multipath, non-linear propagation from signal
Require physics of HFW in pipes (Task 2 and verified in Task 1)
(5) Remove effect of noise and fluid turbulence from signal
Require understanding of signal/noise interaction (Task 3 and verified in Task 1)
(6) Analyse LFW signal to approximate location of faults
Require understanding of LFW and pipe fault interaction (Task 4 and verified in Task 1)
(6) Analyse HFW signal to identify and pinpoint pipe faults and characterise state of devices
Require understanding of HFW and pipe fault interaction (Task 4 and verified in Task 1)

How Does it Work?

Non-Defective



Defective



Different defects, different signatures!!

$$E = \sum (h_i^m - h_i)^2 = \text{minimum}$$

$$\frac{\partial H}{\partial t} + \frac{Q}{A}\frac{\partial H}{\partial x} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} + \frac{a^2}{gA} Q_L \delta(x - x_L) = 0$$

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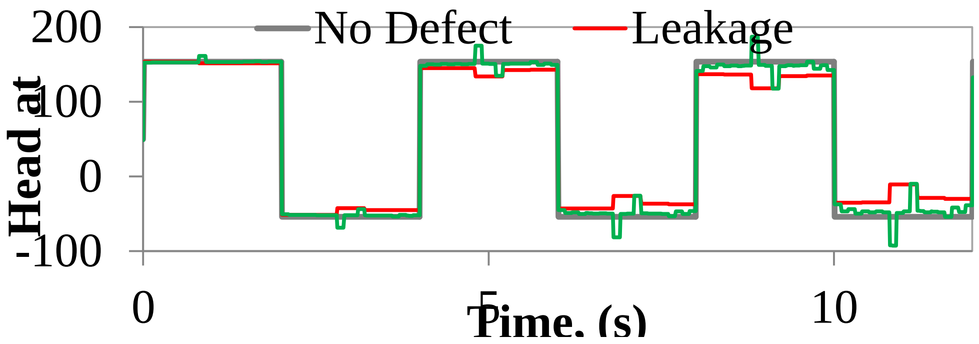
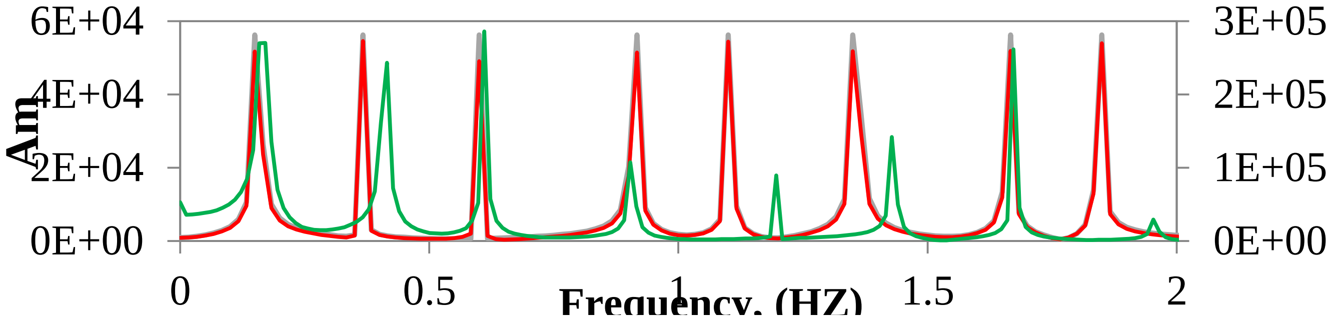




1. Blockages induce frequency shift
2. Leaks induce damped pattern, but no shift
3. Wall thinning; changes wave speed
4. Air blockages; changes wave speed and damp pressure

Experimental Verification

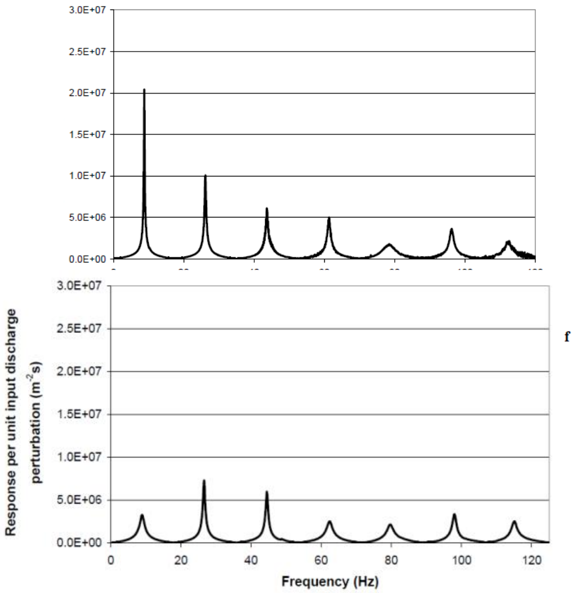
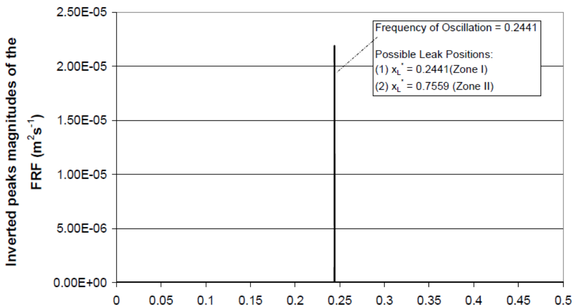
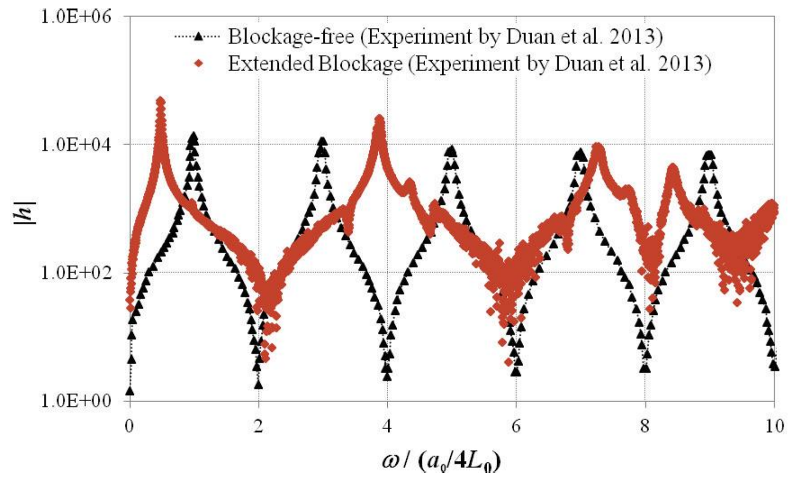
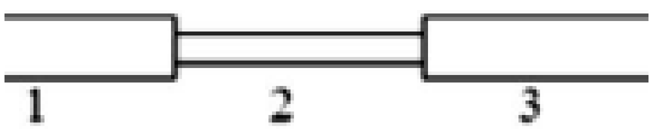


Figure 6-83 – FRF from experimental pipeline with a 1.0 mm leak ($C_d A_L/A = 1.69 \times 10^{-3}$, $x_L^* = 0.75$) using in-line valve closure.

$$\left|h_b\right| = \frac{1}{\frac{Q_{L0}}{4(H_{L0} - z_L)}\left[1 - \cos\left(2mx_L^*\pi - \pi x_L^*\right)\right]}$$

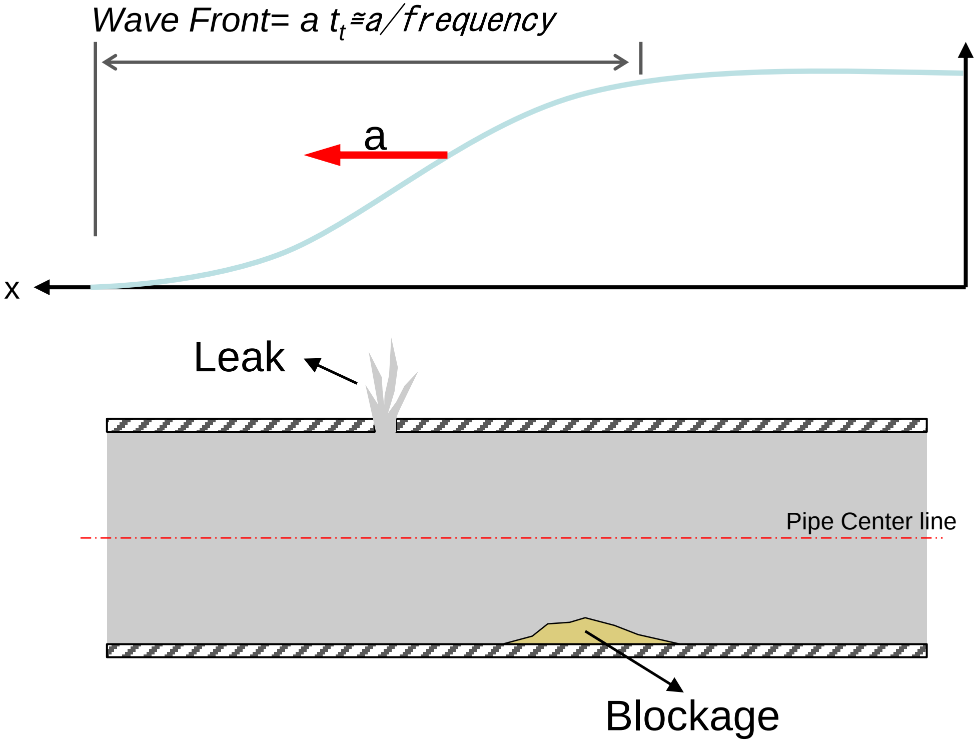






$$\begin{aligned}
&(Y_1 + Y_2)(Y_2 + Y_3)\cos[(\lambda_1 + \lambda_2 + \lambda_3)\omega_{rfb}] \\
&\quad + (Y_1 - Y_2)(-Y_2 - Y_3)\cos[(\lambda_1 - \lambda_2 - \lambda_3)\omega_{rfb}] \\
&\quad - (Y_1 + Y_2)(Y_2 - Y_3)\cos[(\lambda_1 + \lambda_2 - \lambda_3)\omega_{rfb}] \\
&\quad - (Y_1 - Y_2)(-Y_2 + Y_3)\cos[(\lambda_1 - \lambda_2 + \lambda_3)\omega_{rfb}] = 0
\end{aligned}$$

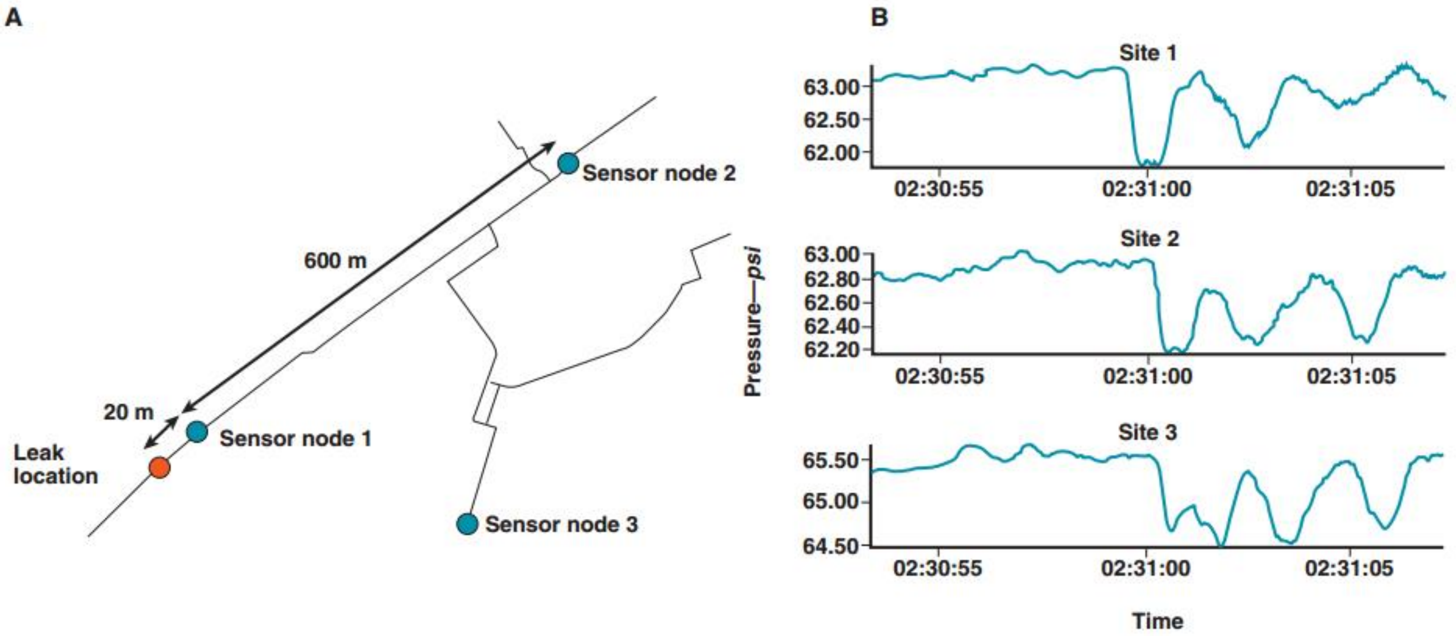
Resolution & Range



Example: Large & Complex Systems-Singapore

Simulated Pipe burst (Allen et al. 2011)

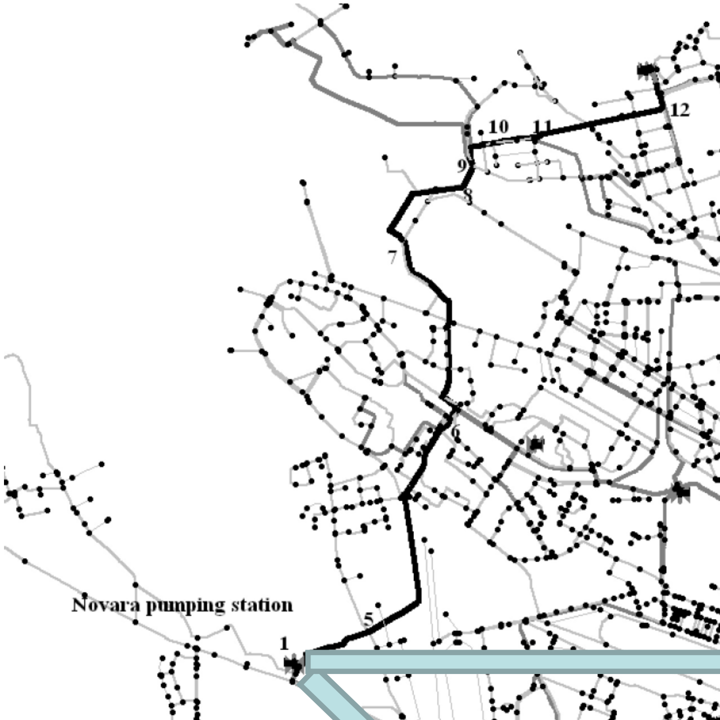
FIGURE 5 A typical leak-off test setup (A) and associated pressure records taken during the test (B) presented over a 15-s window



A wealth of information in 5s, but identification radius of leak is 90m although sensor is only 20 m away! Why?

✓(0.1 s)(1000m/s)= 100m (Reported 90m!)

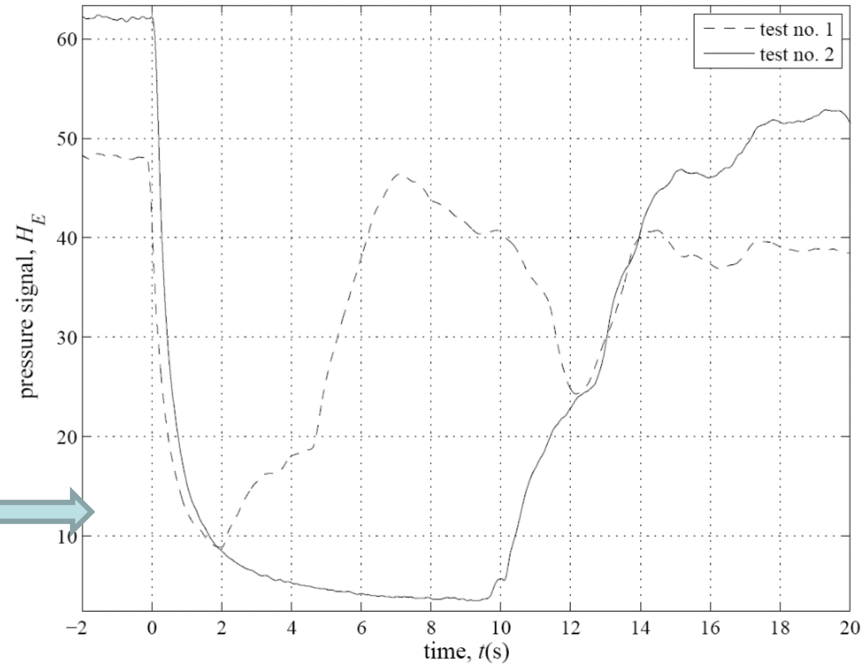
Example: Large & Complex Systems-Milan, Italy



(a)

(b)

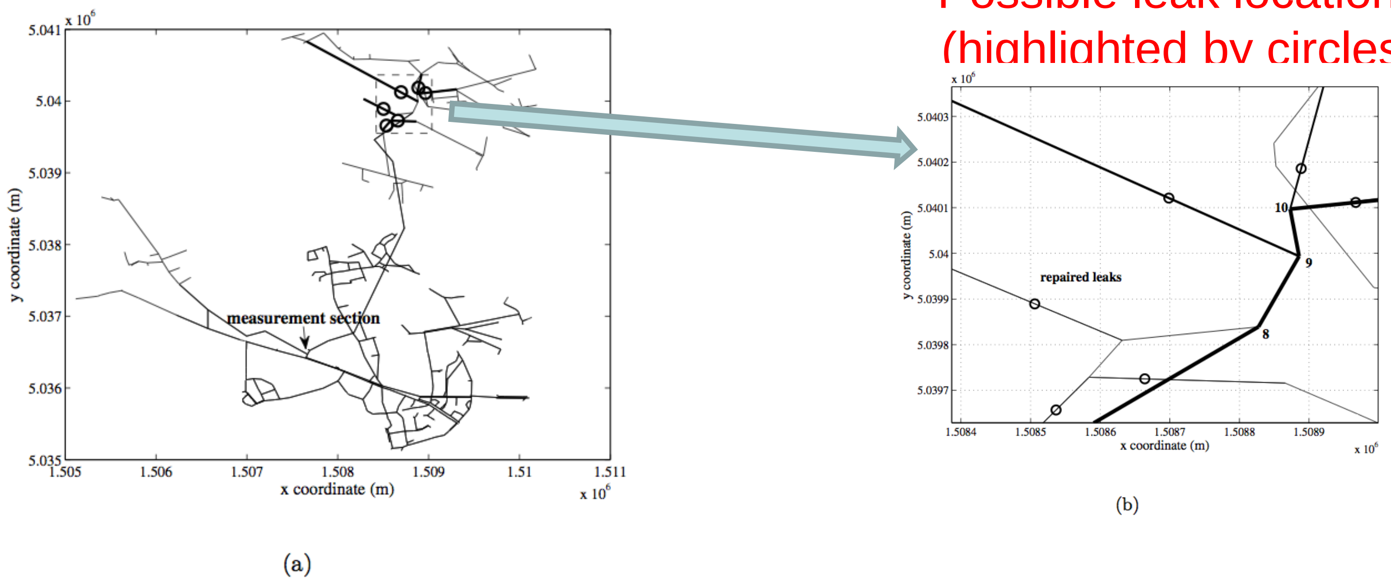
Wave Generation: cut off electricity to pump



Wave Response: measured at pump station

Resolution

Possible leak locations (highlighted by circles)



A wealth of information in 20s: wavespeeds of pipes were found; a blocked section is identified, junctions were identified, leaks were identified…, but the identification radius of leaks is 800m! Why?

✓(1 s)(900m/s)= 900m (Reported 850m!)

Wave Range

$$R \sim \frac{a^3}{2\pi^2 \upsilon_t f^2} \sim \frac{a^3}{\sqrt{F} D f^2 V}$$

- a ≡ Wavespeed $\sim$ 1000m/s
- F ≡ Friction factor $\sim$ 0.02
- f ≡ Frequency
- D ≡ Pipe diameter
- V ≡ Flow velocity $\sim$ 1m/s
- υ_t ≡ Eddy (turbulent) viscosity
- R $\sim$ 10s of km for LFW
- R $\sim$ 100s of m for HFW

LFW: R ~ tens of kilometers
HFW: R ~ kilometer to hundreds of meters

LFW & HFW

Waves:

- Non-intrusive, rapid to perform, inexpensive
- Good for all faults
- Provides “continuous check up” on the system response & performance
- **Able to anticipate problems**

LFW

- Wide range, but low spatial resolution
- Interference with noise is strong
- Team members pioneered techniques, algorithms and methodologies using LFW to image pipes
- These methods have been tested Italy, Canada, Australia, UK, Mexico, New Zealand, Singapore and now HK

HFW

- Low range, high resolution
- Interference with noise is low
- Initial results by team members are promising

Research Strategy

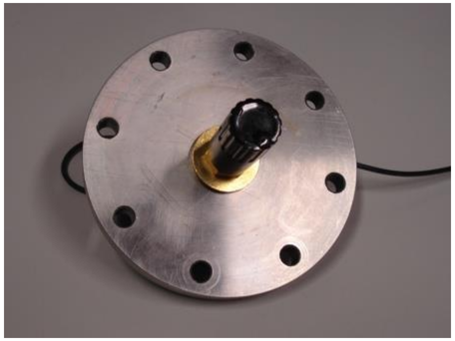
LFW to first identify problematic sections and then HFW to create high resolution images to pinpoint problems

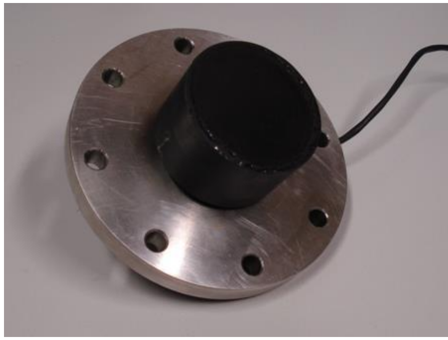
Generation of HFW

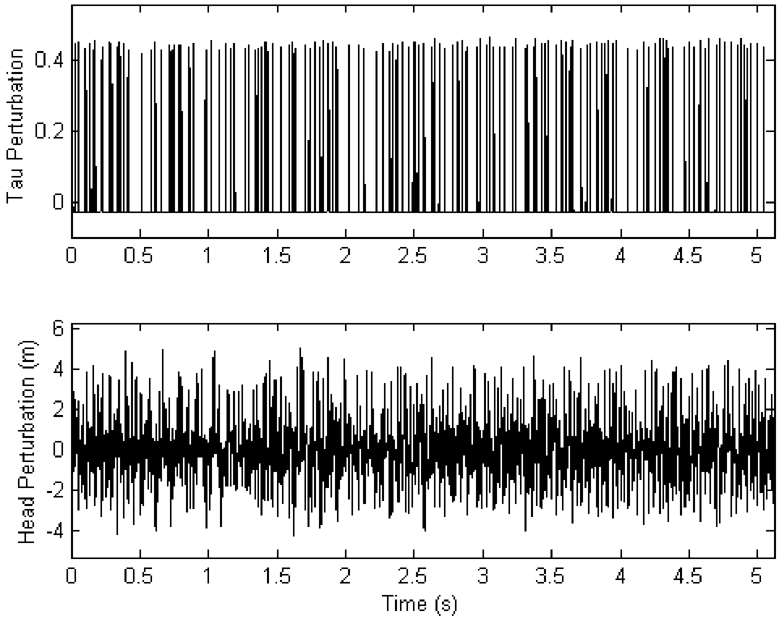
- Piezoelectric Crystal Actuator
- Fully sealed, no water loss

- Crystals move rapidly creating flow changes 100 times faster than valves (wavelength of cm instead of m)

- Being tested in the field





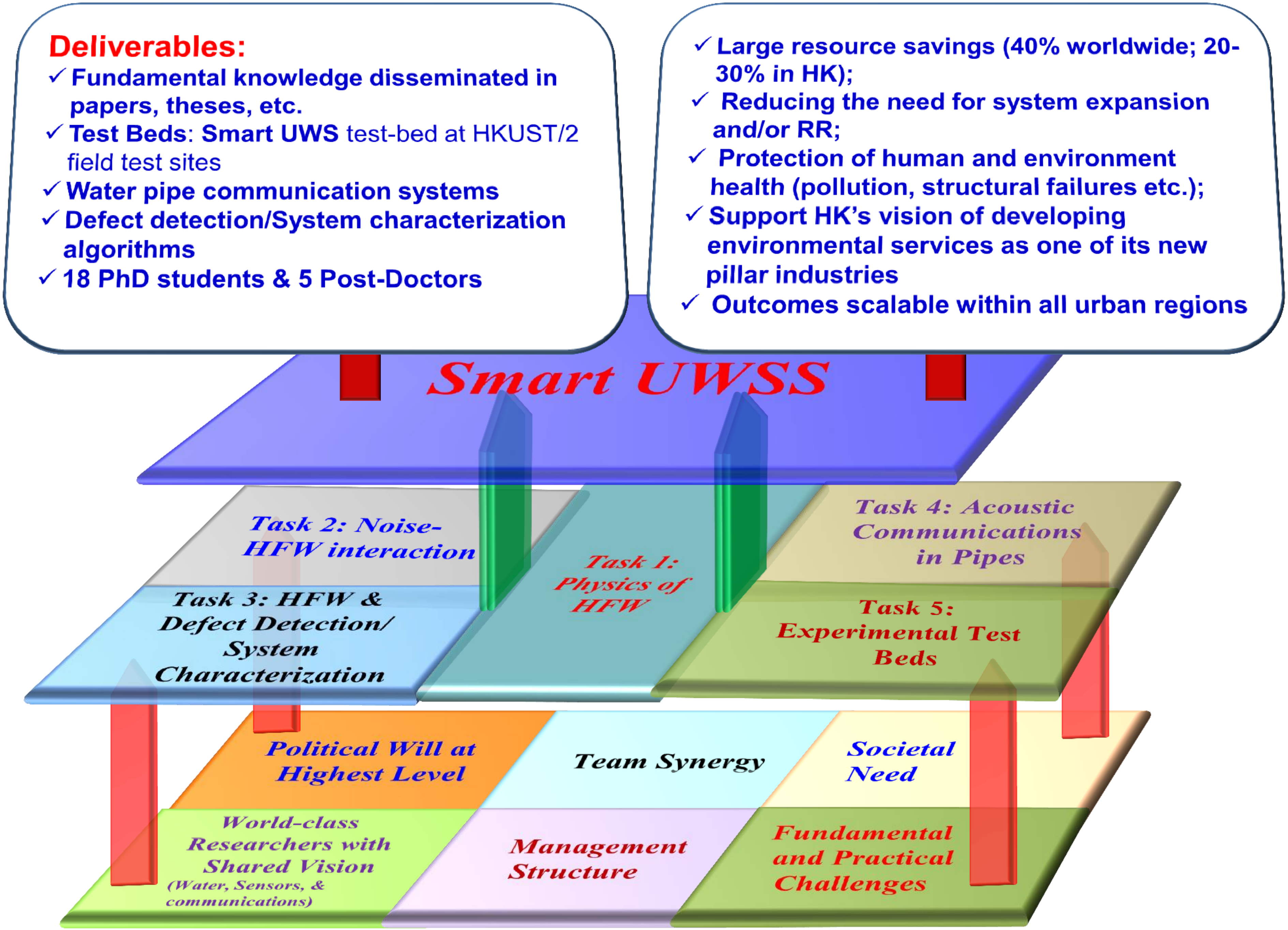


Key Research Questions

- Signals best suited for the problem?
- Effects of multi-path, nonlinearities, turbulence, noise, defects, hydraulic devices, and system topology on HFW?
- Spatial range of HFW?
- Frequency bands are best for in-pipe communications?
- How best to process noisy HFW signals?
- “Signatures” of defects and how can we use them?
- “Signatures” of hydraulic devices on HFW and how can we use them to characterize system state?
- Spacing between sensors to minimize “false alarms” and miss-identification?

Collaborators

- Collaboration with researchers and water authorities in Beijing and elsewhere in China?
- Perhaps joint fields tests in mainland? Test beds? Others???
- Central government and HKSAR are clear on the enormity and importance of the problems in UWSS!



Deliverables:
✓ Fundamental knowledge disseminated in papers, theses, etc.
✓ Test Beds: Smart UWS test-bed at HKUST/2 field test sites
✓ Water pipe communication systems
✓ Defect detection/System characterization algorithms
✓ 18 PhD students & 5 Post-Doctors
✓ Large resource savings (40% worldwide; 20-30% in HK);
✓ Reducing the need for system expansion and/or RR;
✓ Protection of human and environment health (pollution, structural failures etc.);
✓ Support HK's vision of developing environmental services as one of its new pillar industries
✓ Outcomes scalable within all urban regions
Smart UWSS
Task 2: Noise-HFW interaction
Task 1: Physics of HFW
Task 4: Acoustic Communications in Pipes
Task 3: HFW & Defect Detection/ System Characterization
Task 5: Experimental Test Beds
Political Will at Highest Level
Team Synergy
Societal Need
World-class Researchers with Shared Vision
(Water, Sensors, & communications)
Management Structure
Fundamental and Practical Challenges