THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Department of Electronic & Computer Engineering

電子及計算機工程學系

Fault Detection in Acoustic and Electromagnetic Waveguide Channels with Applications to Pipeline and Transmission Line Networks

Ross Murch
with Amar Dubey, Liwen Jing, Yue Li, Zhao Li, Wenjie Wang

Current State of Urban Water Supply Systems

Inefficiencies & deficiencies ~ 30% of water and energy lost around the world (enough to supply 150 cities like Hong Kong)

Leaks

11,028 *Leaks* (HK 2013)

Bursts

257 *Bursts* (HK 2013)

Blockages

Deteriorated/ weakened pipes

Malfunctioning devices

→ Deteriorated Pump

Disruptive


South China Morning Post EDITION: HONG KONG

HONG KONG | NEWS | BUSINESS | TECH | LIFESTYLE | COMMENT | SPORT

Burst water main paralyses business in busy districts

Elaine Yau and Martin Wong

PUBLISHED : Wednesday, 02 March, 2011, 12:00am
UPDATED : Wednesday, 02 March, 2011, 12:00am

A burst water main in Wong Nai Chung Road that brought a day-long drought to some of the city's busiest areas might force engineers to speed

SHARE

Source: Smart UWSS project presentation

Complex, Large and Inaccessible

In HK: ~ 7,000 km of pipes; ~200 pump stations; ~1000s of valves and controls

Source: Smart UWSS project presentation

Waves as diagnostic tools

Non-intrusive, rapid to perform, economical, good for all faults & able to anticipate problems

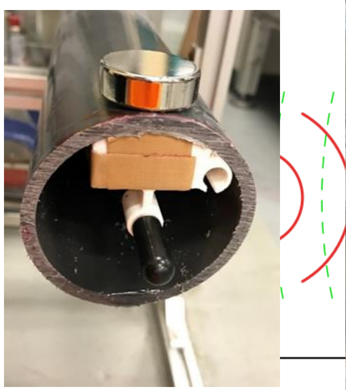
Wave Transmitter

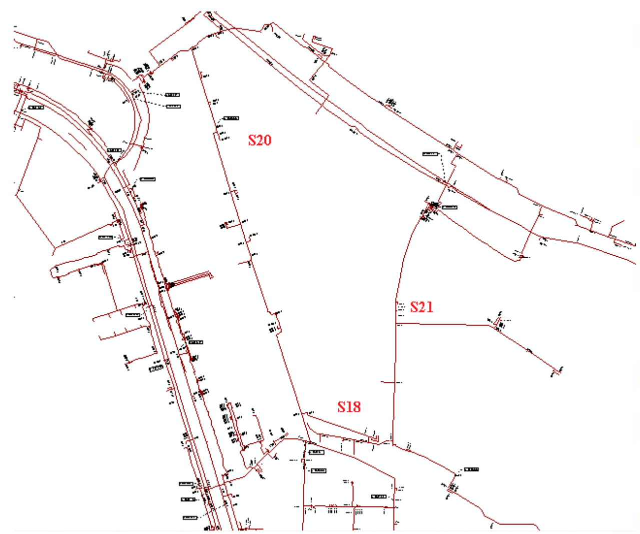
Inaccessible, poorly known, complex **medium/system**

e.g. Human, Ocean

Pipelines?

"Image" ← Wave Theory ← Wave Receiver

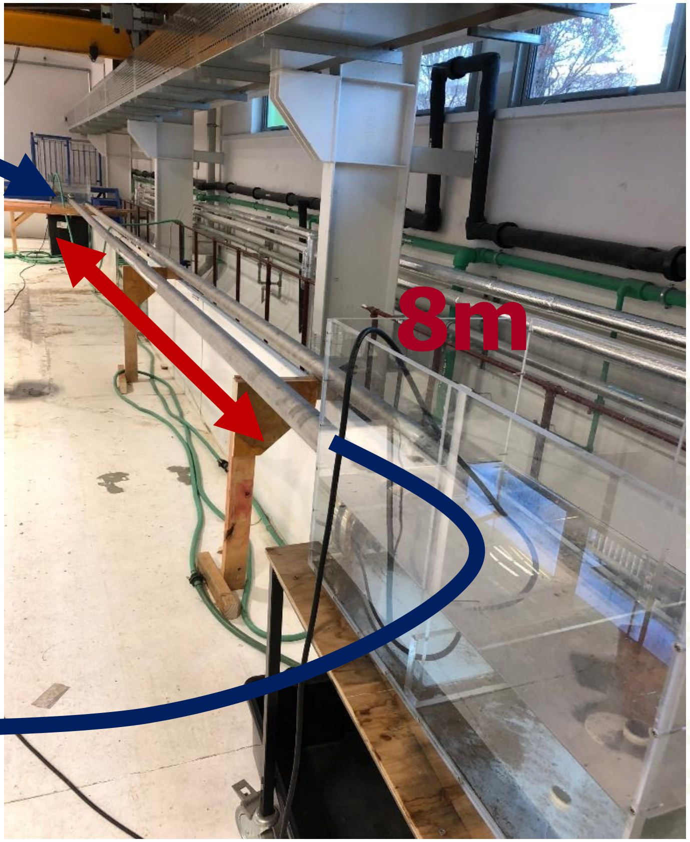




Sources: Smart UWSS project presentation, creative commons

Simple Demonstration

Transmitter



Receiver

- Low frequency acoustic waves as source

Electrical Cable Networks

- Cars, planes and networks have 1000’s km of wires and cables

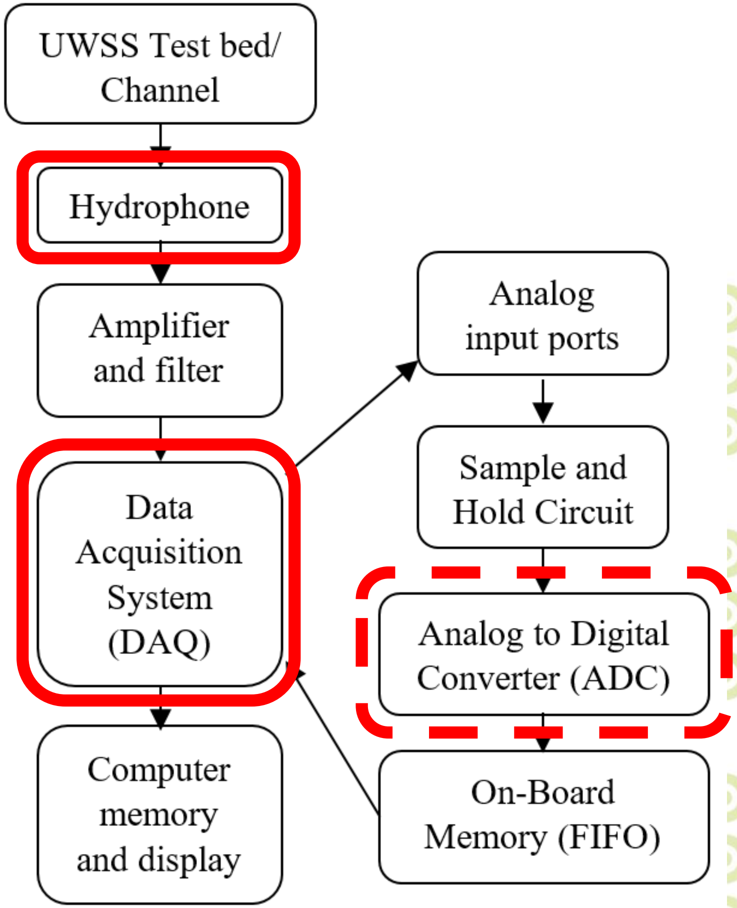
Sources: creative commons, public domain

Challenges and Talk Contents

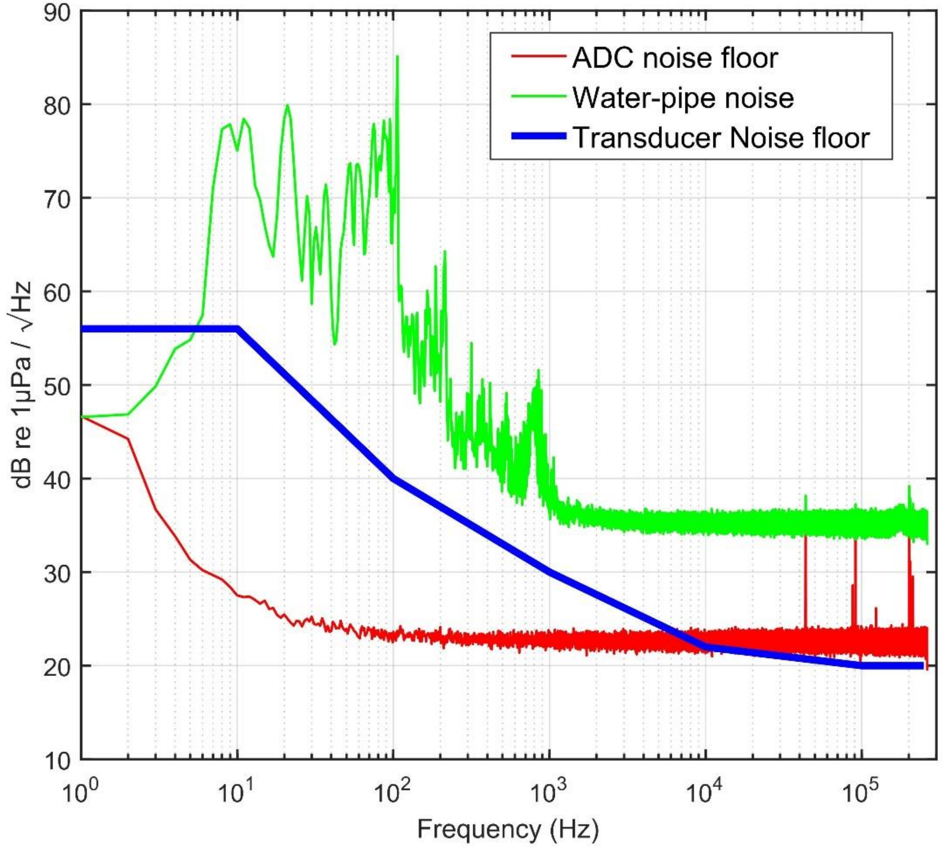
- Pipeline Channel and noise characterization
  - What is the noise PSD and PDF?
  - Channel attenuation and transfer function?
  - Optimum signal and receiver design?
  - Link budget?
  - Waveguide channel with multiple cutoffs?
- Fault Detection
  - Blockage detection
  - Impedance and Shunt Detection
  - Remaining challenges

Pipeline Acoustic Noise Characterization
Noise Measurement System

- Noise is the smallest signal we can measure
- Care needs to be taken in its measurement and analysis.
- Self noise of system needs to be less than the noise we are trying to measure.



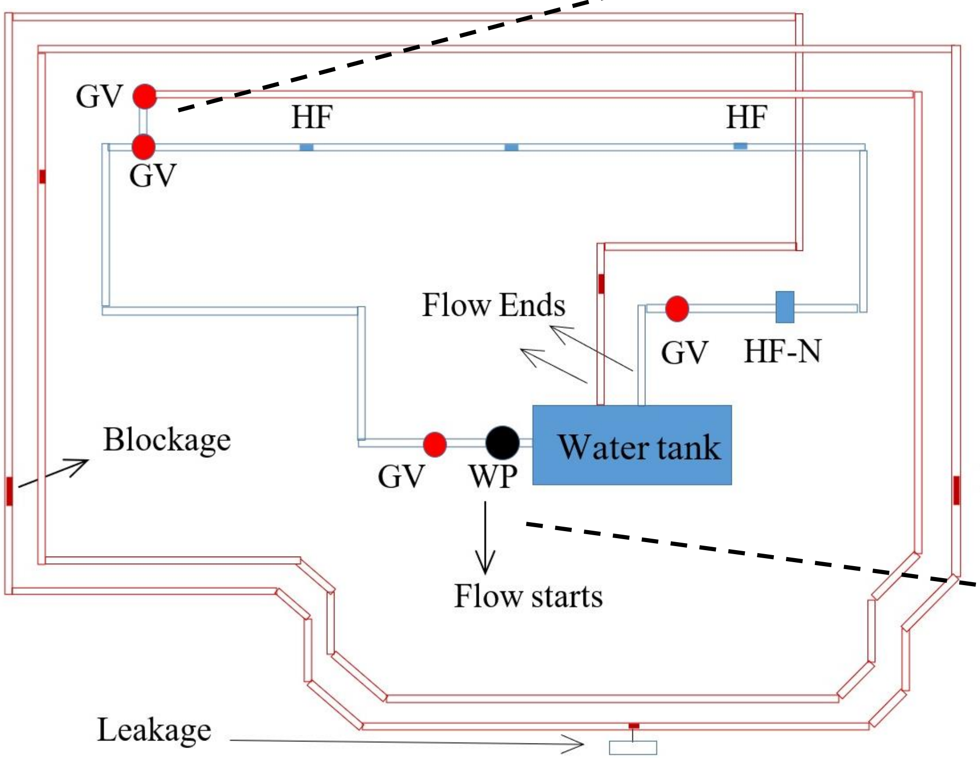
Noise floor of the measurement system

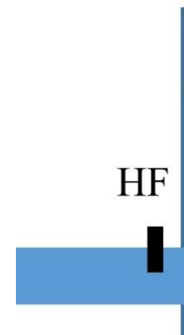


ADC = 16 bit, Full scale input range = ±1V,
Theoretical Quantization error =[1-(-1)]/ 2^{16} ≈ 30μV.
Transducer : TC 4032

Water pipeline systems measured

Pipeline-II





ine-I).

Pipe Material: Steel,

Pipe length and diameter: 7m, 90mm (external).

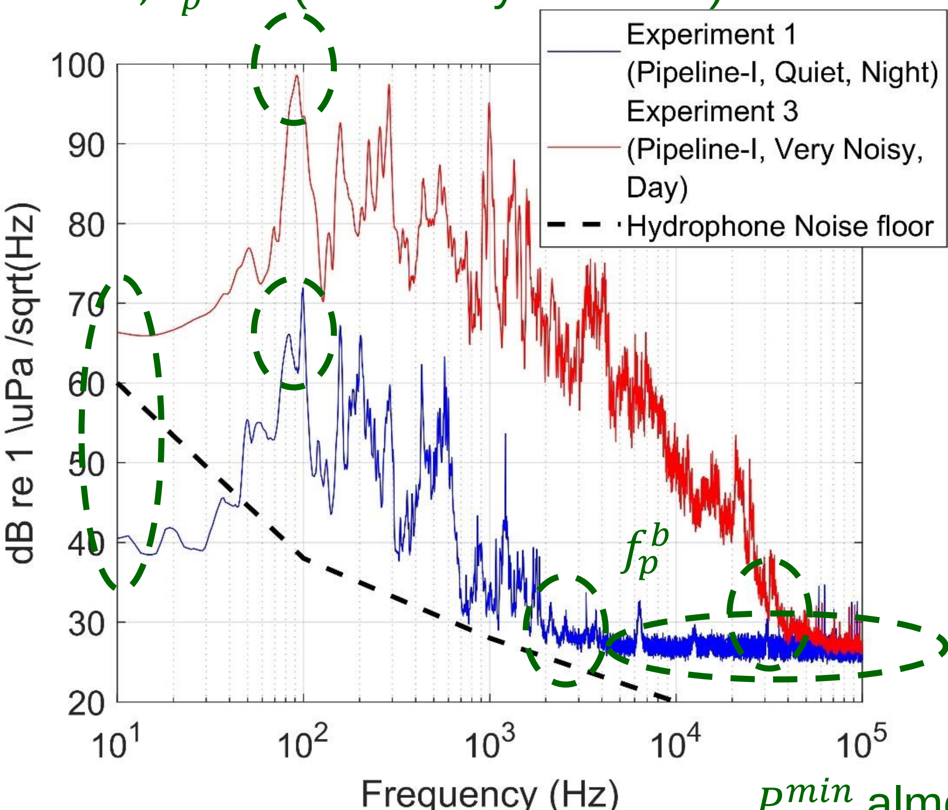
Pipeline-III (Operational Urban Water Supply System)

Campus University of Canterbury, New Zealand.
Hydrants used as access points to water pipelines

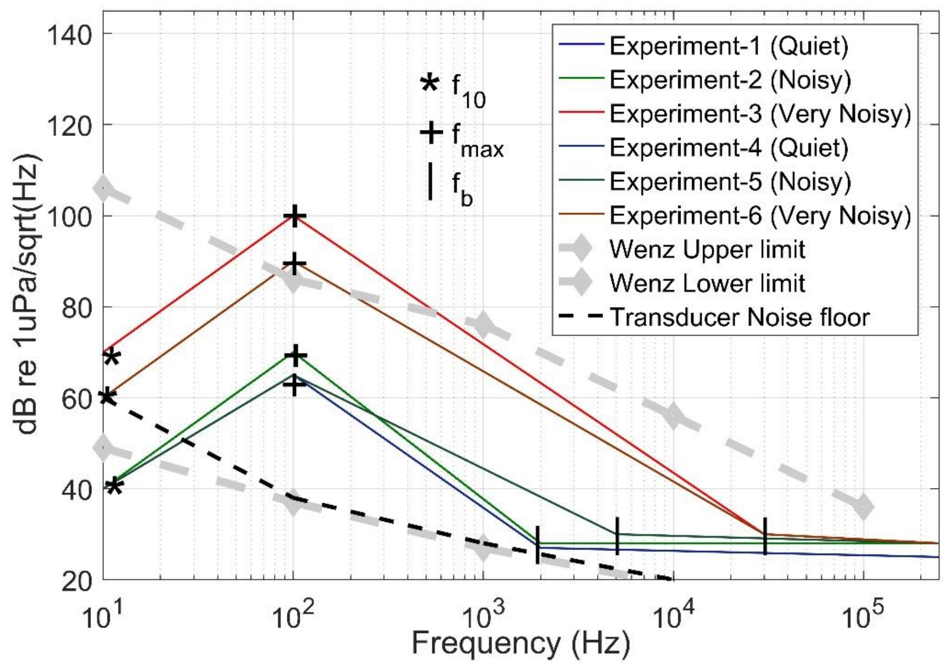
PSD for Pipeline I- No water flow

f_p^{max}, P_p^{max}

$10Hz, P_p^{10Hz}$ (Not always reliable)



Piecewise Linear approximation using 5 parameters



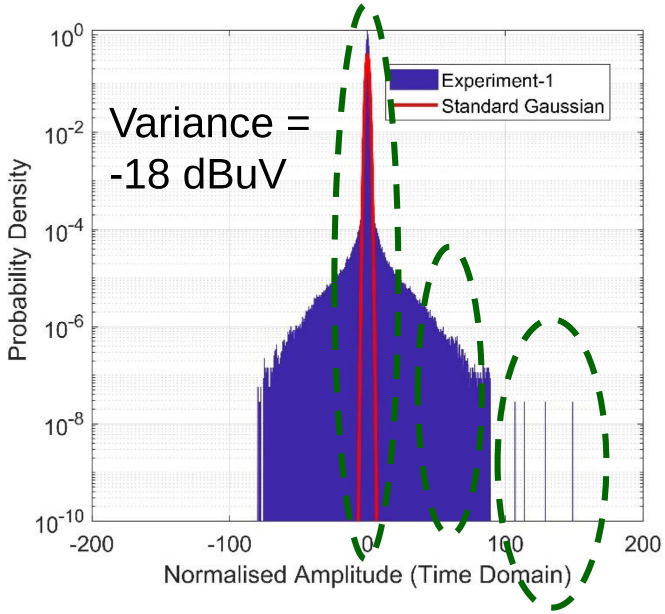
P_p^{min} almost same for all experiments

Parameters only depends on external noise conditions

Presence of 50 Hz and Harmonics, and ADC abnormalities

PSD are flat after f_p^b and the PSD slopes before f_p^b depend on noise conditions.

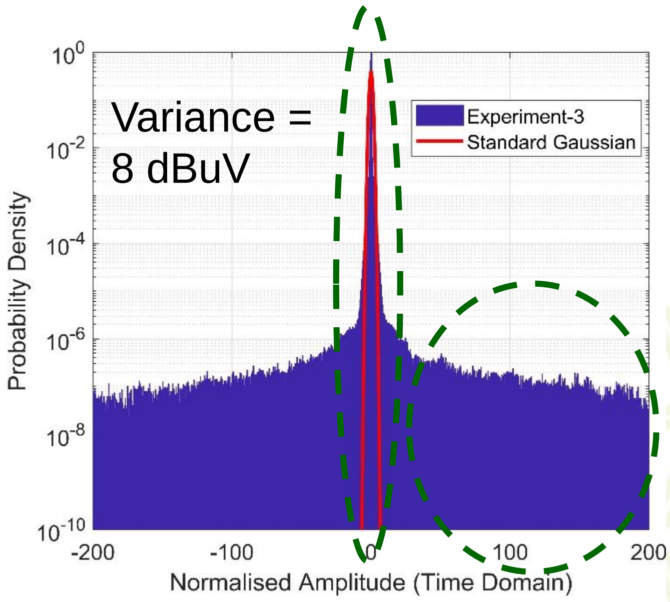
PDF for pipeline I- No water flow in lab



Bulk: nearly Gaussian

Heavy Tails

Low probability Spikes

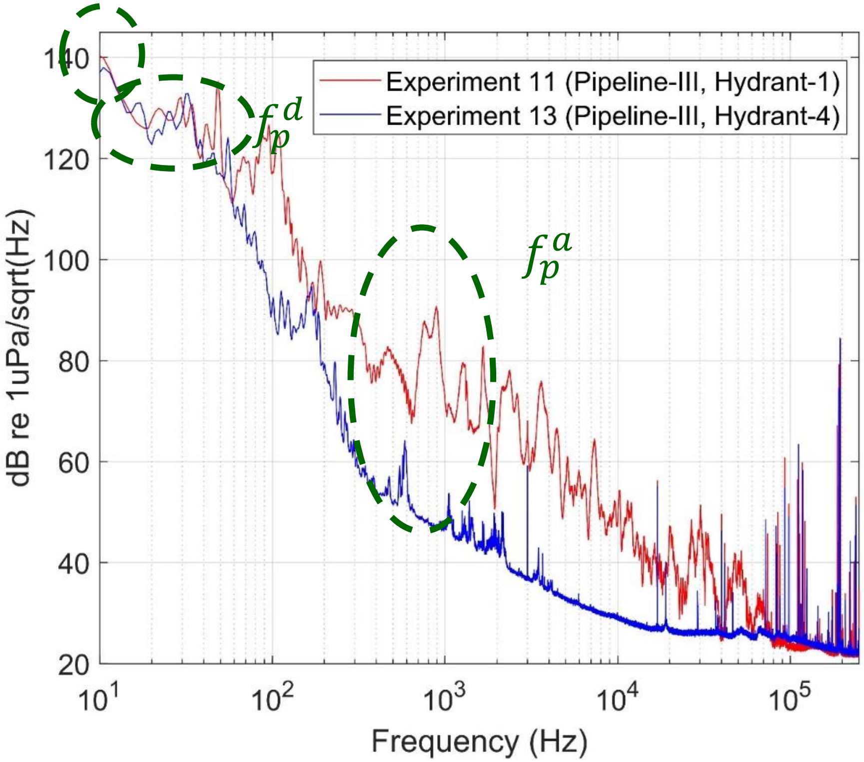


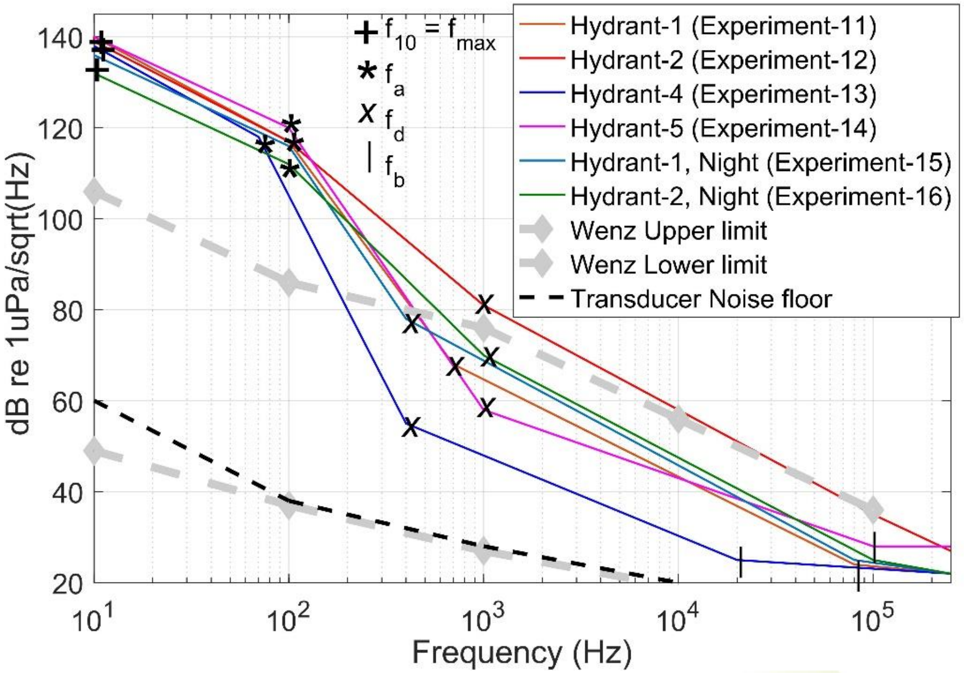
- Sources of heavy tails are external acoustic noise like door bang, speech signals and machine noise

PSD for Pipeline III- Actual water system

(f_p^{max}, P_p^{max}), around 40 dB higher than experiments without flow

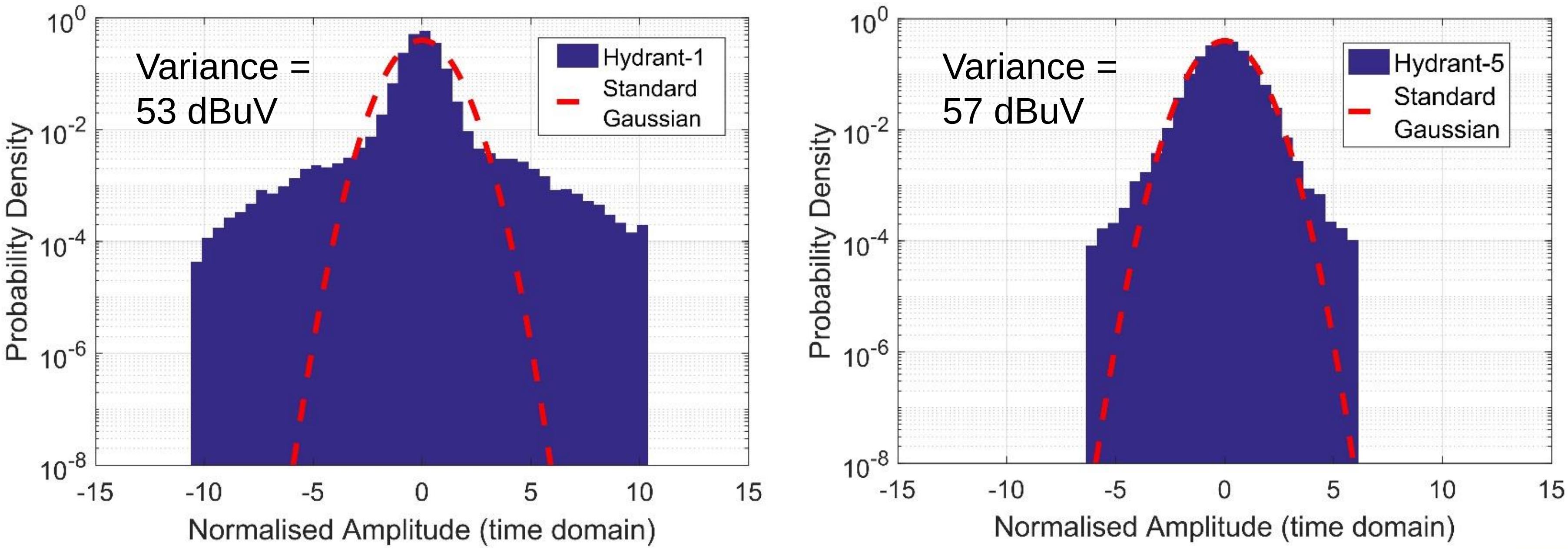
Piecewise Linear approximation using 6 parameters





High power in low frequencies is due to turbulence as Reynolds number $R_e >$ 20000 and slope of the spectrum is verified by Kolmogorov's third hypothesis.

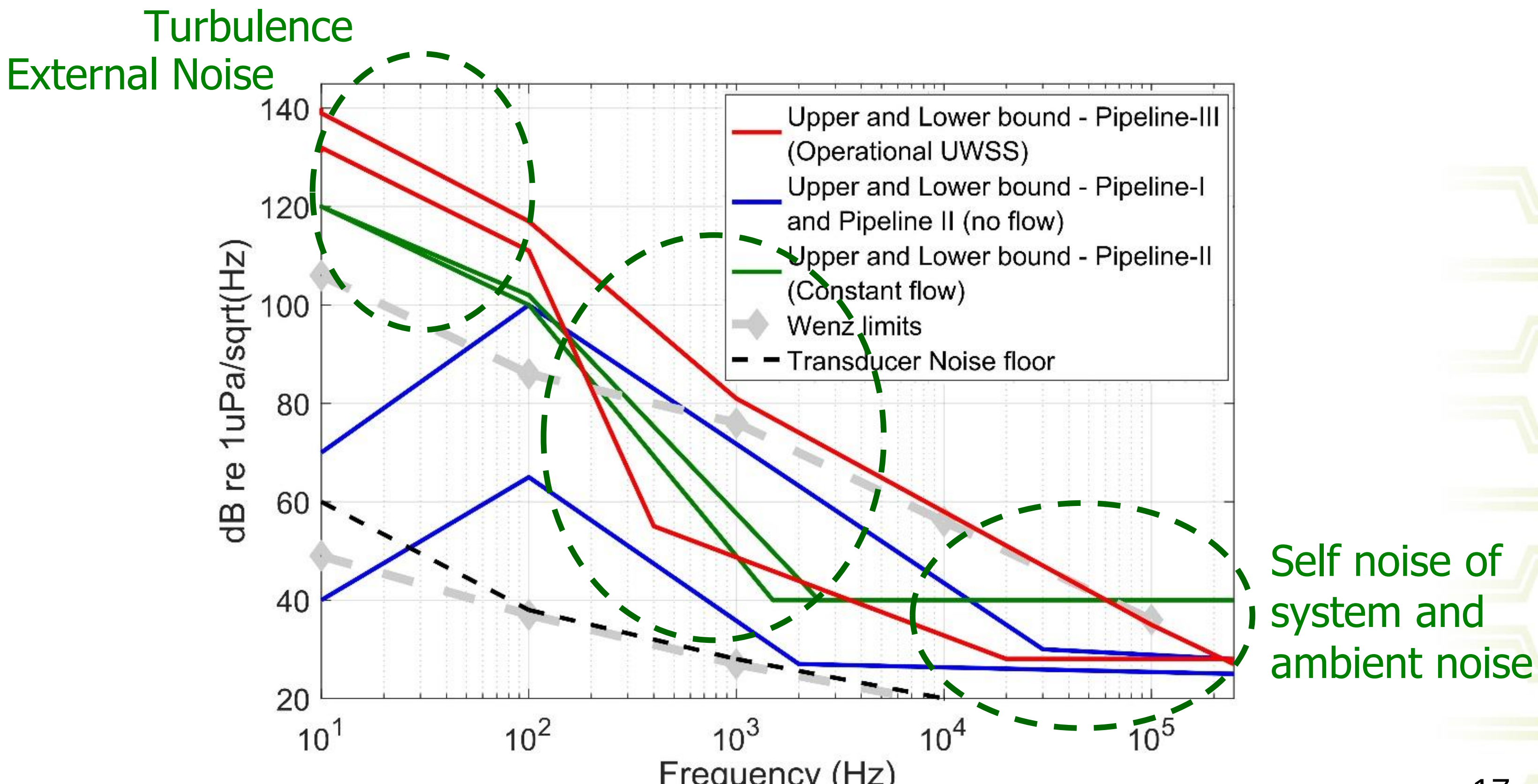
PDF for Pipeline III: actual water system



- Reason for heavy tails is transients in water pressure in operational water system caused by opening/closing of valves, pipe branches and water pumps.

PSD- Analysis and Modeling

Piecewise Linear model for PSD

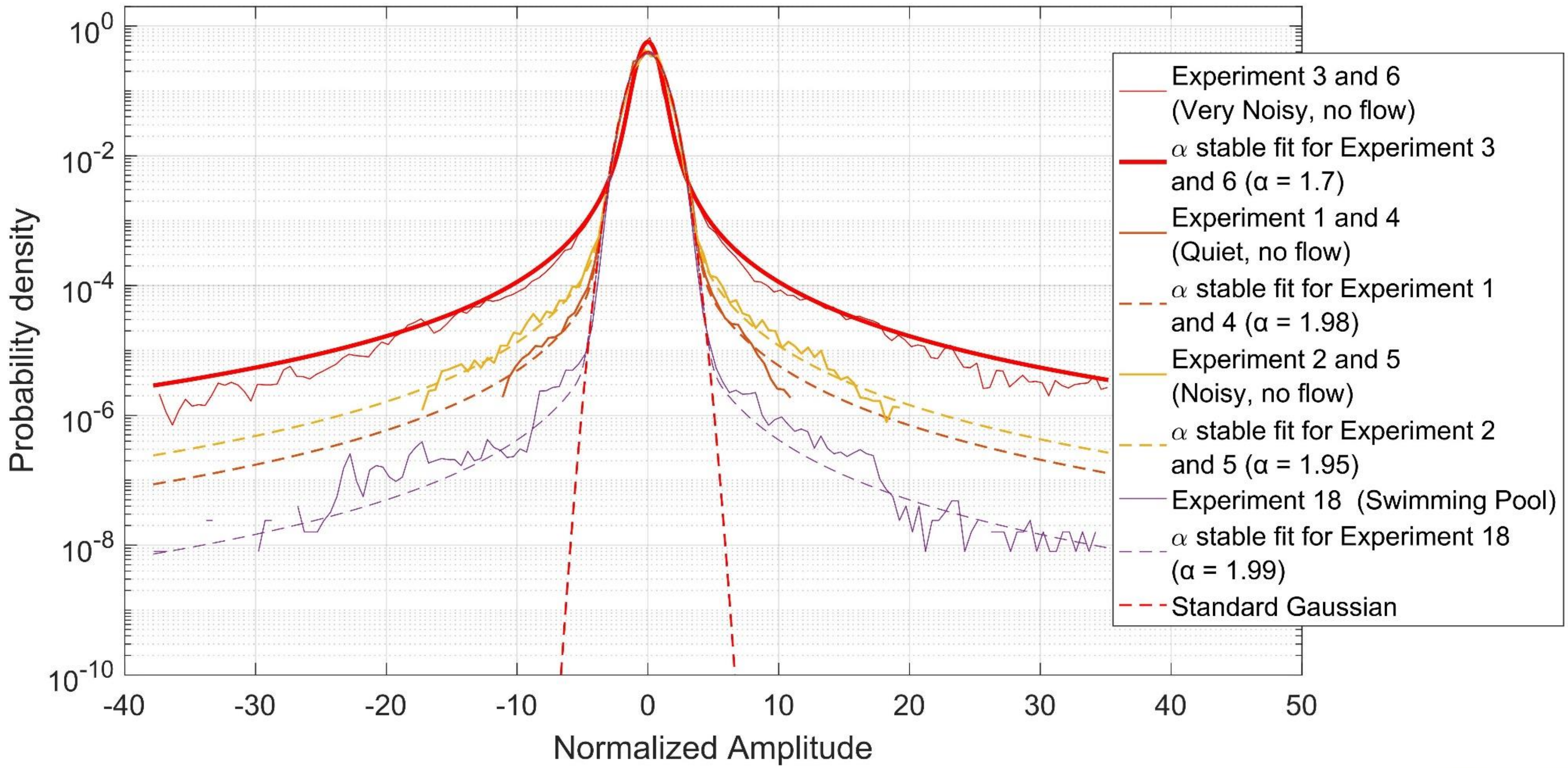


PDF-We propose α-stable

- Stable distributions are a group of probability distributions suitable for modelling heavy tails, large variance and skewness
- Classical central limit theorem: the normed sum of a set of finite variance RVs, will tend towards a normal distribution
- Without the finite variance assumption, the limit may be a stable distribution that is not normal.
- Four parameters: $S(\alpha, \beta, \gamma, \delta)$

α	Shape parameter-Decides the overall shape and tails	$0 < \alpha \leq 2$
β	Decides skewness of the distribution- (β=0:Symmetric)	$-1 \leq \beta \leq 1$
γ	Scale parameter (Directly related to the variance of the data)	$0 < \gamma < \infty$
δ	Location parameter (Directly related to the mean of the data)	$-\infty < \delta < \infty$

α-stable model for UWSS noise

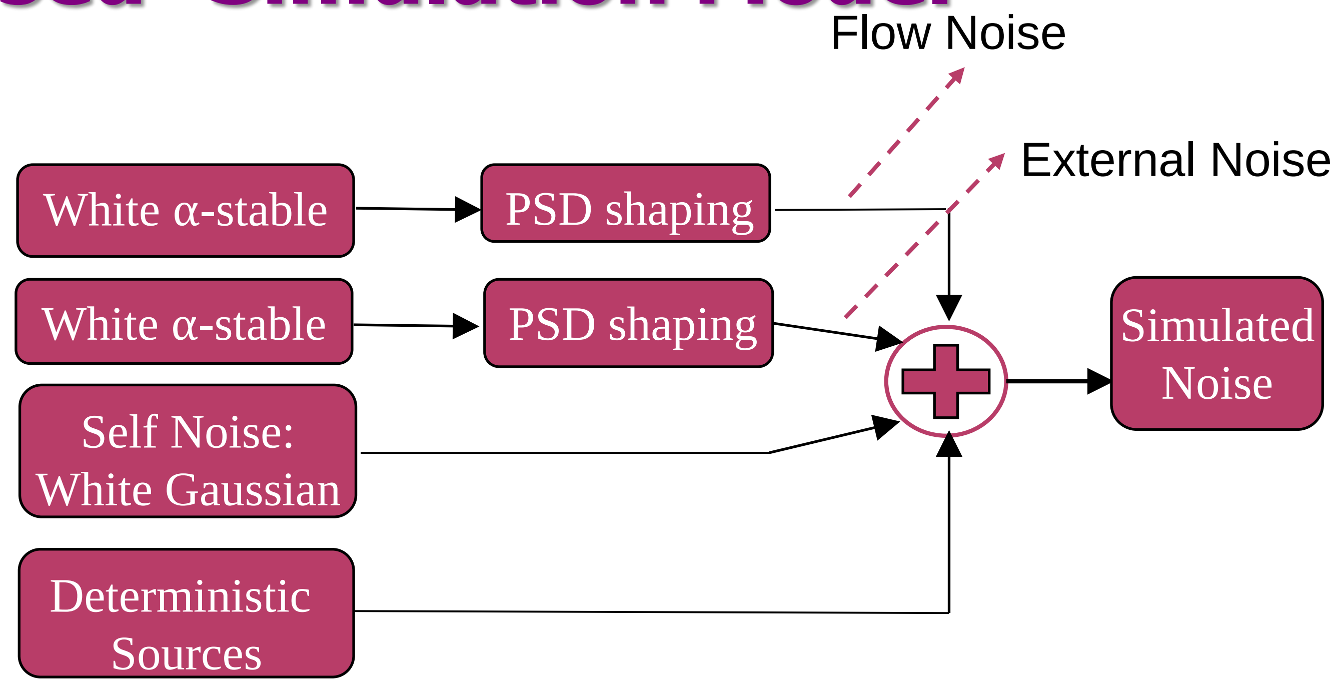


Value of α estimated using MLE method

Simulation Model

- Propose 4 independent noise sources
  - Water flow noise
  - External environment noise
  - System noise
  - Periodic deterministic sources

Proposed- Simulation Model



- Four sources of noise
- PSD/correlation shaping

Summary of Noise characterization

- Channel noise modeled as α-stable noise
  - Unusual noise source- special system design required
- Value of α depends on experimental conditions
- PSD shape depends on flow conditions and external noise
- Propose noise simulation model based on four main sources of noise

[1] Dubey, Amartansh, et al. "Measurement and Spectral Analysis of Acoustic Noise in Water Pipeline Channels." OCEANS 2018-Kobe, Japan. IEEE, 2018.

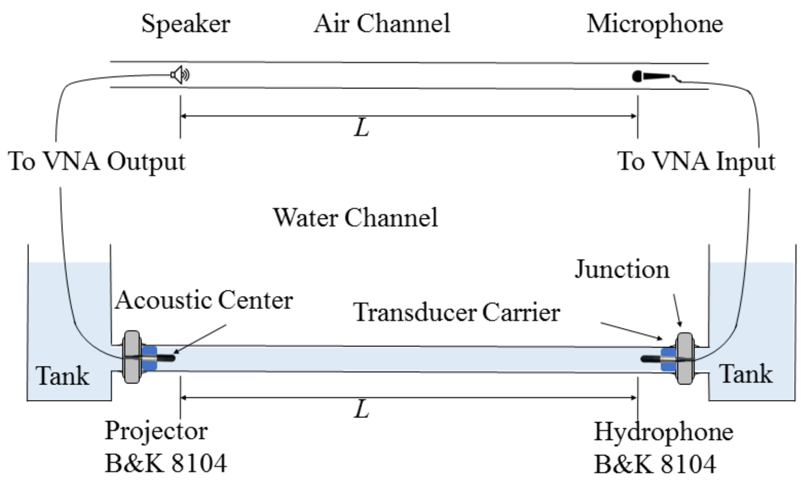
[2] Dubey, Amartansh, et al. (2018) "Measurement and Modeling of Acoustic Noise in water pipeline channel." The Journal of the Acoustical Society of America, Manuscript in preparation.

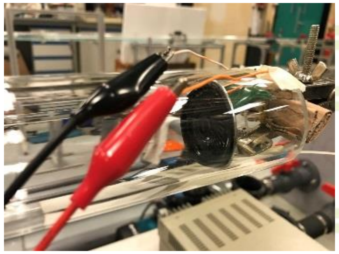
Challenges and Talk Contents

- Pipeline Channel and noise characterization
  - What is the noise PSD and PDF?
  - Channel attenuation and transfer function?
  - Optimum signal and receiver design?
  - Link budget?
  - Waveguide channel with multiple cutoffs?
- Fault Detection
  - Blockage detection
  - Impedance and Shunt Detection
  - Remaining challenges

Measurement Setup

- The channels: Acrylic-air (rigid), Steel-water (elastic), HDPE-water (elastic)
- Equipment: Transducers (Bruel and Kjaer 8104), Speaker and Microphone, Vector Network Analyzer (Bode 100 Omicron).





Dispersion Curve

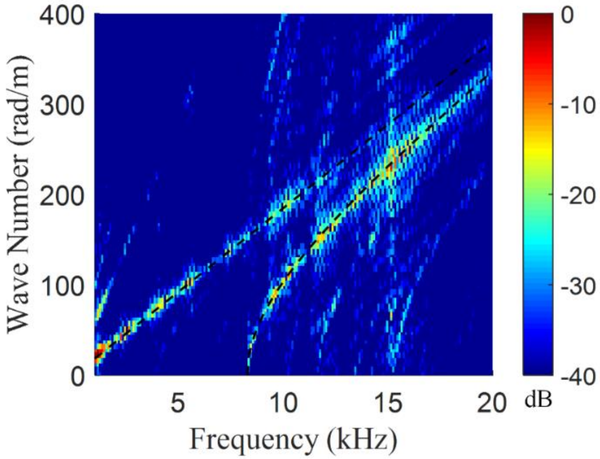
- k and z are spatial Fourier transform pairs

Axial Wavenumber

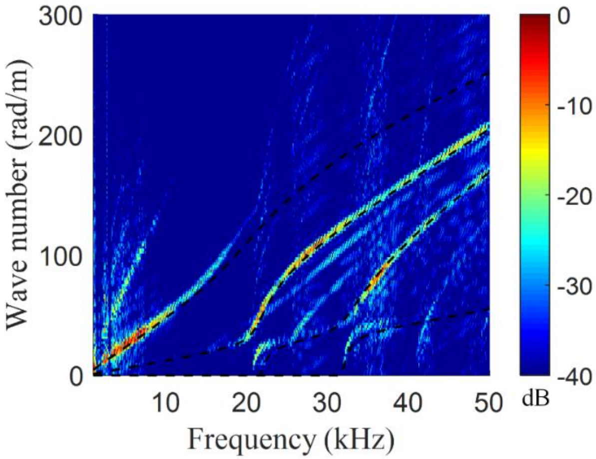
$$H(f,r,\theta,z) = \boxed{\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}} G_{nm}(f,r,\theta,z)e^{j\boxed{k_{nm}(f)}z}$$ where $G_{nm}(f,r,\theta,z) = B(f)A_{nm}(f)R_{nm}(r)\cos(n\theta)e^{-\alpha_{nm}(f)z}$

Summation of modes

$$\mathscr{H}(f,r,\theta,k) = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty}\mathscr{G}_{nm}(f,r,\theta,k)\otimes\delta(k-k_{nm}(f))$$



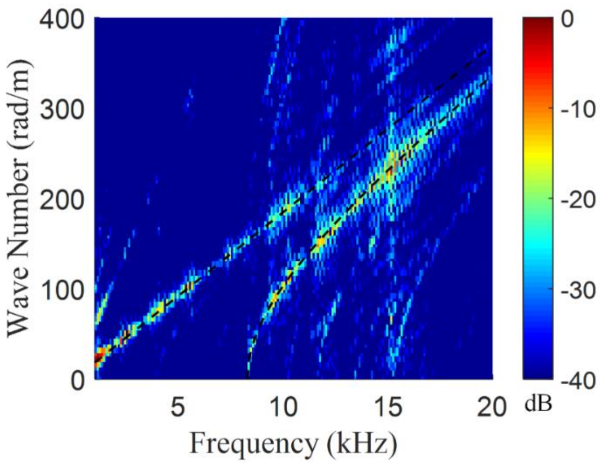
Acrylic-Air



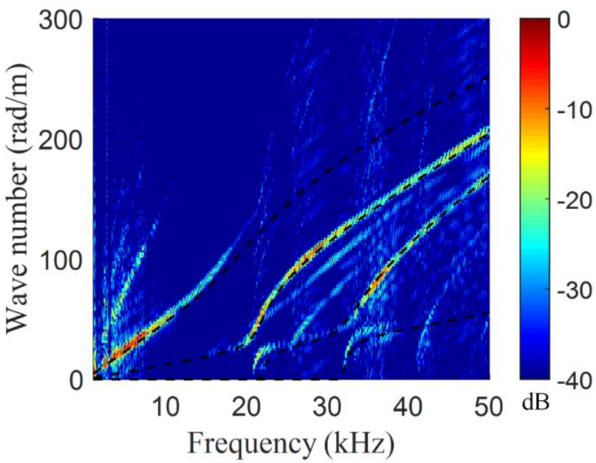
Steel-Water

Dispersion Curve

- Wavenumber k and group velocity v_g $$v_{nm}(f_0) = \frac{2\pi df}{dk_{nm}}|_{f_0}$$
- Need to include Elastic boundary conditions
  - Otherwise: wrong cutoff, wrong shape of dispersion curves
  - Wave propagates in both water and pipe wall



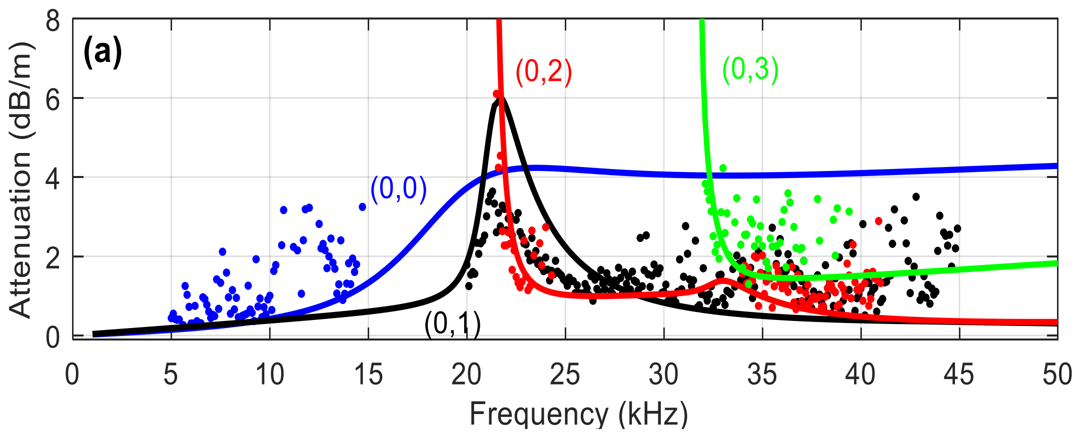
Acrylic-Air

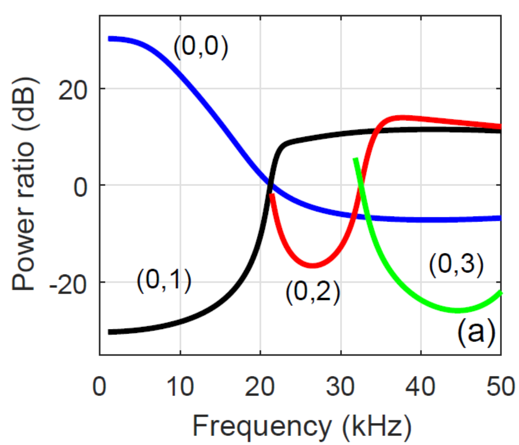


Steel-Water

Attenuation in Water Channel

- High attenuation occur around cutoff frequencies.
- High attenuation also occurs when the mode is pipe wall dominant (power ratio <0 dB).



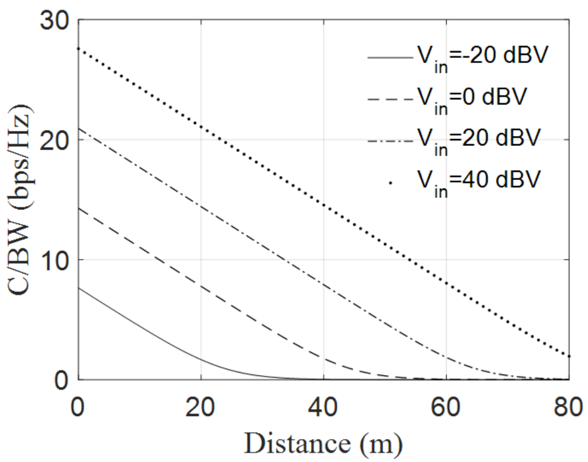


Channel Capacity

- For an SNR of 10 dB we can achieve a range of over 50 m
- Demonstrates that acoustic communication in steel-water waveguides is indeed possible.
- We can observe that for the 20kHz to 30kHz band useful capacity can be obtained up to 50 m for V_{in} greater than 20 dBV.

$$SNR = V_{\text{in}}[\text{dBV}] + TVR(f)[\text{dB}] - \alpha_{nm}(f)[\text{dB}] \cdot z - F_{\text{d}}[\text{dB}] - V_{\text{noise}}^{\text{pressure}}[\text{dB re }\mu\text{Pa}/\sqrt{\text{Hz}}] - 10\log(BW).$$

$$C = BW\log_2(1 + SNR)$$



Summary of Channel Characterization

- Proposed model predicts essential channel features such as mode cutoffs, dispersion curves and delay spread.
- Elastic boundary condition need to be considered for all water pipes.
- Attenuation for a steel-air water pipe is around 1dB/m
- Estimated communication range of 50 m
- Plane wave mode (below 8.3kHz in acrylic-air channel and below 15kHz in steel-water channel) can be utilized for fault detection

[1] Z. Li, L.Jing and R.D. Murch, "Propagation of monopole source excited acoustic waves in a cylindrical high-density polyethylene (HDPE) pipeline", the Journal of the Acoustical Society of America, vol. 142(6), 3564-3579, 2017.

[2] L.Jing, Z. Li, Y.Li and R.D. Murch, "Channel Characterization of Acoustic Waveguides Consisting of Straight Gas and Water Pipelines", IEEE Access, vol.6, pp.6807-6819, 2018.

[3] L.Jing, Y. Li and R.D. Murch, "Wideband modeling of the acoustic water pipe channel." OCEANS 2016-Shanghai. IEEE, 2016.

[4] L.Jing, Z. Li and R.D. Murch, "Experimental Study of Acoustic Channel Characteristics of Rigid and Elastic Pipelines." OCEANS 2017-Aberdeen. IEEE, 2017.

[5] Z. Li, L. Jing, W. Wang, Y. Li, A. Dubey, P. Lee and R.D. Murch, "Experimental Measurement and Analysis of Acoustic Wave Propagation in Water-filled Steel Pipeline Using the Iterative Quadratic Maximum Likelihood Algorithm, 175th Meeting of Acoustical Society of America, Minneapolis, 2018.

Challenges and Talk Contents

- Pipeline Channel and noise characterization
  - What is the noise PSD and PDF?
  - Channel attenuation and transfer function?
  - Optimum signal and receiver design?
  - Link budget?
  - Waveguide channel with multiple cutoffs?
- Fault Detection
  - Blockage detection
  - Impedance and Shunt Detection
  - Remaining challenges

Summary of pipeline communication

- Identify special features of wideband waveguide channel
- Use adaptive delay spread OFDM
- Shorten the length of cyclic prefix
- Improve transmission efficiency
- For these examples around 25% increase in throughput

[1] Y.Li, L.Jing, Z. Li and R.D. Murch, "Subcarrier Delay Spread Based Adaptive OFDM for Mobile Wideband Waveguide Channels", IEEE Transactons on Communications, vol.66(5), 2206-2218, 2018.

Challenges and Talk Contents

- Pipeline Channel and noise characterization
  - What is the noise PSD and PDF?
  - Channel attenuation and transfer function?
  - Optimum signal and receiver design?
  - Link budget?
  - Waveguide channel with multiple cutoffs?
- Fault Detection
  - Blockage detection
  - Impedance and Shunt Detection
  - Remaining challenges

Waves as diagnostic tools for UWSS

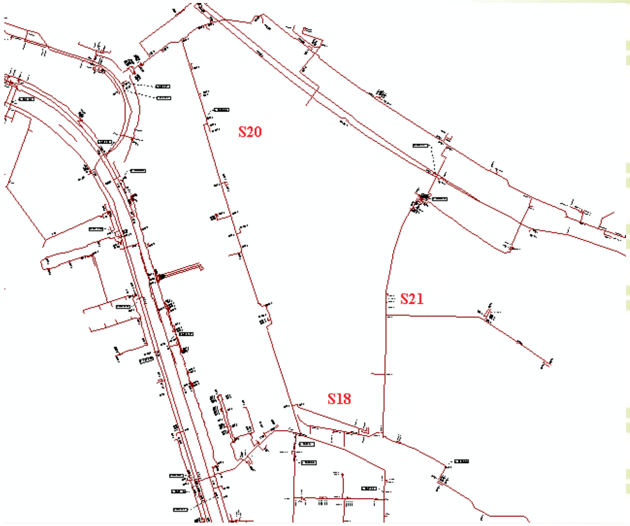
Non-intrusive, rapid to perform, economical, good for all faults & able to anticipate problems

Wave Transmitter → Inaccessible, poorly known, complex **medium/system**

e.g. Human, Ocean

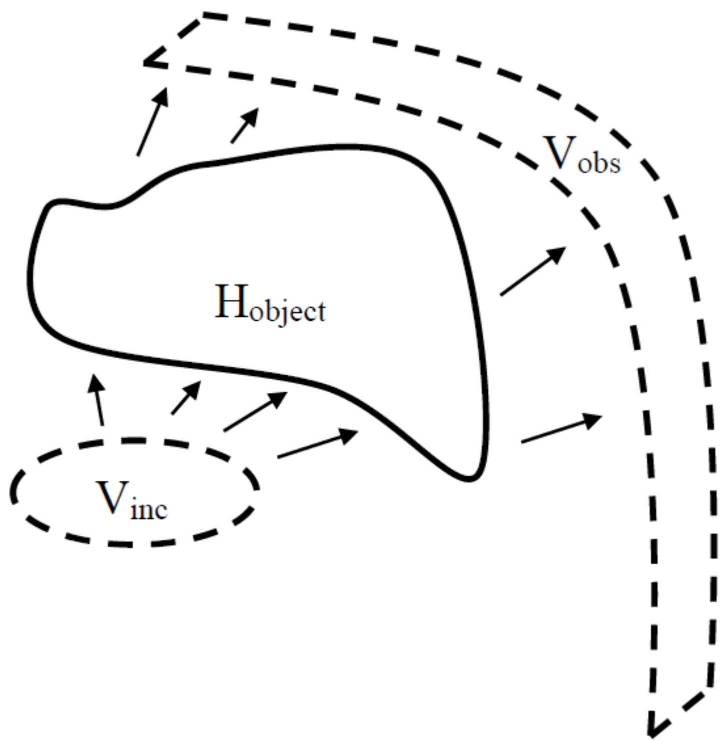
Pipelines?

→ Wave Receiver → Wave Theory → "Image"



Source: Smart UWSS project presentation

Direct Problem and Inverse Problem



Direct Problem

$V_{inc} + Hobject \longrightarrow V_{obs}$

Inverse Problem

$V_{inc} + V_{obs} \longrightarrow H_{object}$

❑ Problem

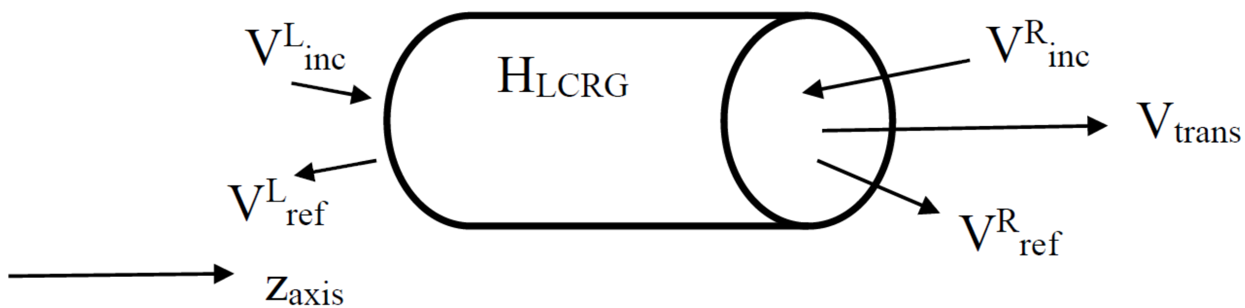
How to find defects and faults.

❑ Proposed solution

Insert signals into the networks and measure reflections to detect defects and faults.

❑ Challenge

Difficult to estimate the signals and parameters inside the networks.



Exact solution first proposed in 1950’s by Gelfand-Levitan. Practical application of the solution limited

Wave Equations and Definitions

	Transmission Line	Acoustic Pipeline
Fundamental Equations	$\frac{\partial i}{\partial z}+G_0 v+C_0\frac{\partial v}{\partial t}=0$ $\frac{\partial v}{\partial z}+R_0 i+L_0\frac{\partial i}{\partial t}=0$	$\frac{\partial u}{\partial z}+\frac{A}{\rho c^2}\frac{\partial p}{\partial t}=0$ $\frac{\partial p}{\partial z}+\frac{\rho}{A}\frac{\partial u}{\partial t}+R\ u\ =0$
Propagation Constant	$\gamma=\alpha+j\beta$ $=\sqrt{(R_0+j\omega L_0)(G_0+j\omega C_0)}$	$\gamma=\alpha+j\beta$ $=\sqrt{-\frac{\omega^2}{c^2}+\frac{jA\omega R}{\rho c^2}}$
Characteristic Impedance	$Z_0=\begin{cases}\sqrt{\frac{R_0+j\omega L_0}{G_0+j\omega C_0}} & lossy\\ \sqrt{\frac{L_0}{C_0}} & lossless\end{cases}$	$Z_0=\begin{cases}\frac{\rho c^2\gamma}{j\omega A} & lossy\\ \frac{\rho c}{A} & lossless\end{cases}$
Time-Harmonic Equations (lossy)	$\frac{dI}{dz}+\frac{\gamma}{Z_0}V=0$ $\frac{dV}{dz}+\gamma Z_0 I=0$	$\frac{dU}{dz}+\frac{\gamma}{Z_0}P\ =0$ $\frac{dP}{dz}+\gamma Z_0 U\ =0$

Wave Equations and Definitions

- ***F*** represents voltage ***V*** or pressure ***P***.
- ***Q*** represents current ***I*** or volume velocity ***U***.

$$\frac{dQ(z,k)}{dz} + \frac{\gamma(z)}{Z(z)}F(z,k) = 0$$

$$\frac{dF(z,k)}{dz} + \gamma(z)Z(z)Q(z,k) = 0$$

- $\gamma(z)$ propagation constant and $Z(z)$ is the channel characteristic impedance.

Liouville Transformation

- Liouville transformation:

$$x(z) = \int_0^z \frac{c(0)}{c(s)} ds.$$

- Wave equations:

$$\frac{dQ(x,k)}{dx} = -\frac{\gamma(x)}{Z(x)\nu(x)} F(x,k)$$

$$\frac{dF(x,k)}{dx} = -\frac{\gamma(x)Z(x)}{\nu(x)} Q(x,k)$$

- Low loss case:

$$\frac{d^2F(x,k)}{dx^2} - (\alpha_b + jk)^2 F(x,k) = \frac{\mathrm{d}\ln\mathrm{Z(x)}}{dx}\frac{dF(x,k)}{dx}$$

$$\frac{\mathrm{d}^2 F_{inc}}{\mathrm{d}x^2} - (\alpha_b + jk)^2 F_{inc} = 0$$

$$\frac{d^2F_s(x,k)}{dx^2} - (\alpha_b + jk)^2 F_s(x,k) = \frac{\mathrm{d}\ln\mathrm{Z(x)}}{dx}\frac{dF(x,k)}{dx}$$

Born Approximation

- Use incident wave and known frequency independent attenuation to approximate the total wave:

$$F(x,k) = F_{inc}(x,k) = e^{-jkx-\alpha_b x}.$$

$$F_s(x,k) = \int_0^b \frac{Z'(y)}{Z(y)} F'(y,k) g(x,y) \mathrm{d}y \quad \text{where} \quad g(x,y) = -\frac{1}{2(\alpha_b + jk)} e^{-(\alpha_b+jk)|x-y|}$$

$$F_s(0,k) = \frac{1}{2}\mathcal{F}\left[\frac{\mathrm{d}\ln[Z(x)]}{\mathrm{d}x}\right](2k)$$

- A straightforward final solution (explicit expression):

$$Z(x) = Z(x=0)e^{\int_0^{2x} 2\mathcal{F}^{-1}[F_s(0,k)e^{\alpha_b x}](s)ds}$$

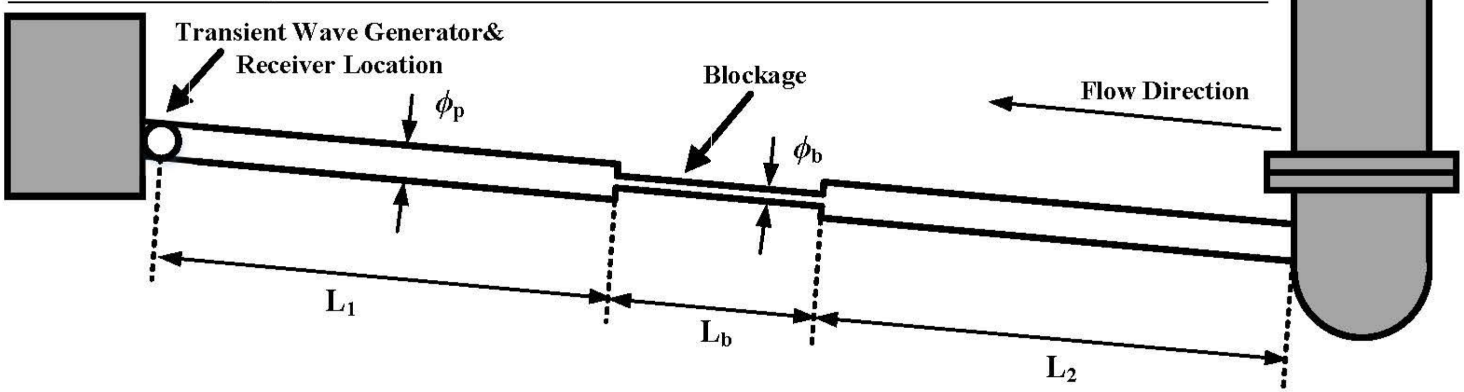
- The compensation for know frequency independent loss can be achieved by directly multiplying $e^{\alpha_b x}$ to the time domain impulse response.

Simulation Results

Cross-sectional Area Reconstruction (explicit expression)

$$A(x) = A(0)e^{-\int_0^{2x} 2\mathcal{F}^{-1}[P_s(0,k)e^{\alpha c x}](s)ds}$$

	ϕ_p (mm)	ϕ_b (mm)	L_1 (m)	L_b (m)	Material	c (m/s)
Italy (Mild)	93.3	73.3	76.8	24	HDPE	367
Italy (Severe)	93.3	38.3	76.8	24	HDPE	367
New Zealand (Short)	72.4	22.5	21.0	6	Steel	1183
New Zealand (Long)	72.4	22.5	21.0	12	Steel	1183

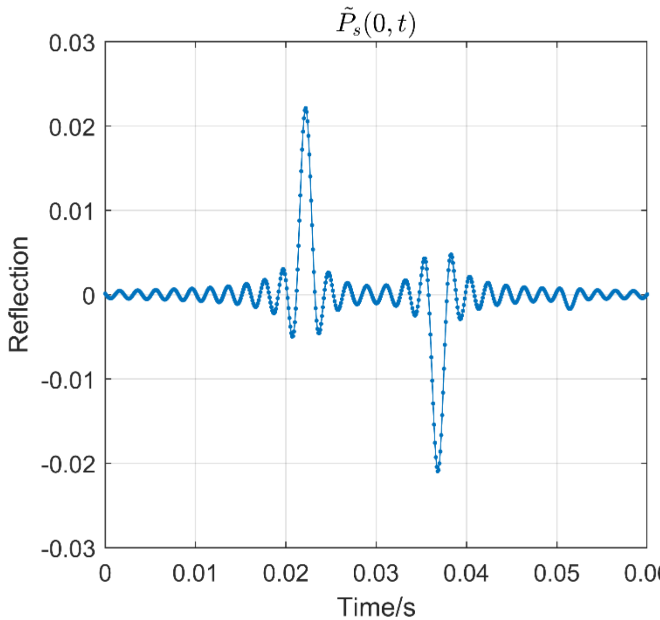


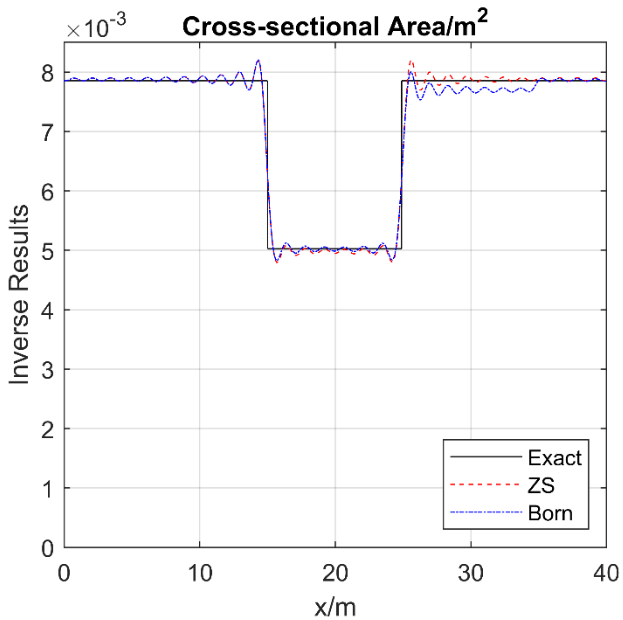
Explicit expression and examples

- Cross-sectional Area

$$A(x) = A(0)e^{-\int_0^{2x} 2\mathcal{F}^{-1}[P_s(0,k)e^{\alpha c x}](s)ds}$$

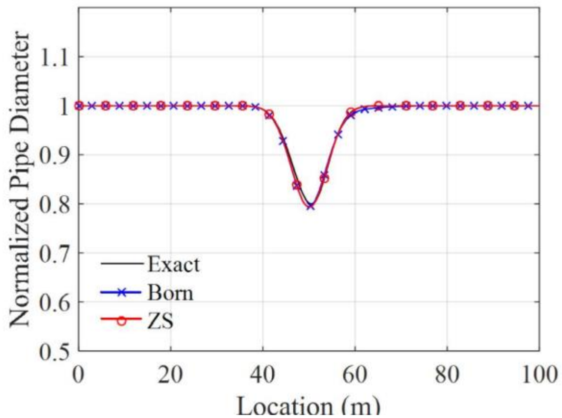
$$A(x) = A(0)e^{-\int_0^{2x} 2[\widetilde{P_s}(0,s/c)e^{\alpha c x}]ds}$$

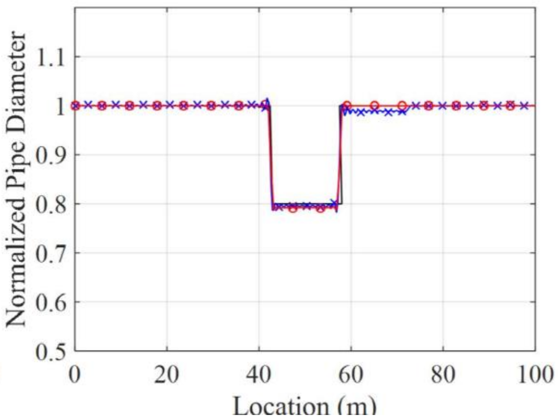


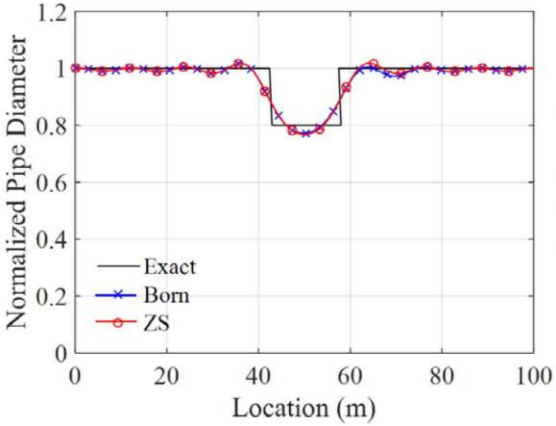


Simulation Results (Water Pipeline)

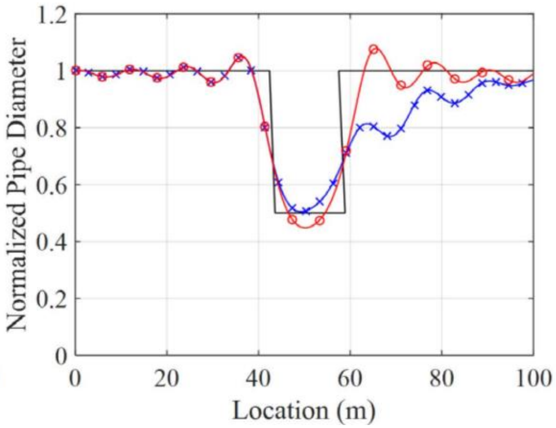
Ideal Case
(BW=500Hz,
Mild Blockage)



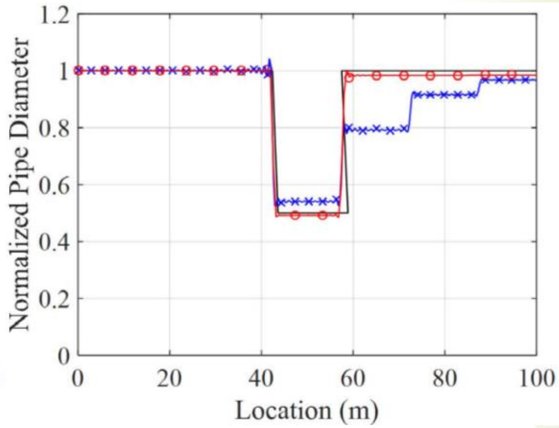




(BW=50Hz,
Mild Blockage)



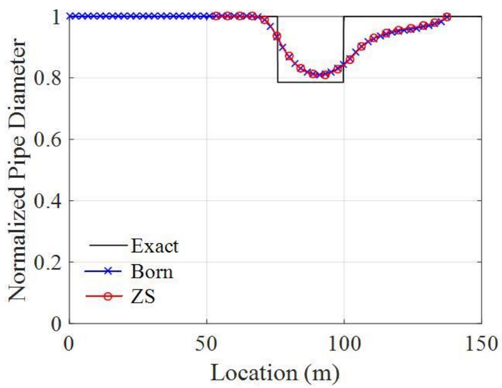
(BW=50Hz,
Severe Blockage)

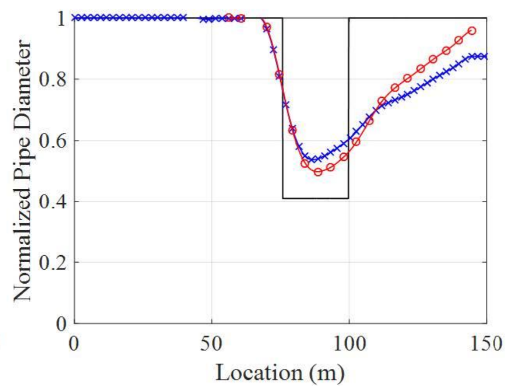


(BW=500Hz,
Severe Blockage)

Experimental Results (Water Pipeline)

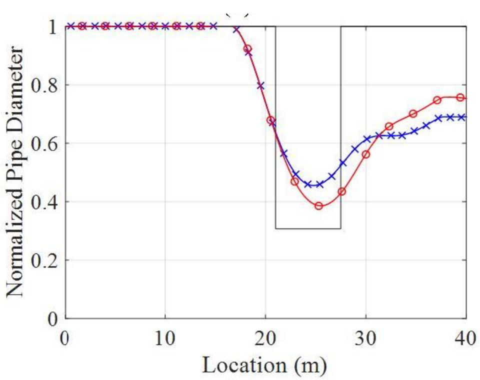
Italy
Mild Blockage

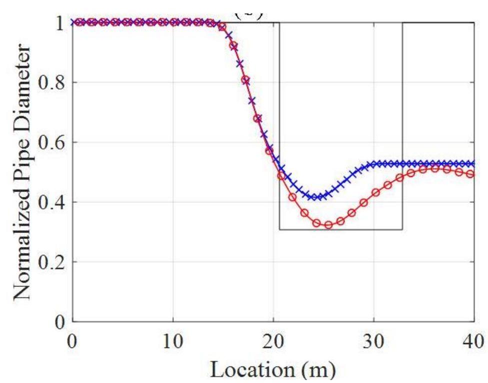




Italy
Severe Blockage

New Zealand
Short Blockage



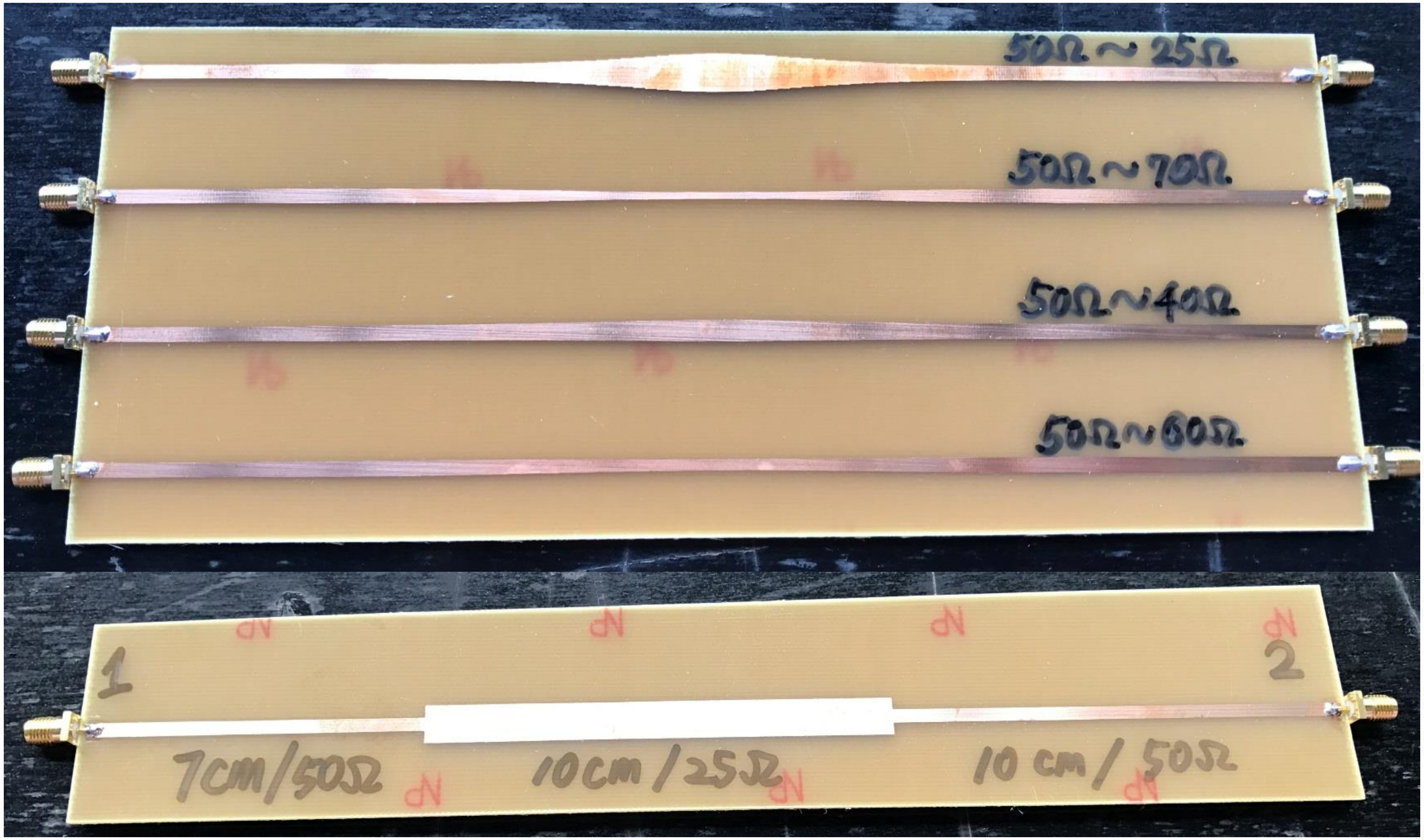


New Zealand
Long Blockage

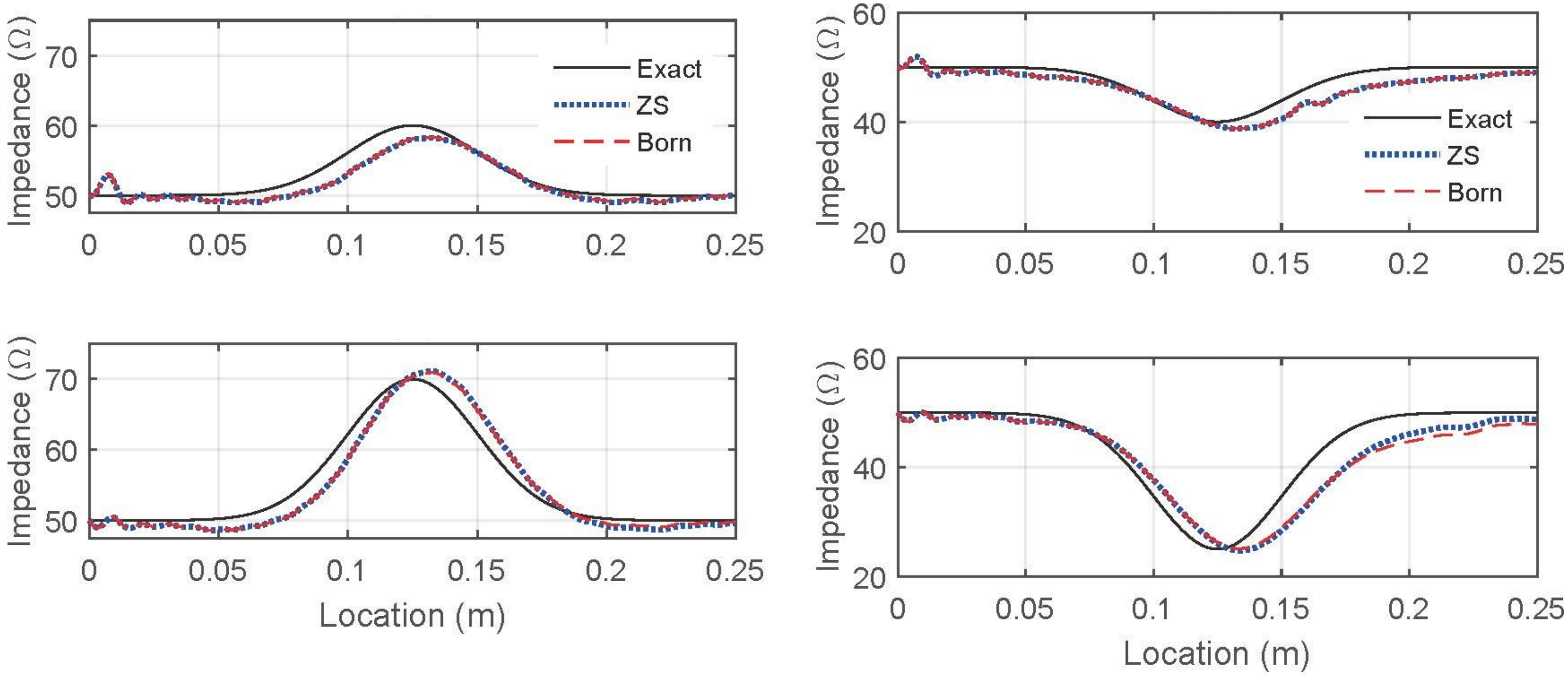
Experimental Results (Water Pipeline)

- The position of the blockage can be found and a rough reconstruction of the blockage shape can be obtained.
- The probing signal is valve closure, so that the frequency bandwidth is limited (Italy test: 30Hz; New Zealand test: 50Hz).

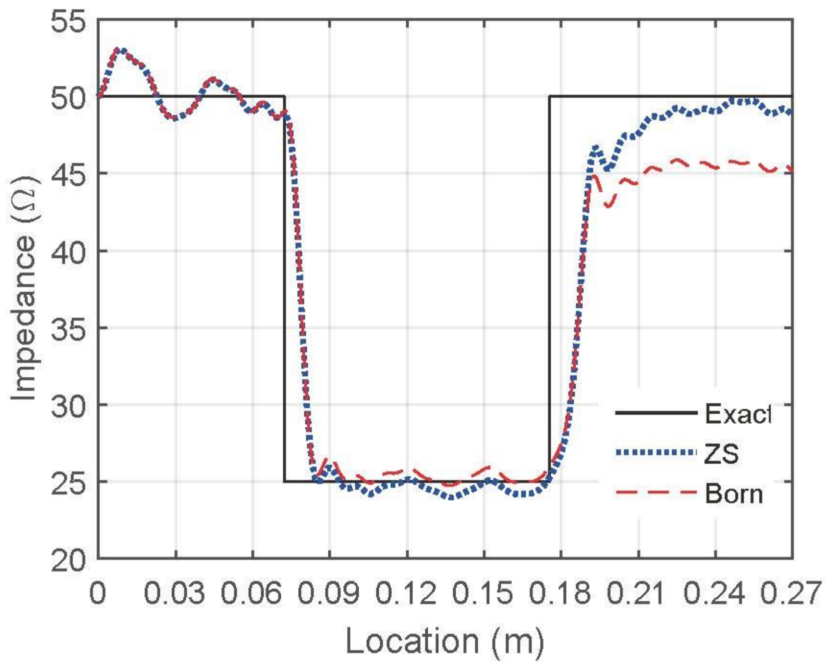
Experimental Results (Transmission Line)



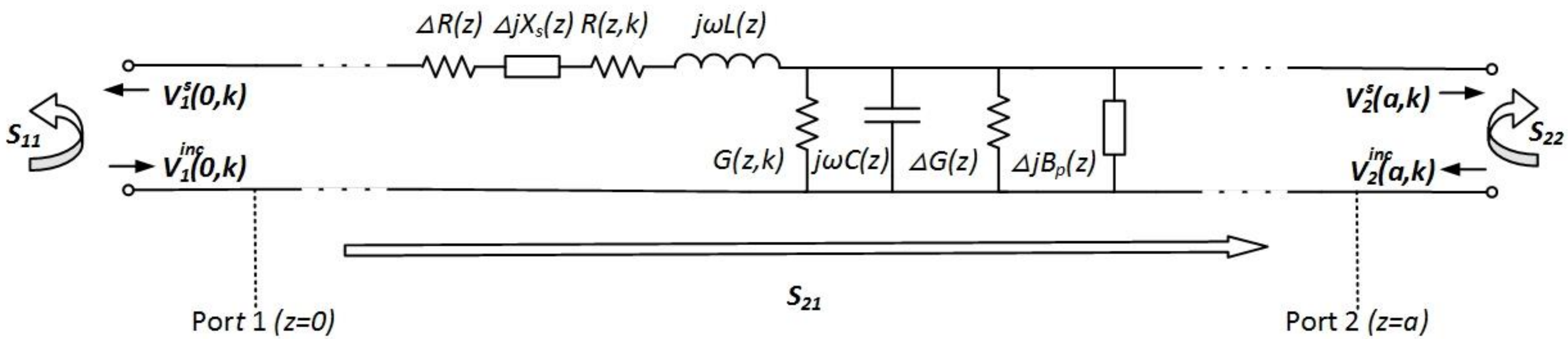
Experimental Results (Transmission Line)



Experimental Results (Transmission Line)



Distributed LCRG Transmission Line Model



- *L(z)*, *C(z)*, *R(z,k)* and *G(z,k)* are related to impedance *Z(z)* faults.
- ΔG is related to shunt conductance fault.
- ΔR is related to series resistance fault.
- ΔX_s and ΔB_p are related to reactive faults.

Formulation

- Telegrapher's equation:

$$\frac{\mathrm{d}F(z,k)}{\mathrm{d}z} = -\left(j\omega L(z) + R(z,k) + \Delta R(z)\right) Q(z,k)$$
$$\frac{\mathrm{d}Q(z,k)}{\mathrm{d}z} = -\left(j\omega C(z) + G(z,k) + \Delta G(z)\right) F(z,k)$$

- Wave equations involving impedance and propagation constant:

$$\frac{\mathrm{d}F(z,k)}{\mathrm{d}z} = -\gamma(z,k)Z(z,k)Q(z,k) - \Delta R(z)Q(z,k),$$
$$\frac{\mathrm{d}Q(z,k)}{\mathrm{d}z} = -\frac{\gamma(z,k)}{Z(z,k)}F(z,k) - \Delta G(z)F(z,k).$$

Impedance (blockages) and Shunt Conductance (leak) Profile Separation

- Following similar Born approximation procedure we can obtain solution for shunts and impedances (leaks and blockages)

$$F_s(0,k) = S_{11}(k) \simeq \int_0^b p(y) e^{-j2ky} e^{-2\alpha_b(k)y} dy$$

$$p(x) = \frac{Z'(x)}{2Z(x)} - \frac{\Delta G(x) Z(x)}{2\nu(x)}$$

$$p(x) = \mathcal{F}^{-1}\left[S_{11}(k) e^{2\alpha_b(k)x}\right](2x)$$

- Kernel *p(x)* has two terms relating to impedance fault ***Z(z)*** and shunt conductance fault ***ΔG*** respectively.
- Conducting 2-port measurement is essential for separating the two terms.

Frequency Dependent Loss Compensation

- Although the attenuation coefficient $e^{2\alpha_b(k)x}$ is frequency dependent, it varies slowly with frequency (typically increases around 3dB/m/GHz) compared to e^{2jkx}. Therefore we can collapse the second integral with respect to *k.*

$$\mathcal{F}^{-1}[S_{11}(k)e^{\alpha_b(k)2x}](2x) = \int_{-\infty}^{\infty}\left[\int_0^b p(y)e^{-j2ky}e^{-2\alpha_b(k)y}dy\right]e^{\alpha_b(k)\cdot 2x}e^{jk\cdot 2x}dk$$

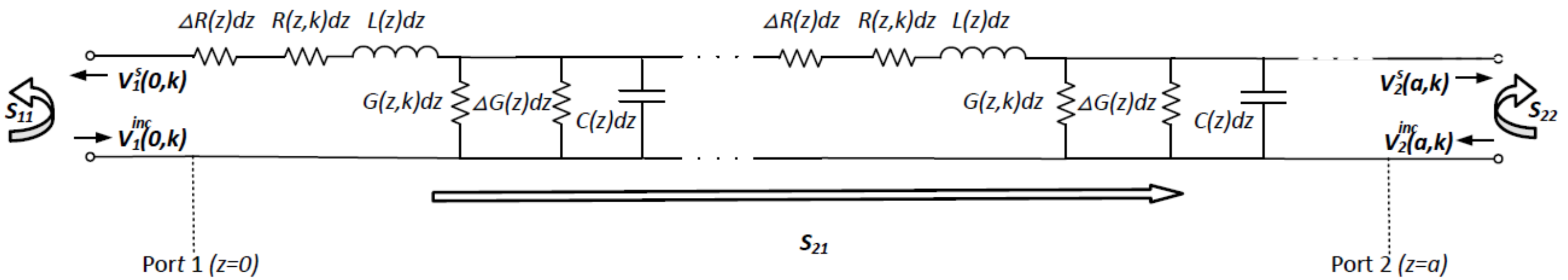
$$\mathcal{F}^{-1}[S_{11}(k)e^{2\alpha_b(k)x}](2x) = \int_0^b p(y)e^{-2\alpha_b(k)y}e^{2\alpha_b(k)x}\delta(2(x-y))dy$$

- In essence we can reconstruct $p(x)$ by multiplying $S_{11}(k)$ by $e^{2\alpha_b(k)x}$ and then take the inverse Fourier Transform, for each x, with respect to k. This allows us to reconstruct $p(x)$.

$$p(x) = \mathcal{F}^{-1}[S_{11}(k)e^{2\alpha_b(k)x}](2x)$$

2-Port Measurement

- Explore the symmetry of kernel $p(x)$.

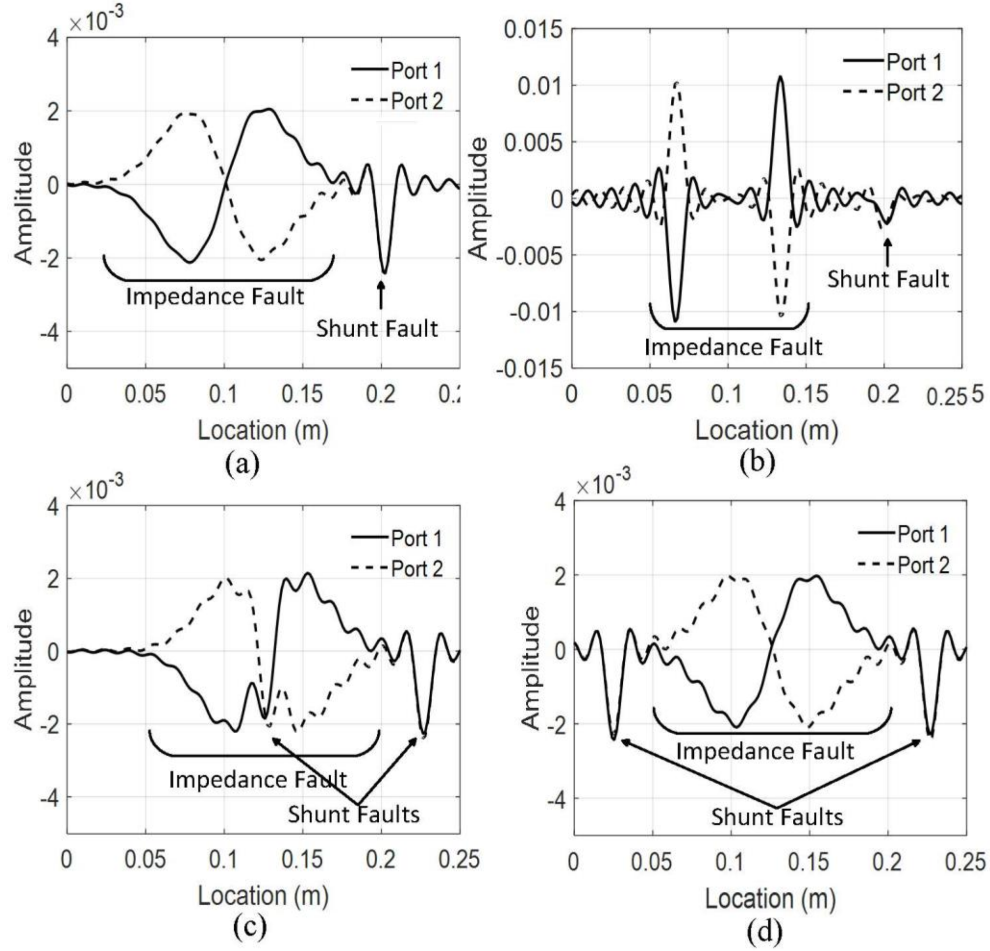


$$p_1(x) = \mathcal{F}^{-1}[S_{11}(k)e^{2\alpha_b(k)x}](2x)$$

$$p_2(b-x) = \mathcal{F}^{-1}[S_{22}(k)e^{2\alpha_b(k)(b-x)}](2(b-x))$$

Examine *p(x)* from Two Ports

- Neither $p_1(x)$ nor $p_2(b-x)$ can be used for determining the impedance and shunt conductance faults directly.
- $$\frac{Z'(x)}{Z(x)} = p_1(x) - p_2(b-x)$$
- $$\frac{\Delta G(x) Z(x)}{\nu(x)} = -(p_1(x) + p_2(b-x))$$
- The shunt fault is symmetric because its p(x) part has Z(x) term.
- The impedance fault is anti-symmetric because its p(x) part has the derivative of Z(x).



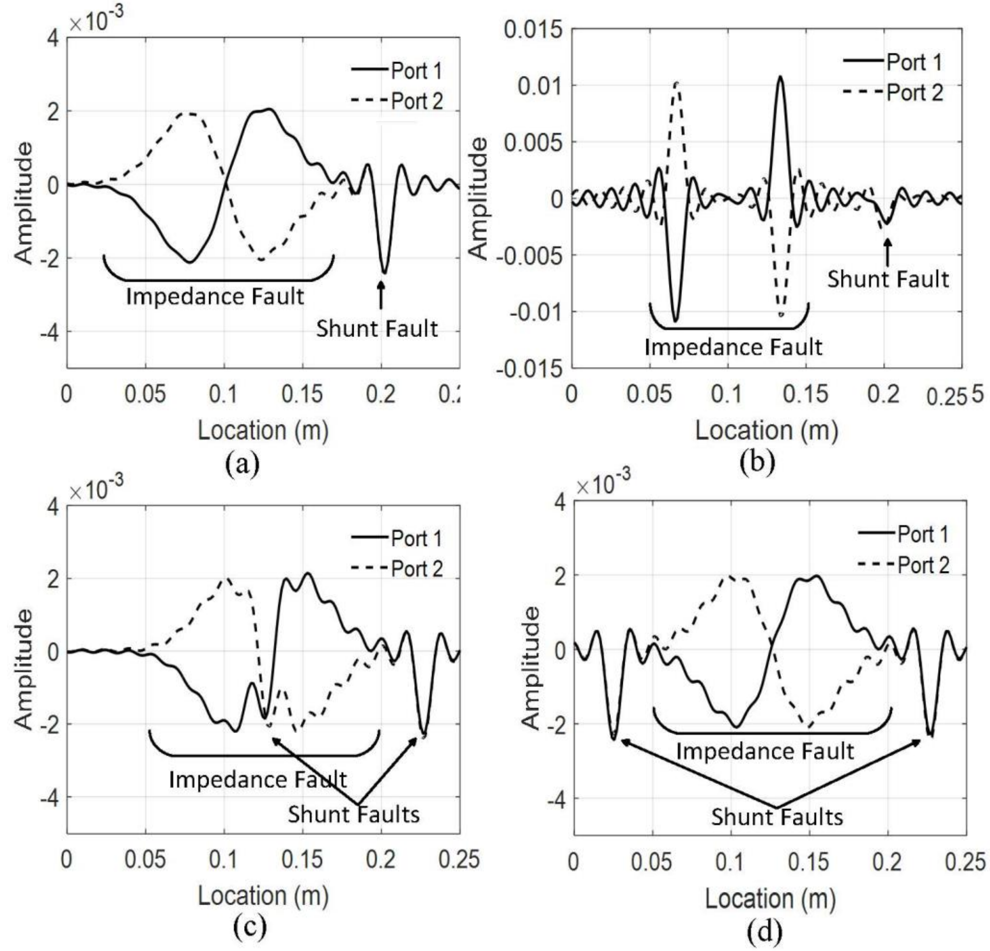
Examine *p(x)* from Two Ports

$$Z(x) = Z_0 e^{\int_0^x [p_1(s) - p_2(b-s)] \mathrm{d}s}$$

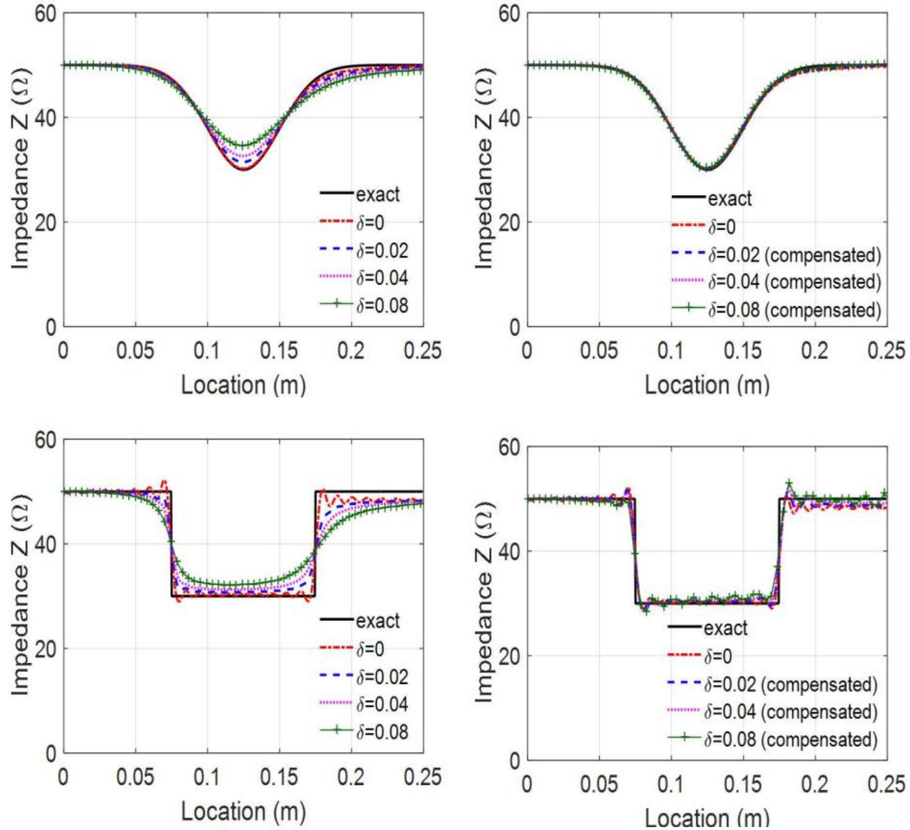
$$= Z_0 \exp\left\{ \int_0^x \left[\mathcal{F}^{-1}[S_{11}(k) e^{2\alpha_b(k)s}](2s) - \mathcal{F}^{-1}[S_{22}(k) e^{2\alpha_b(k)(b-s)}](2(b-s)) \right] ds \right\}$$

$$\Delta G(x) = \frac{-\nu(x) \cdot [p_1(x) + p_2(b-x)]}{Z(x)}$$

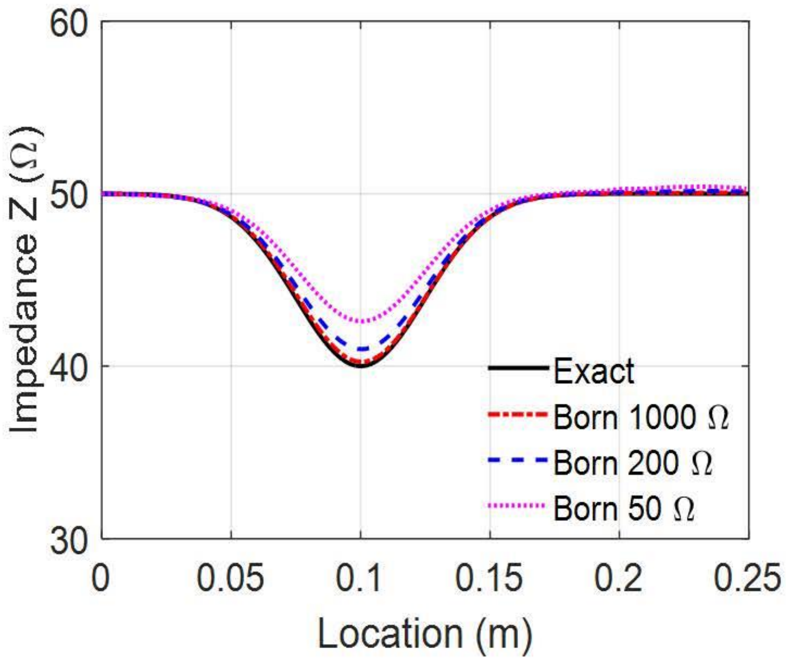
$$= -\frac{\nu(x)}{Z(x)} \cdot \left[\mathcal{F}^{-1}[S_{11}(k) e^{2\alpha_b(k)x}](2x) + \mathcal{F}^{-1}[S_{22}(k) e^{2\alpha_b(k)(b-x)}](2(b-x)) \right]$$

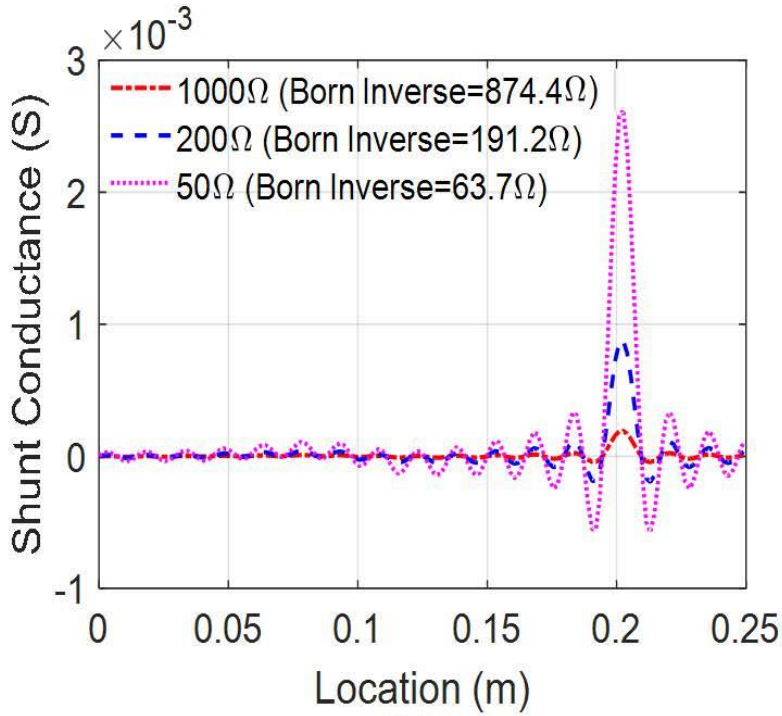


Simulation results-Loss Compensation

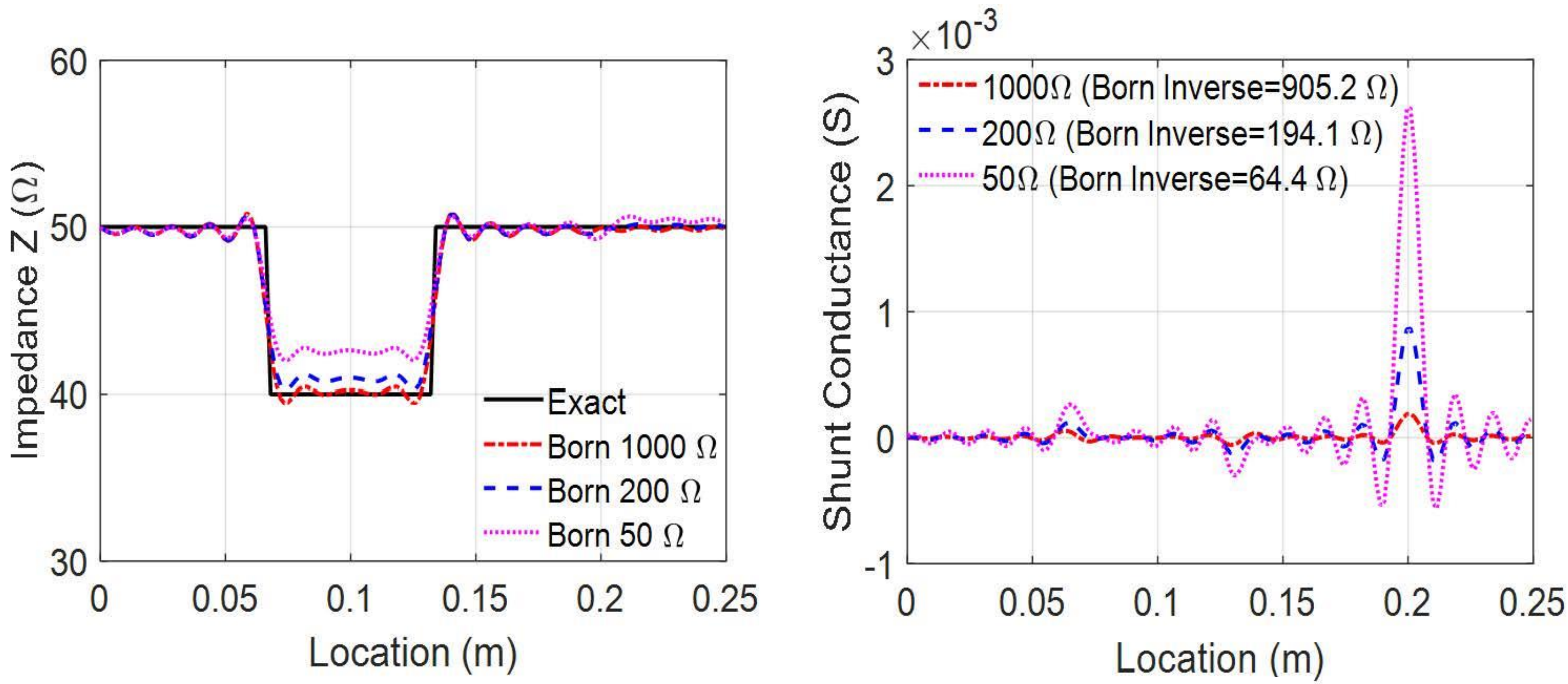


Simulation Results

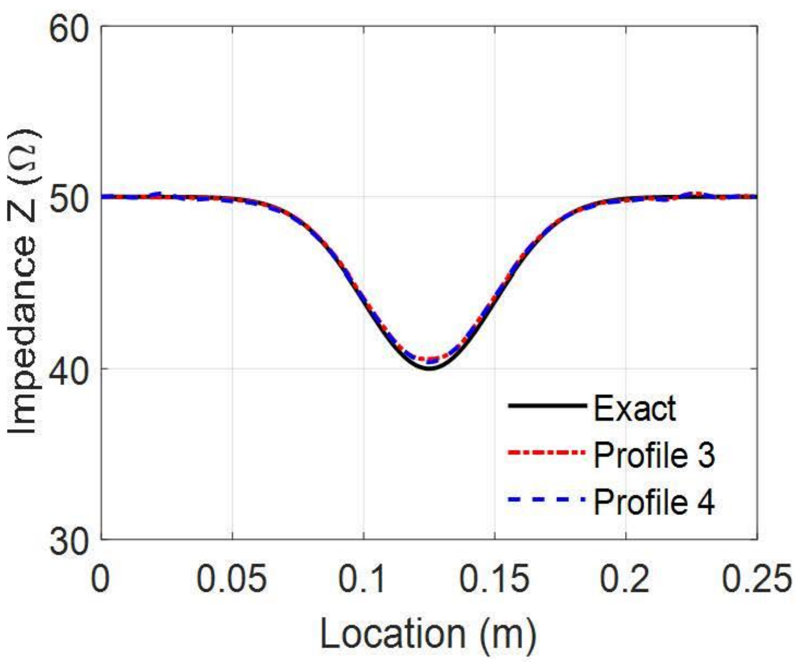


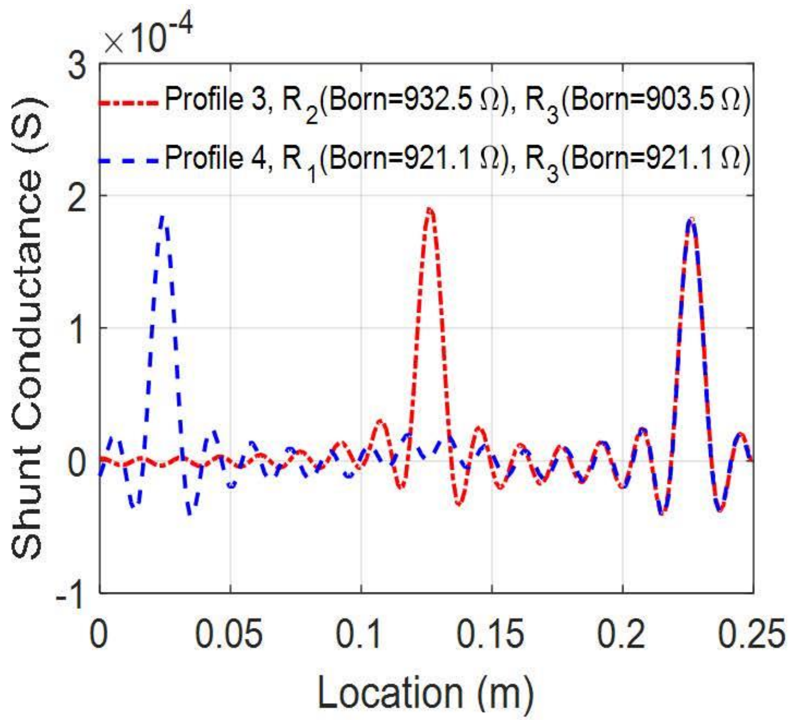


Simulation Results



Simulation Results

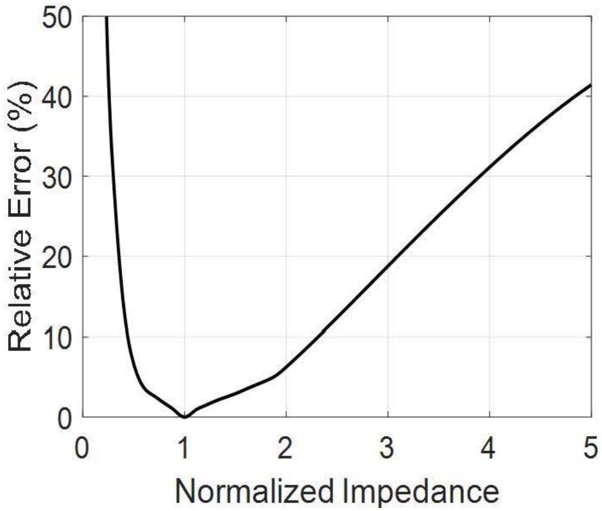


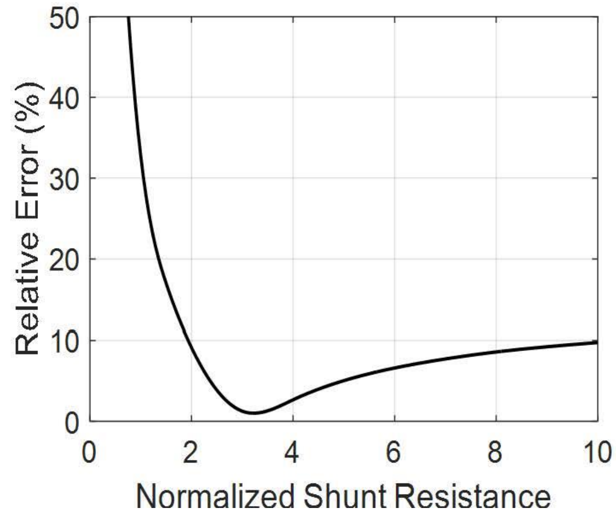


Relative Errors of the Reconstructions

- Relative Errors $e_{rel}^{Z} = \max_{z} \left| \frac{Z_{recon}(z) - Z_{exact}(z)}{Z_{exact}(z)} \right|$

$$e_{rel}^{Shunt} = \max_{i} \left| \frac{R_{recon}(z_i) - R_{exact}(z_i)}{R_{exact}(z_i)} \right|$$



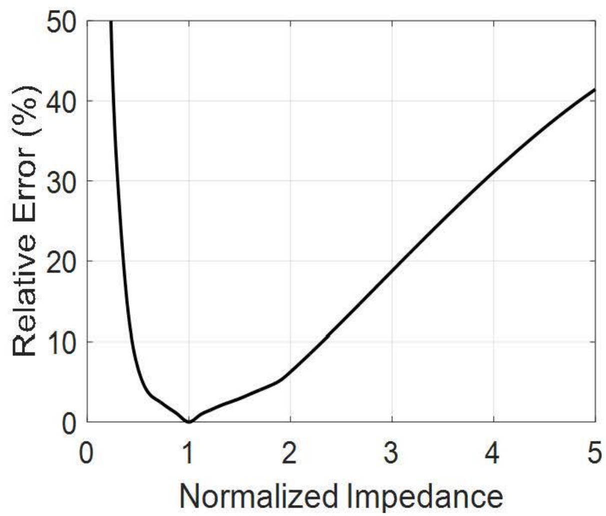


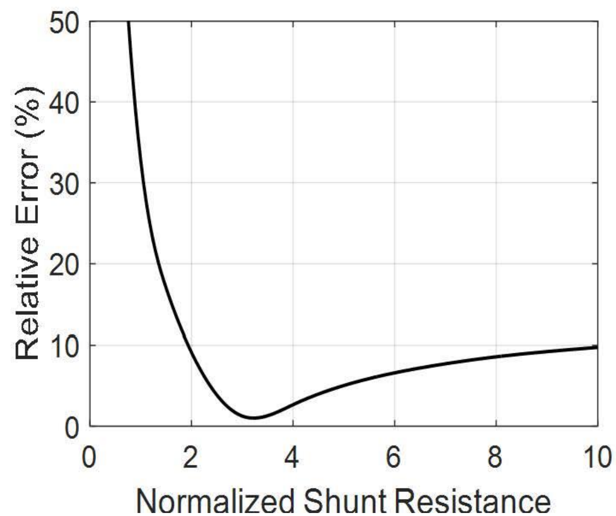
Relative Errors of the Reconstructions

- Validity range

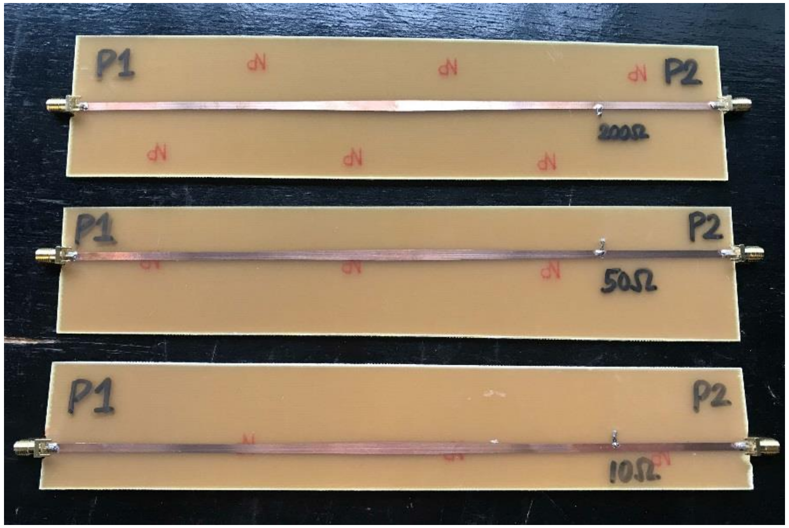
$$|Z'(x)dx/[2Z(x)]| < 1/4 \qquad 3/5Z(x) < Z(x+\Delta x) < 5/3Z(x)$$

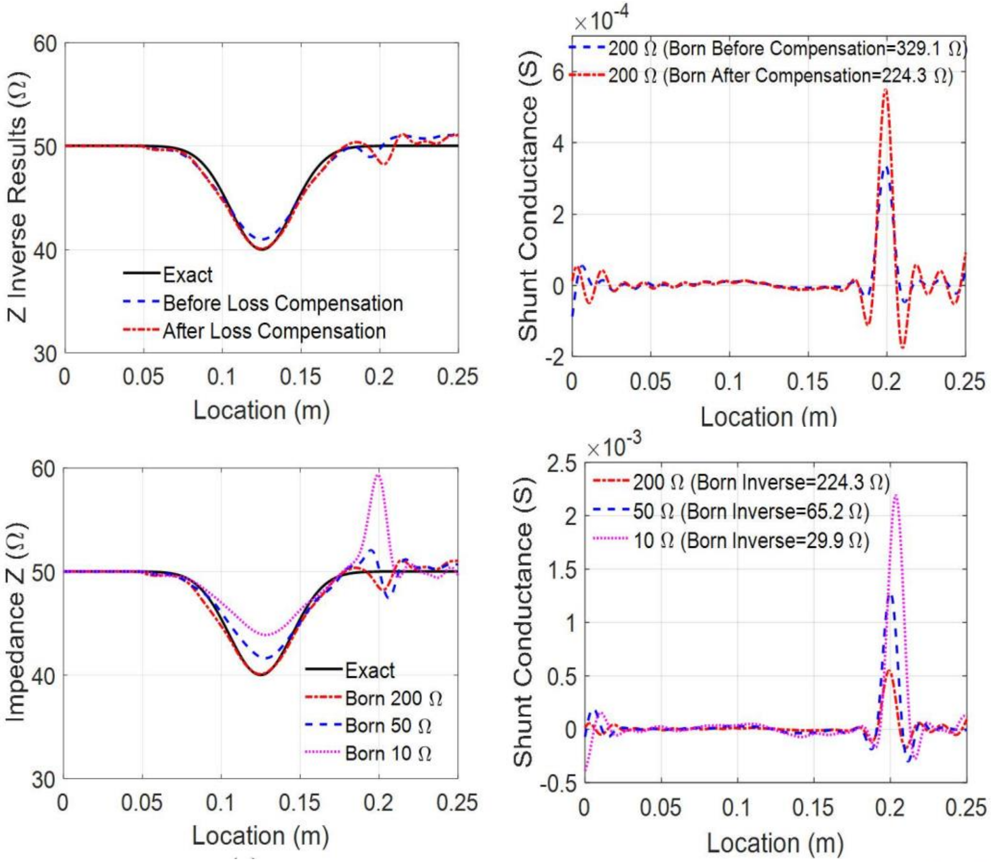
$$\Delta G(x)Z(x)/2\nu(x) \simeq \Delta G(x)Z(x)/2 < 1/4 \qquad \Delta G(x) < 1/[2Z(x)]$$



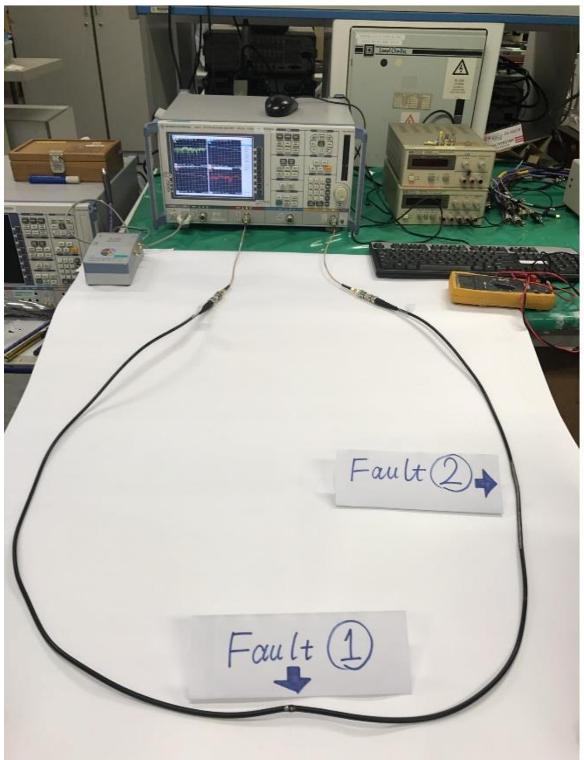


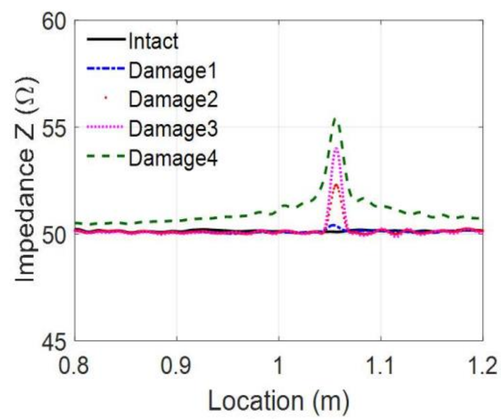
Experimental Results: Microstrip Line (FR4)

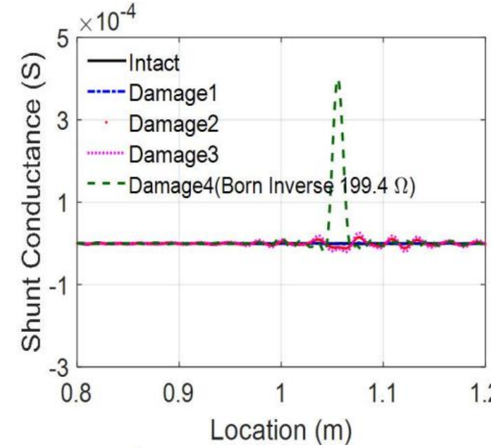


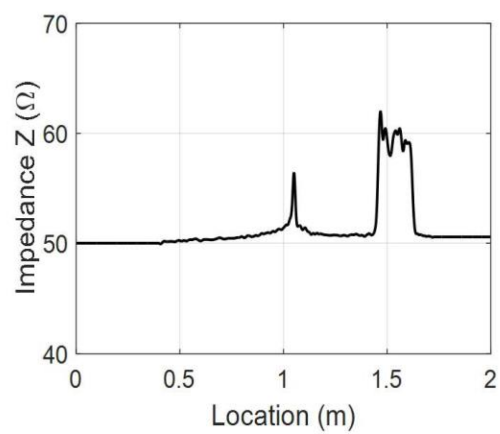


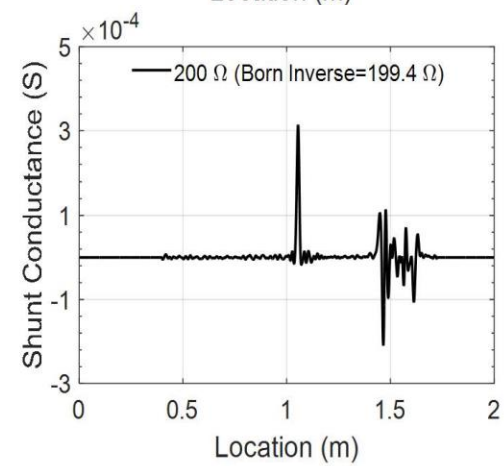
Experimental Results: Coaxial Cable











Summary of fault detection

- An analytical solution for reconstructing the spatial profile of the blockages (distributed impedance ***Z)*** and leaks (shunt conductance ***△G)***
- Explicit straightforward expression
- Separating the blockages from the leaks using full 2-port S-parameters of the transmission line.
- Using transmission loss measurements to estimate the frequency dependent losses along the line and compensating for them.
- Performing simulations and experiments to show that the technique performs well in a wide variety of cable and feedline configurations.

[1] L.Jing, W. Wang, Z. Li, R.D. Murch, "Detecting Impedance and Shunt Conductance Faults in Lossy Transmission Lines", IEEE Transactions on Antennas and Propagation, vol.66(7), pp.3678-3689, 2018.

[2] L.Jing, Z. Li, W. Wang, A. Dubey, P. Lee, S. Meniconi, B. Brunone, R.D. Murch, "An Approximate Inverse Scattering Technique for Reconstructing Blockage Profiles in Water Pipelines Using Acoustic Transients", the Journal of the Acoustical Society of America Express Letters, vol.143(5), EL322-327, 2018.

[3] W. Wang, L.Jing, Z. Li and R.D. Murch, "Utilizing the Born and Rytov Inverse Scattering Approximations for Detecting Soft Faults in Lossless Transmission Lines", IEEE Transactions on Antennas and Propagation, vol.65(12), 7233-7243, 2017.

Further Challenges

- Pipeline assessment is interested in deterioration- such as pipeline thickness, radius, pipeline material type
  - Can these be deduced from acoustic measurements?
  - Also includes estimations of L(z), C(z), R(z), G(z) in transmission lines
- Often pipelines and cables are networked together
  - What measurements are required to determine faults in networks
- What is the acoustic source
  - Mechanical valves too slow and not consistent, PZT transducers too low power
- How to handle alpha-stable noise in inverse methods
- Many other challenges:
  - Sensing Technology, Internet of Things, Robotic Fish, Energy Conservation, System Optimization, Cyber Security
- Other problems… determining building plans from WiFi signals

Pipeline Assessment

- Estimate pipeline parameters for deterioration

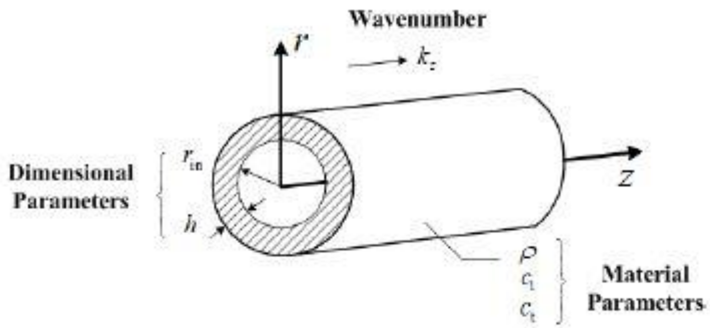
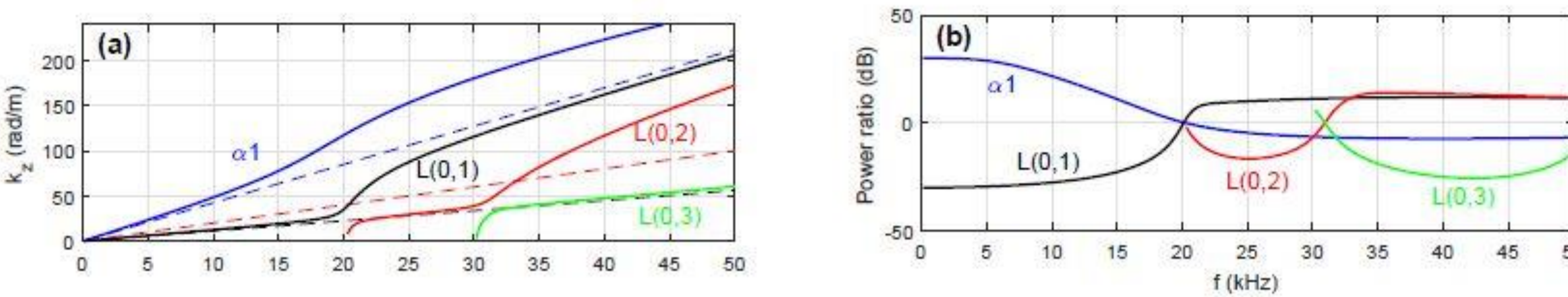


TABLE I
DIMENSIONAL AND MATERIAL PARAMETERS OF DIFFERENT WATER-FILLED PIPELINES.

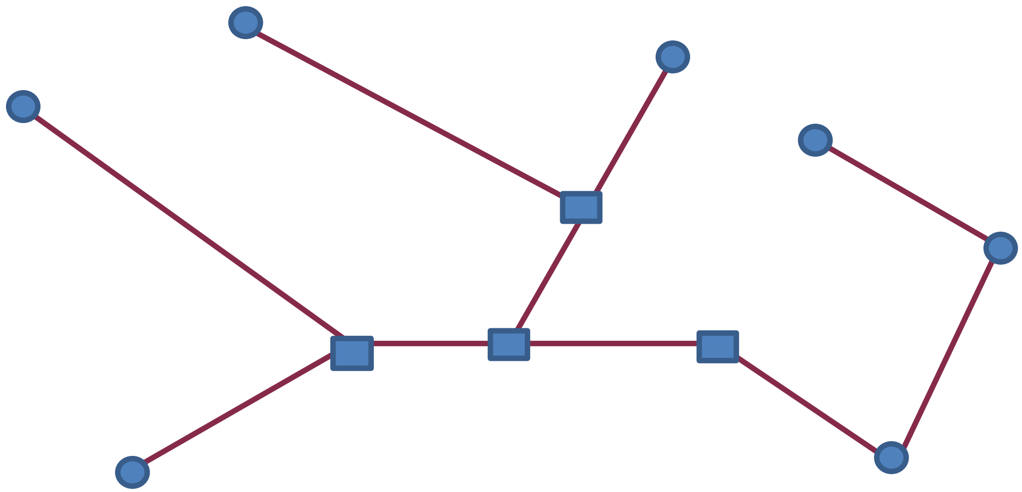
	r_{in} (mm)	h (mm)	ρ (g/cm^3)	c_l (m/ms)	c_t (m/ms)
P1 (Steel)	34.45	3.65	8	5.589	3.137
P2 (Steel)	36.45	1.65	8	5.589	3.137
P3 (Copper)	36.10	2.00	8.9	4.652	2.234
Water			1	1.48	



Z. Li, etal, " Nonlinear Bayesian Inversion for Estimating Water Pipeline Dimensional and Material Parameters Using Ultrasonic Wave Dispersion", *In preparation for submission to IEEE Transactions UFFC*, 2018

Extension to network

- Solutions of single pipes or cables but not networked



- Visible and hidden junctions
- Make use of graph theory and modes?
- Any known theoretical results?
- Can it be mapped to a 1D problem?

Conclusions

- Critical need for assessment of pipelines
- One method is to use acoustic signals in the pipelines in a format such as pipeline sonar
- Requires development of signal processing and communication techniques
- Have proposed that:
  - Acoustic noise in water pipelines is alpha-stable
  - Acoustic channel requires modeling of the elastic pipe wall- leads to waves that propagate in the wall and water with power switching between them
  - Special communication techniques for multimode waveguide transmission
  - Straightforward explicit expressions for blockage and leak detection
- Largely unexplored area- further research required

This is a large team effort

Funding

Hong Kong research grants council

Theme based funding and general research funding

Large interdisciplinary team

Civil: Ghidaoui, Lee, Dimitrakopoulos, Katafygiotis

Elec: Murch, Palomar, Mckay, Lau

Mech: Zhang

Math: Xu

HKUST

Lee Brunone Karney Yang Duan Zou Youcef-Tomi Zheng

Publications

- **Journal Papers**

[1] L.Jing, Z. Li, Y.Li and R.D. Murch, "Channel Characterization of Acoustic Waveguides Consisting of Straight Gas and Water Pipelines", *IEEE Access*, vol.6, pp.6807-6819, 2018.

[2] L.Jing, W. Wang, Z. Li, R.D. Murch, "Detecting Impedance and Shunt Conductance Faults in Lossy Transmission Lines", *IEEE Transactions on Antennas and Propagation,* vol.66(7), pp.3678-3689, 2018.

[3] L.Jing, Z. Li, W. Wang, A. Dubey, P. Lee, S. Meniconi, B. Brunone, R.D. Murch, "An Approximate Inverse Scattering Technique for Reconstructing Blockage Profiles in Water Pipelines Using Acoustic Transients", *the Journal of the Acoustical Society of America Express Letters*, vol.143(5), EL322-327, 2018.

[4] Z. Li, L.Jing and R.D. Murch, "Propagation of monopole source excited acoustic waves in a cylindrical high-density polyethylene (HDPE) pipeline", *the Journal of the Acoustical Society of America*, vol. 142(6), 3564-3579, 2017.

[5] W. Wang, L.Jing, Z. Li and R.D. Murch, "Utilizing the Born and Rytov Inverse Scattering Approximations for Detecting Soft Faults in Lossless Transmission Lines", *IEEE Transactions on Antennas and Propagation*, vol.65(12), 7233-7243, 2017.

[6] Y.Li, L.Jing, Z. Li and R.D. Murch, "Subcarrier Delay Spread Based Adaptive OFDM for Mobile Wideband Waveguide Channels", *IEEE Transactons on Communications*, vol.66(5), 2206-2218, 2018.

[7] Dubey, Amartansh, et al. (2018) "Measurement and Modeling of Acoustic Noise in water pipeline channel." *The Journal of the Acoustical Society of America, Manuscript in preparation.*

[8] Z. Li, L.Jing, W. Wang, P. Lee and R.D. Murch, "The influence of pipeline thickness and radius on guided wave attenuation in water-filled steel pipes: theoretical analysis and experimental measurement", *submitted to the Journal of the Acoustical Society of America*, 2018

[9] Z. Li, etal, " Guided acoustic wave interaction with flanged junctions in water-filled steel pipelines", *In preparation for submission to the Journal of the Acoustical Society of America*, 2018

[10] Z. Li, etal, " Nonlinear Bayesian Inversion for Estimating Water Pipeline Dimensional and Material Parameters Using Ultrasonic Wave Dispersion", *In preparation for submission to IEEE Transactions UFFC*, 2018

[11] W. Wang, Z. Li, L. Jing, P. Lee and R.D. Murch, "A Straightforward Method for Estimating the Size of Leaks in Water Pipelines using Acoustic Transients", submitted to the Journal of the Acoustical Society of America Express Letters, 2018

Publications

- **Conference Papers**

[1] L.Jing, Y. Li and R.D. Murch, "Wideband modeling of the acoustic water pipe channel." OCEANS 2016-Shanghai. IEEE, 2016.

[2] L.Jing, Z. Li and R.D. Murch, "Experimental Study of Acoustic Channel Characteristics of Rigid and Elastic Pipelines." OCEANS 2017-Aberdeen. IEEE, 2017.

[3] A. Dubey, L. Jing, Z. Li, P. Lee and R.D. Murch, "Measurement and Analysis of Acoustic Noise in Water Pipeline Channels", *OCEANS 2018-Kobe*, IEEE, 2018.

[4] Z. Li, L. Jing, W. Wang, Y. Li, A. Dubey, P. Lee and R.D. Murch, "Experimental Measurement and Analysis of Acoustic Wave Propagation in Water-filled Steel Pipeline Using the Iterative Quadratic Maximum Likelihood Algorithm, *175th Meeting of Acoustical Society of America*, Minneapolis, 2018.