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Modeling and Visualization for Imaging of Subsurface Damage

Neil Goldfine, Scott Denenberg, Brian Manning, Zachary Thomas
JENTEK Sensors, Inc., 110-1 Clematis Avenue, Waltham, MA 02453-7013

Rasheed Al Rushaid, Frederick Haught
Al Rushaid Technologies Co., Al Turki Business Park, Office Villa #4; 7244 King Saud Road,
Ad Doha Al Janubiyah, Dhahran 34455, Kingdom of Saudi Arabia

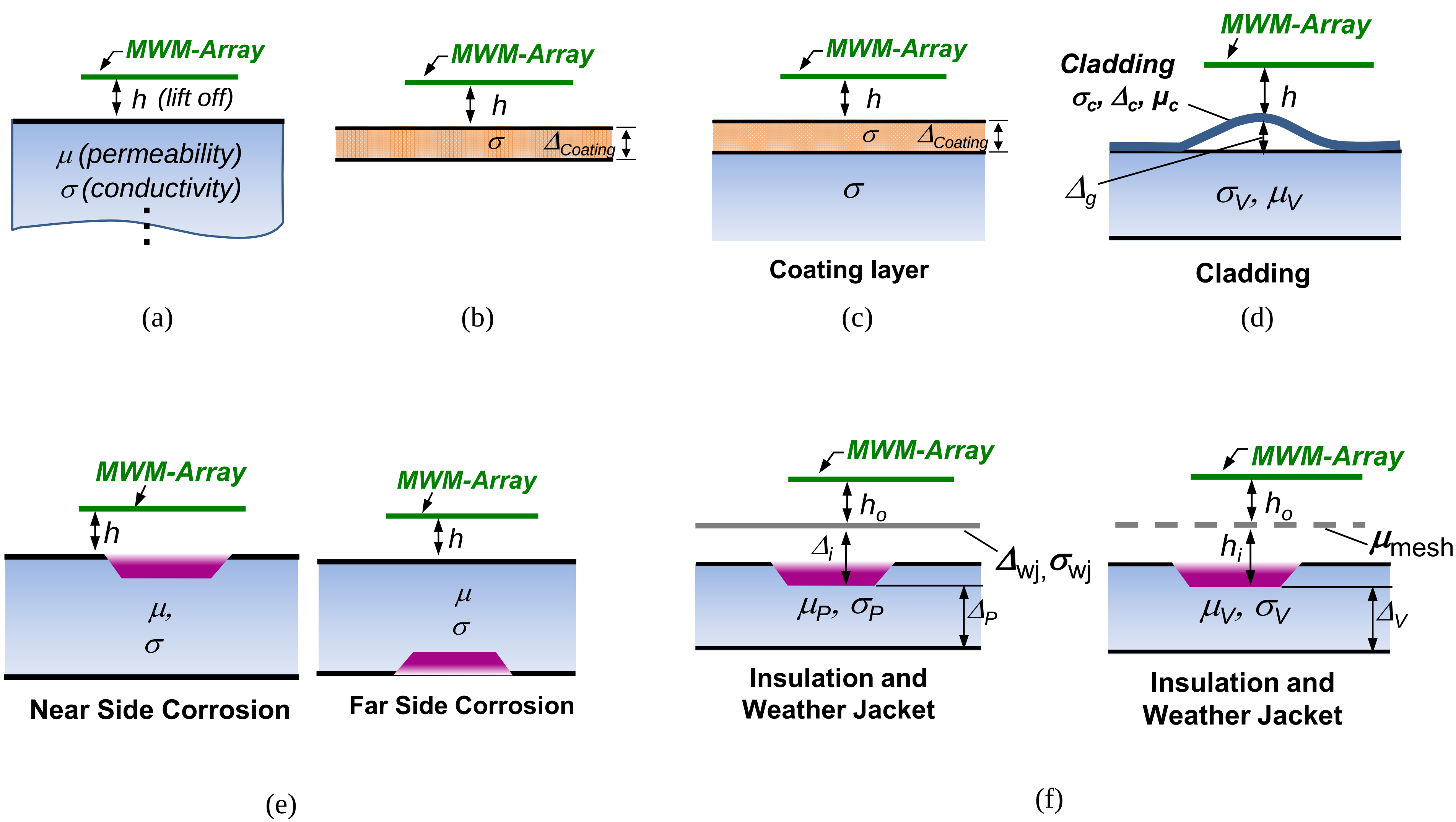
Outline

- **Practical Applications**
- **Problem Definitions:** ***From Simple to Complex***
- **Sensing Methodology**
- **HyperLattice Databases**
- **Example Results**
- **Summary**

Practical Applications

1. Internal **and** external corrosion imaging through
   - Insulation
   - Concrete with wire mesh (fireproofing, weight coat)
   - Other coatings
2. Hydrogen blister imaging (*through cladding overlay*)
3. Buried crack detection
4. Coating characterization
5. In-line inspection for surface and subsurface defects
6. Stress mapping from outside and inside pipelines, structures

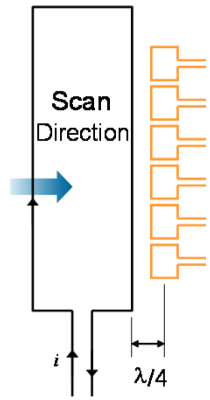
Problem Definitions: from simple to complex



Sensing Methodology

1. Sensors: MWM®-Arrays

- **Paradigm shift** in sensor design (first priority is predictable response based on physics-based modeling)



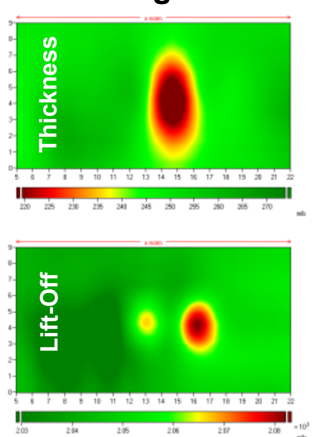
2. Next Generation Electronics

- 10x signal-to-noise improvement
- Very low frequencies (deep penetration)
- Crack detection through up to 0.5 inches of material
- Reduced drift

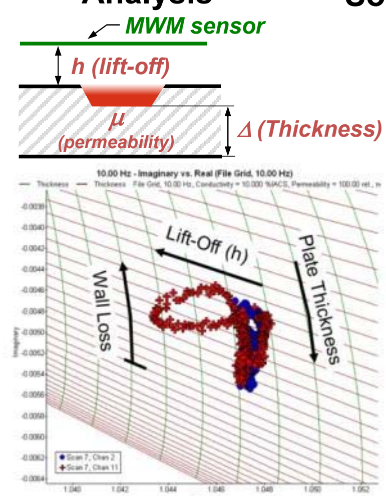
3. GridStation Software using HyperLattices®

- **Rapid, autonomous data analysis** Performs multivariate inverse method (MIM) using precomputed databases
  - Defect Images
  - Performance Diagnostics
  - Noise Suppression

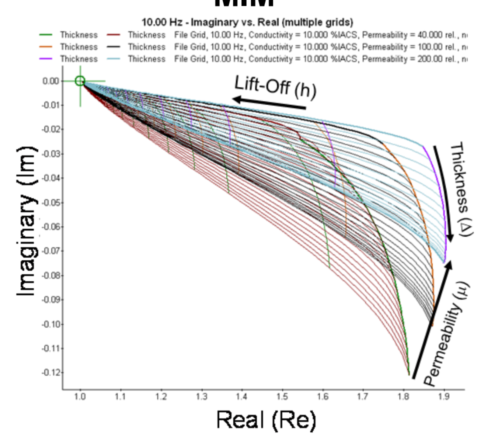
Images



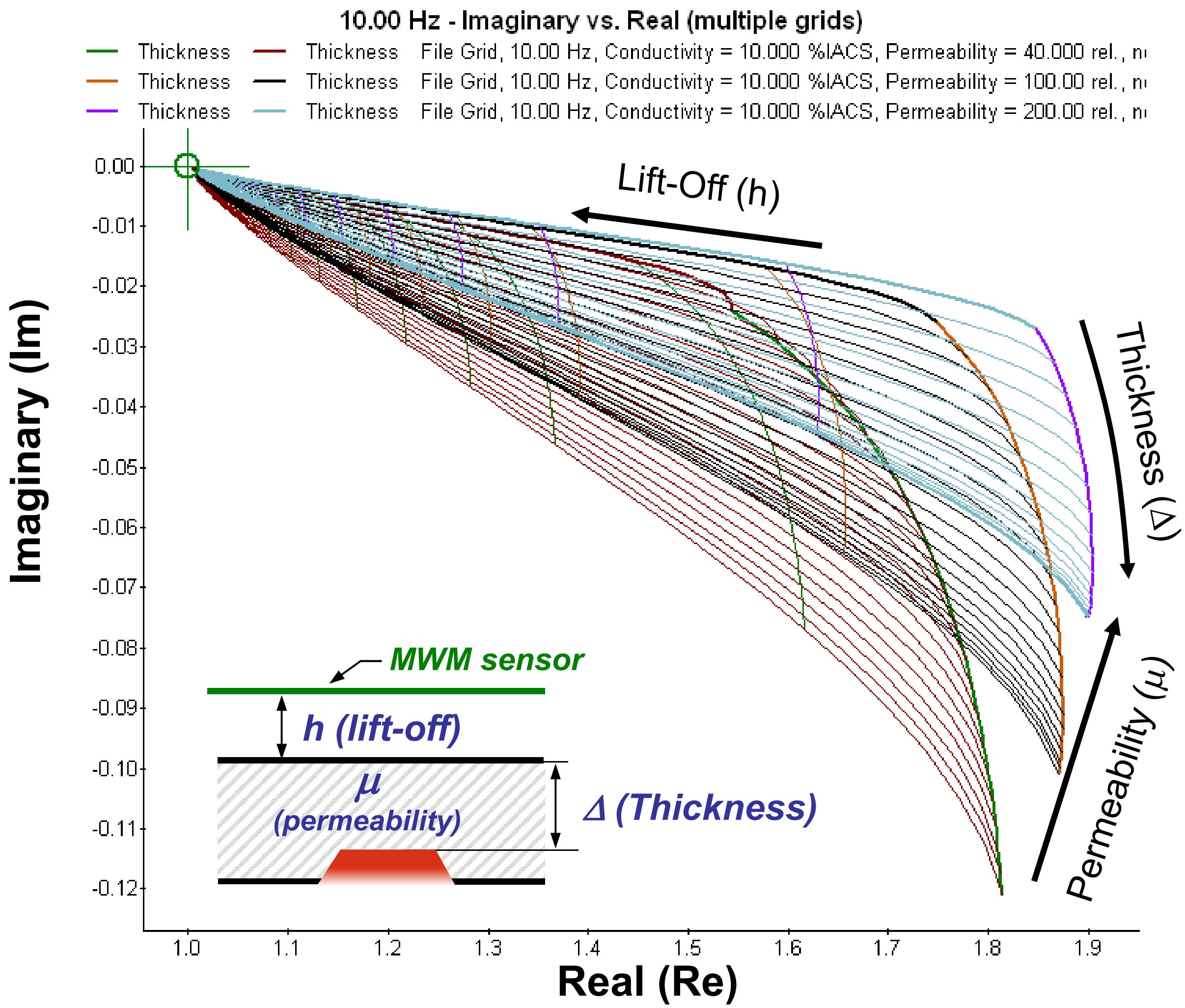
Analysis



Solve Multiple Unknown Problems MIM



Definition of Real and Imaginary Parts of the complex Transimpedance Z=v/jωi



$\omega = 2\pi f$

- GridStation Lattices for MR-MWM-Array **wall loss imaging**
- Used for **external and internal** wall loss imaging

|Z| = Magnitude

θ = Phase

$$|Z| = \sqrt{Re^2 + Im^2}$$

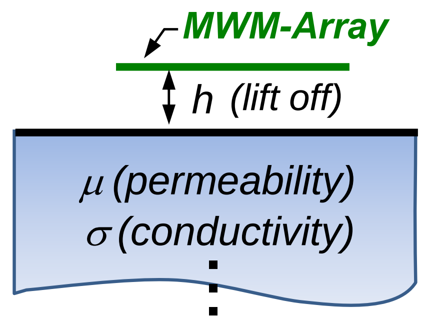
$$\theta = \arctan(Im/Re)$$

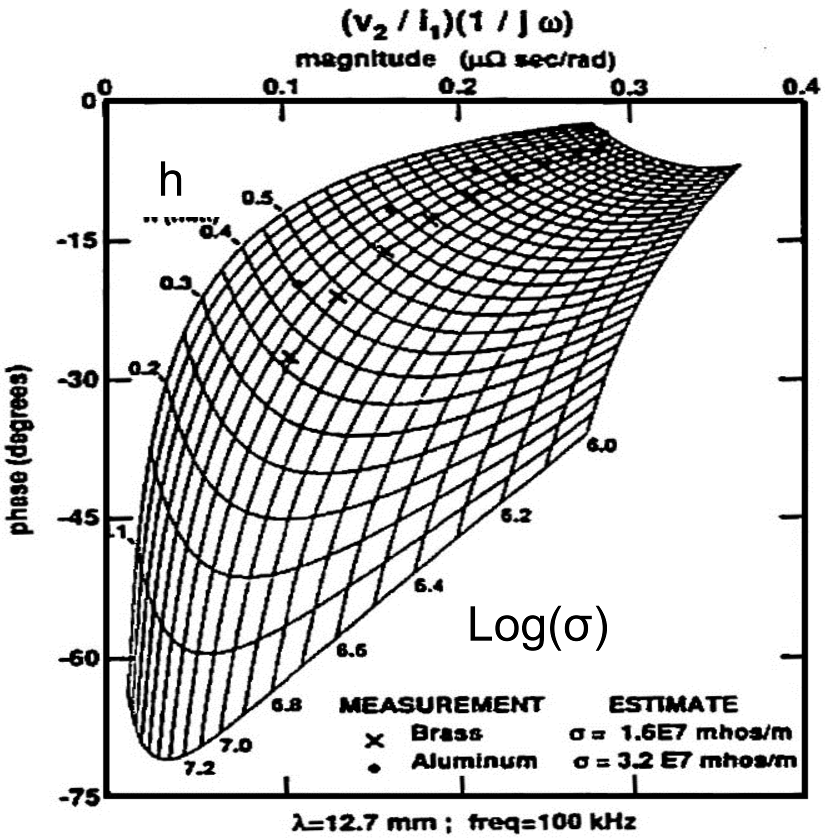
$$Re = |Z|\sin(\theta)$$

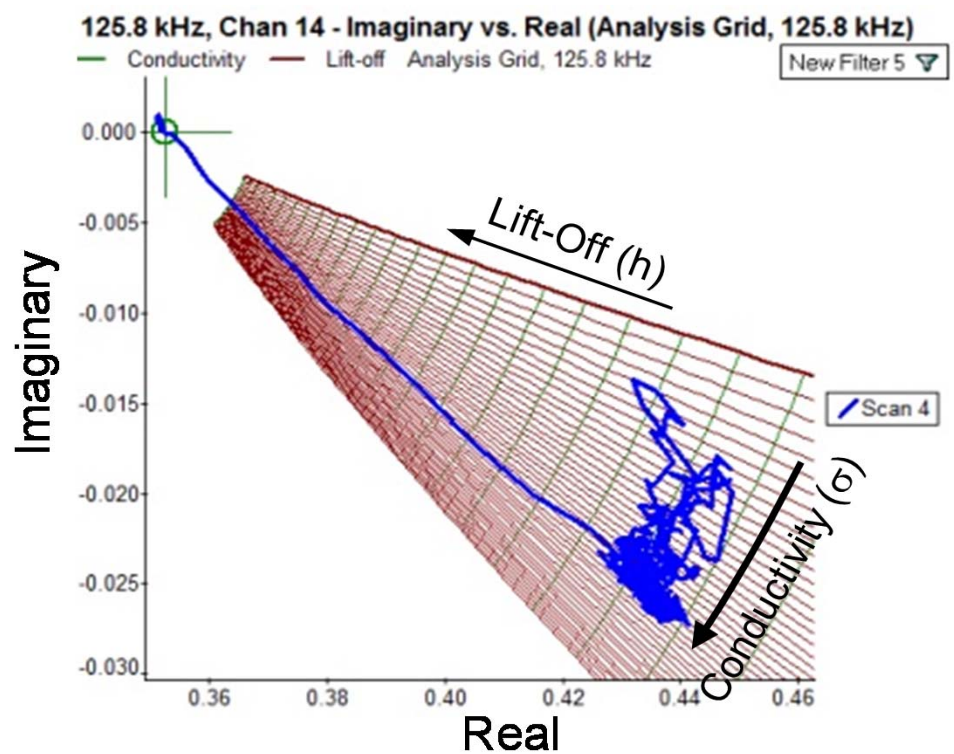
$$Im = |Z|\cos(\theta)$$

HyperLattices (precomputed response databases)

a) 2- Unknowns: conductivity (σ) and lift-off (h), with magnetic permeability (μ) assumed constant

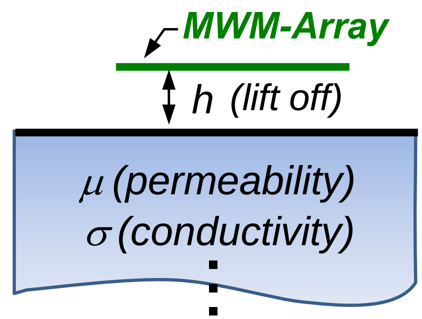


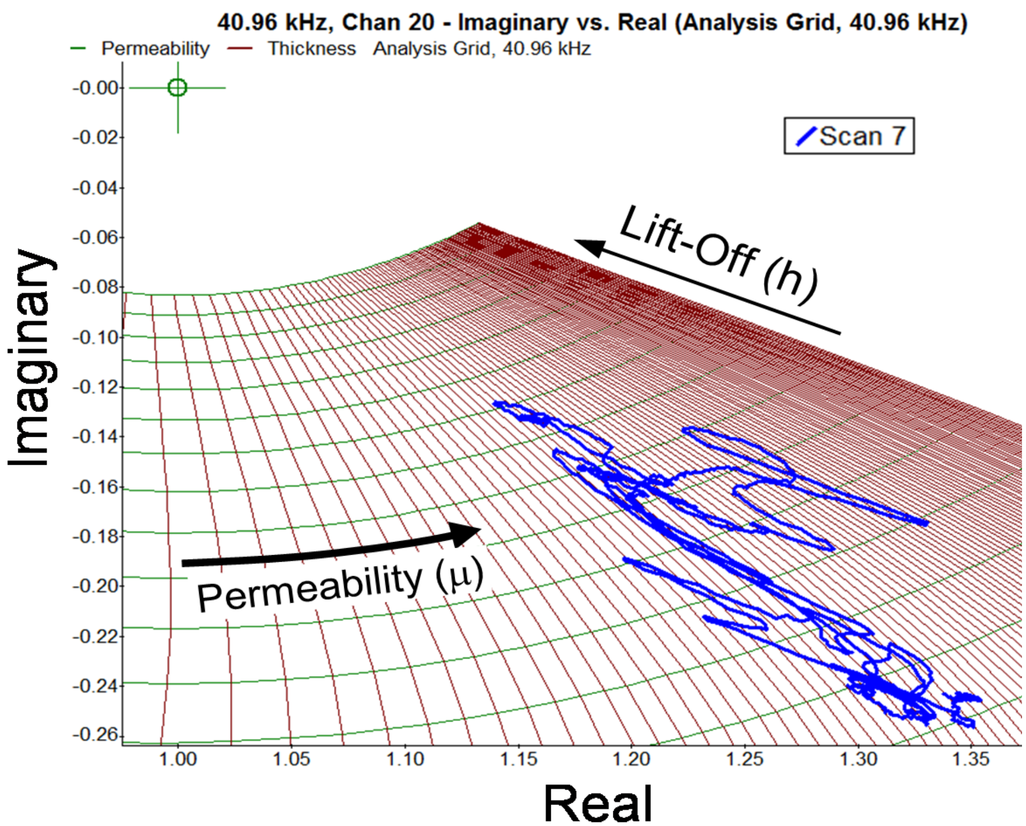




HyperLattices (precomputed response databases)

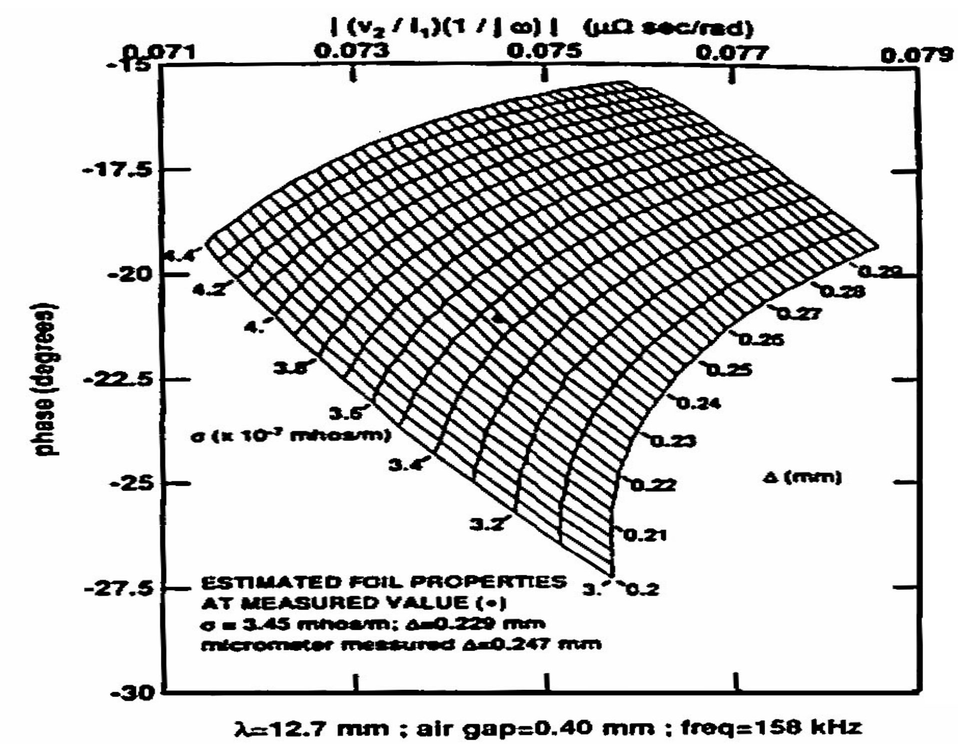
a) 2- Unknowns: magnetic permeability (μ) and lift-off (h), with conductivity (σ) assumed constant

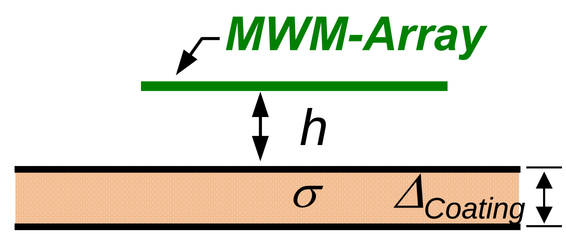




HyperLattices (precomputed response databases)

b) 3- Unknowns: coating conductivity, coating thickness, and lift-off, using hierarchical method.
Grid is for conductivity and thickness of the coating.
The lift-off is determined at a higher frequency, taken simultaneously.

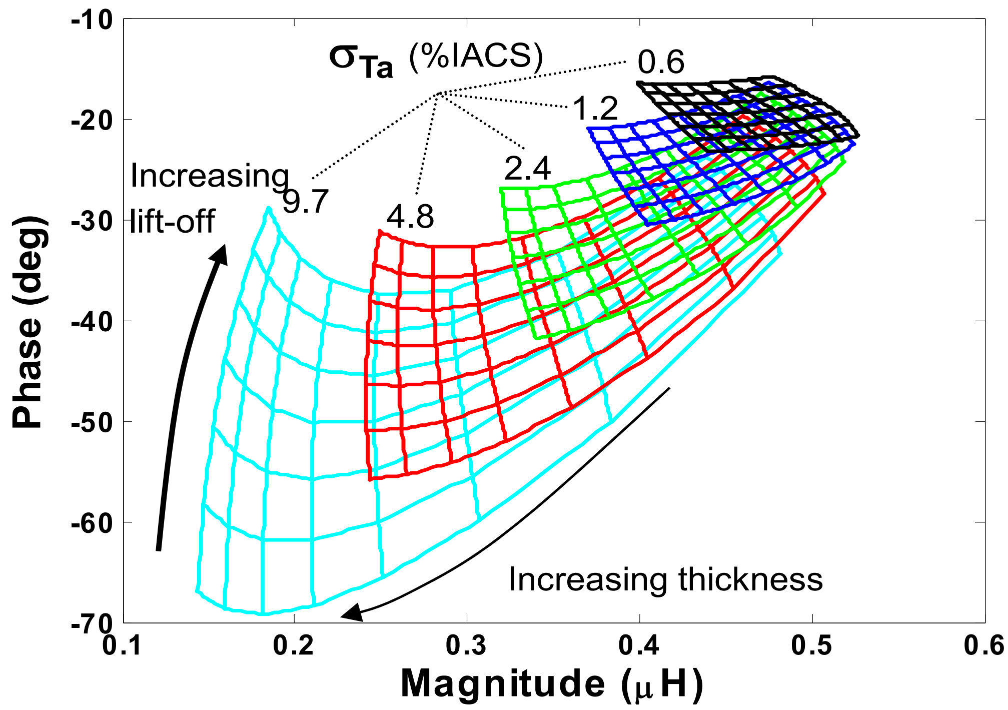


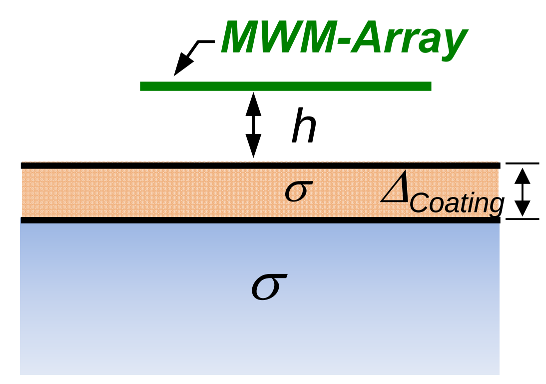


HyperLattices (precomputed response databases)

c) 3-Unknowns: coating thickness, coating conductivity, and lift-off. Two frequencies are needed.

Each frequency provides two equations to solve for up to two unknowns. Two frequencies is enough for 3 or 4 unknowns.

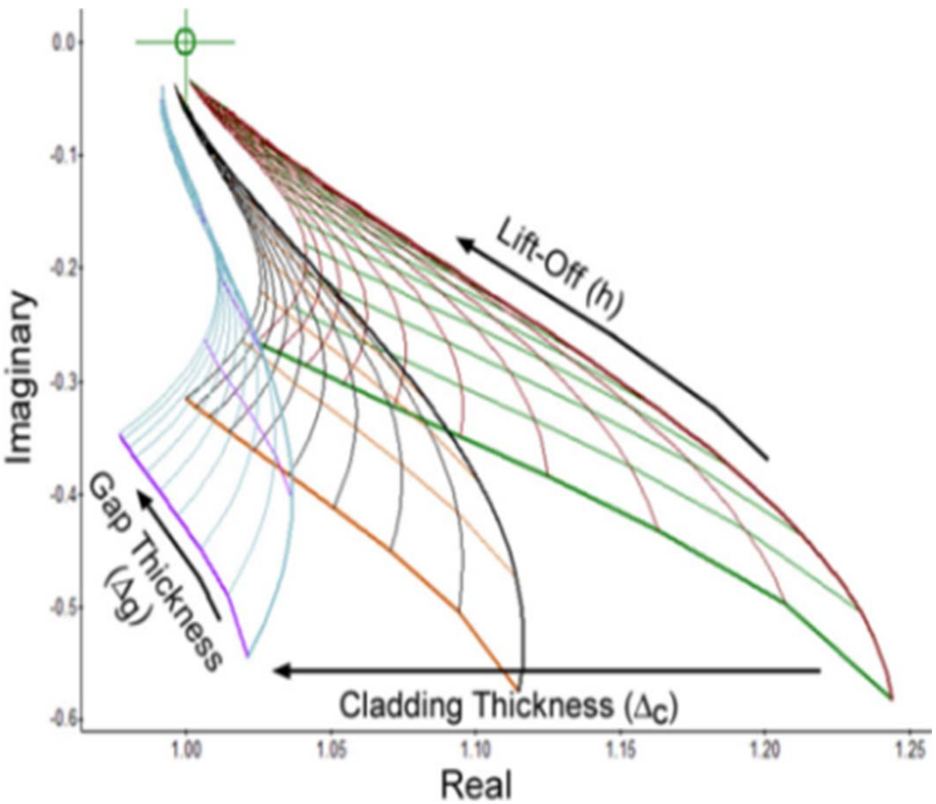


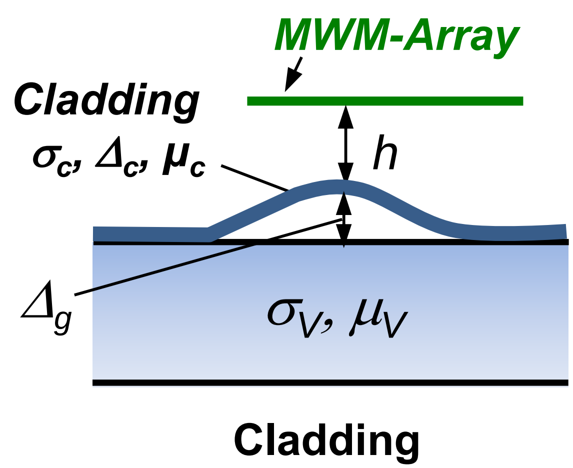


Coating layer

HyperLattices (precomputed response databases)

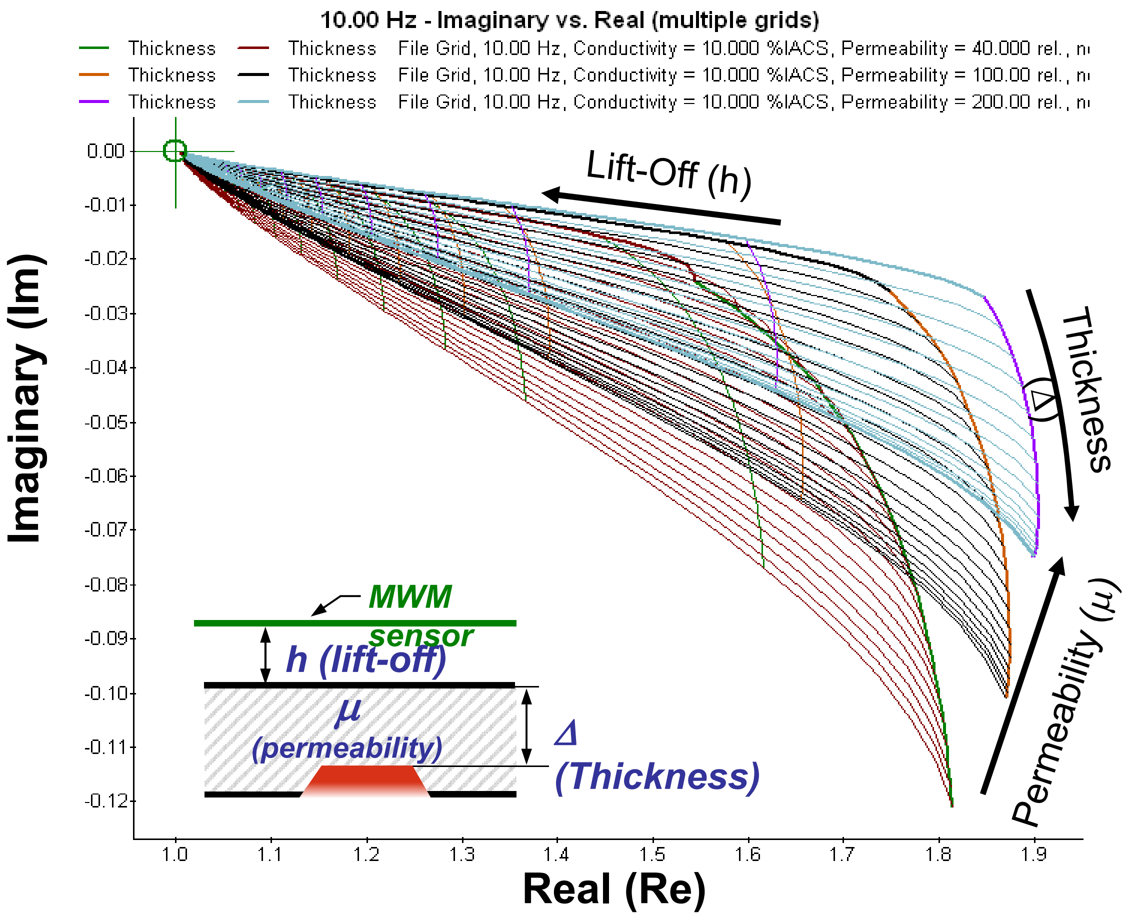
d) 3- Unknowns: cladding thickness, blister gap, and lift-off

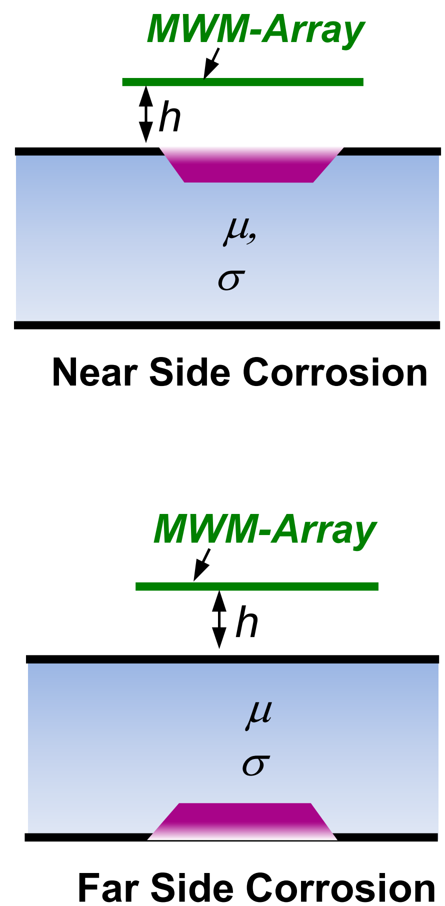




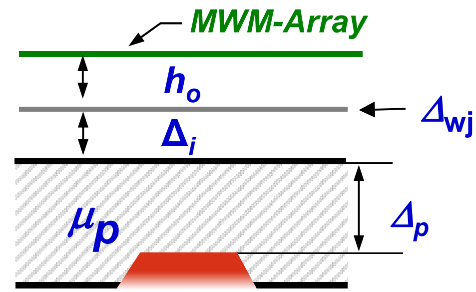
HyperLattices (precomputed response databases)

e) 3- Unknowns: pipe wall permeability, pipe wall thickness, and lift-off





Scanners and Implementation in the plant



$h, \Delta_{wj}, \Delta_i, \Delta_p, \mu_p$

h_o = distance between sensor & external surface of weather jacket

Δ_{wj} = weather jacket thickness

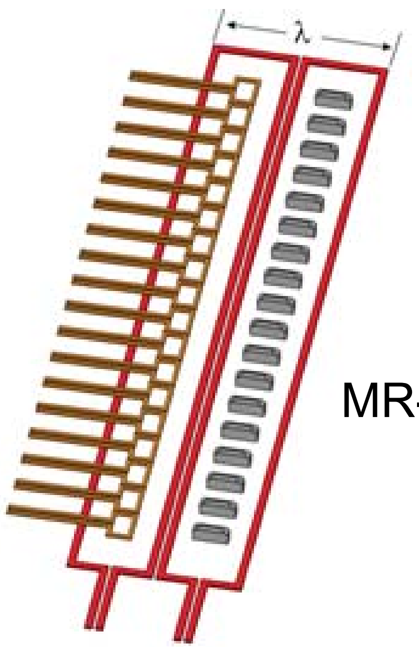
Δ_i = insulation thickness + external metal loss

Δ_p = remaining pipe wall thickness

μ_p = pipe magnetic permeability

Sensor Selection

- Decay rate determined by skin depth at high frequency and sensor dimensions at low frequency
- Large dimensions needed for thick coatings/insulation
- Low frequencies needed to penetrate through steel pipe wall



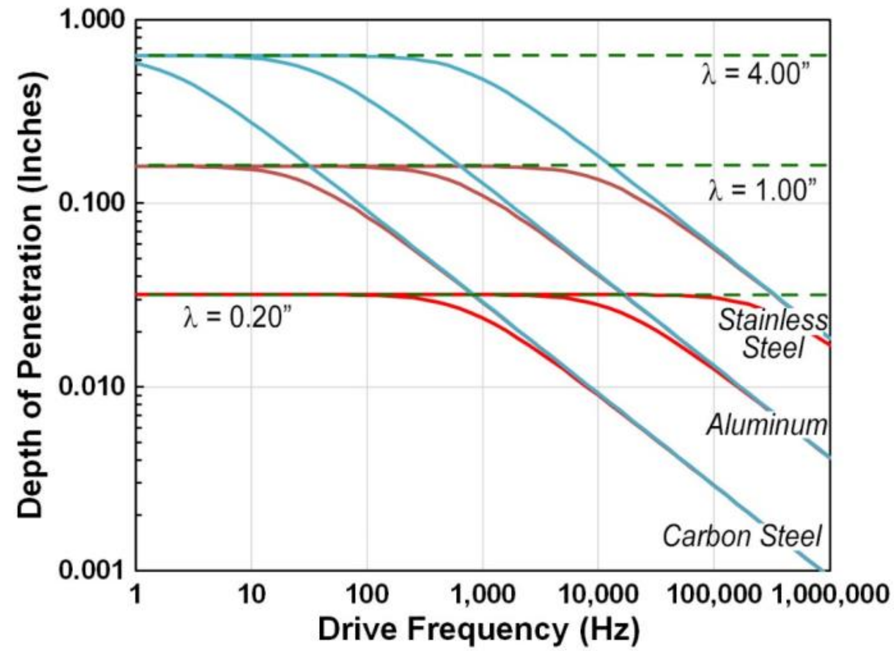
MR-MWM-Array

Depth of Penetration = $1/\mathrm{Re}(\Gamma_n)$

Low Frequency Limit = $\frac{\lambda}{2\pi}$

$$\Gamma_n = \sqrt{(2\pi n/\lambda)^2 + j2/\delta^2}$$

Skin depth: $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$



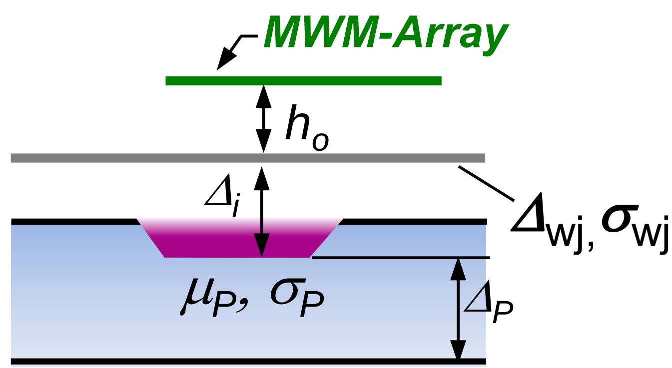
1 inch = 25.4 mm

HyperLattices (precomputed response databases)

(f, left) 5- Unknowns:

1. pipe wall permeability,
2. pipe wall thickness,
3. weather jacket thickness (assume conductivity)
4. insulation thickness
5. lift-off (distance to weather jacket)

Can't visualize easily



Insulation and Weather Jacket

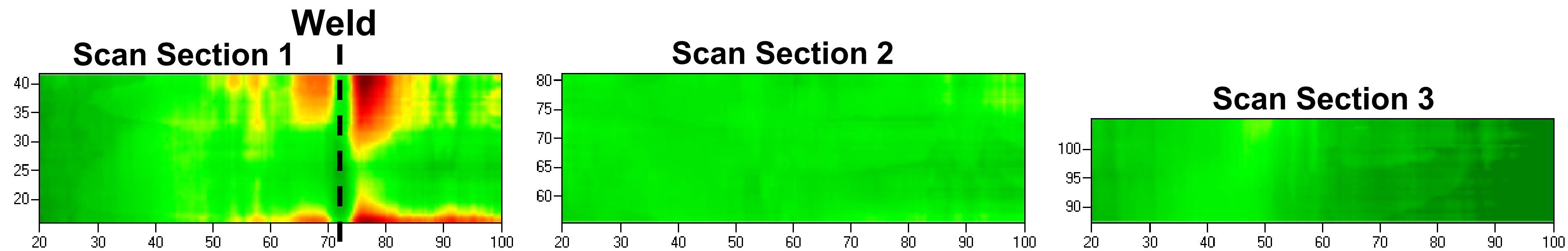
Example: Corrosion Imaging on Refinery Piping

Inspection was performed with the pipe in production at high temperature

CUI Performance Evaluation Results (July 2013)

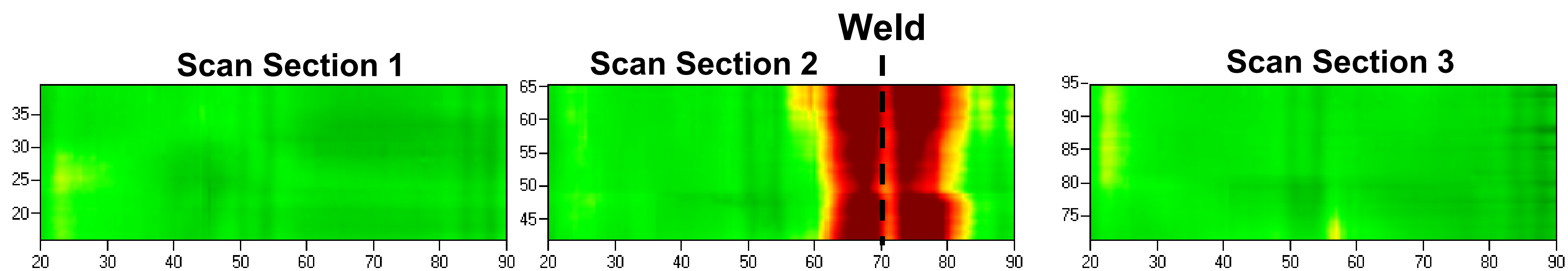
Internal Corrosion – Sample A

16” Schedule 80 (0.500” wall)
2” insulation with aluminum weather jacket
0.100” max wall loss (20%) over 20-25 inches (full circumference)



Internal Corrosion – Sample B

16” Schedule 80 (0.500” wall)
2” insulation with aluminum weather jacket
0.175” max wall loss (35%) over 20-25 inches (full circumference)

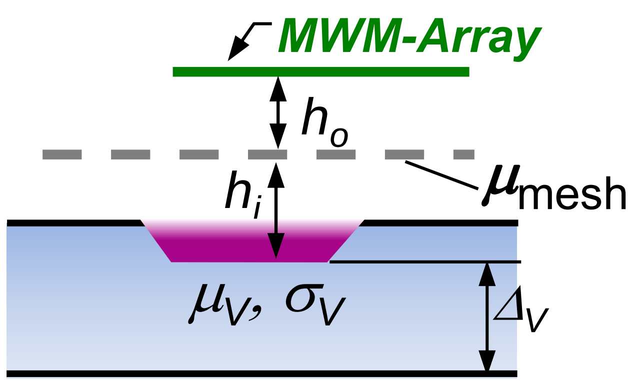


HyperLattices (precomputed response databases)

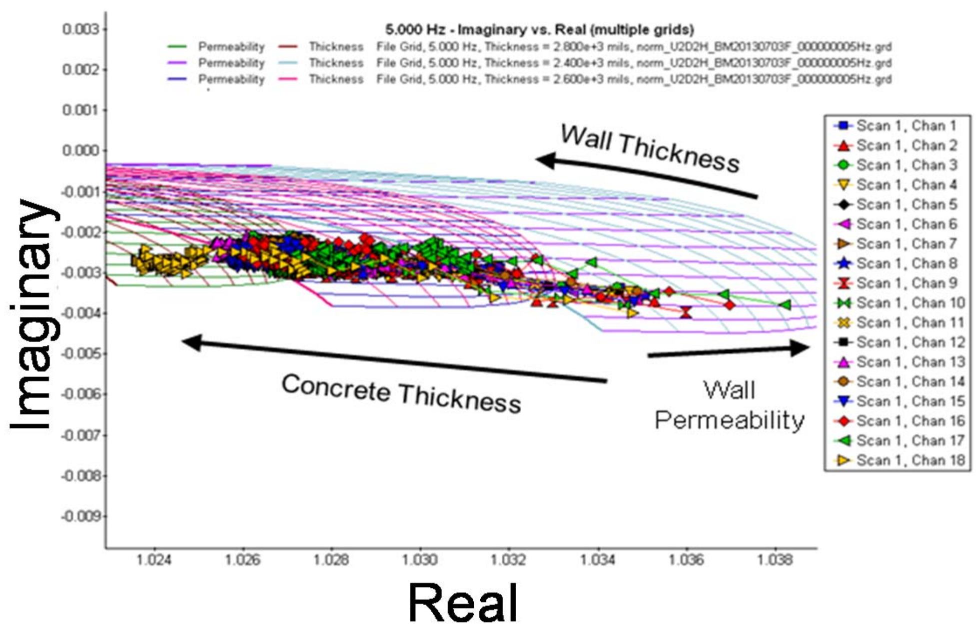
(f, right) 5- Unknowns:

1. vessel wall permeability,
2. vessel wall thickness,
3. , 4., permeability and position of wire mesh (simple layer)
5. vessel wall permeability

Can’t visualize easily

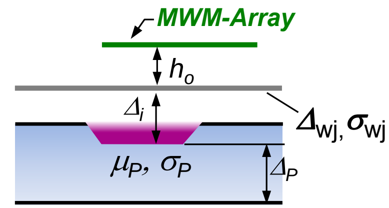


Insulation and Weather Jacket



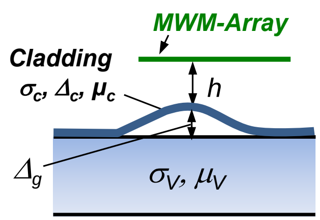
Summary

1. **Internal and external corrosion imaging through**
   - Insulation
   - Concrete with wire mesh (fireproofing, weight coat)
   - Other coatings



Insulation and Weather Jacket

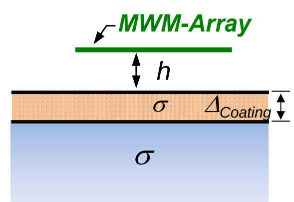
2. **Hydrogen blister imaging (through cladding overlay)**



Cladding

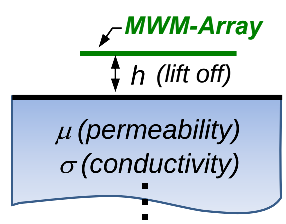
3. **Buried crack detection**

4. **Coating characterization**



Coating layer

5. **In-line inspection for surface and subsurface defects**



6. **Stress mapping from outside and inside pipelines, structures**