15 Mar 2018

Microwave Materials Characterization and Imaging for Structural Health Monitoring

Reza Zoughi
Missouri University of Science and Technology, zoughi@mst.edu

INSPECTING AND PRESERVING
INFRASTRUCTURE THROUGH
ROBOTIC EXPLORATION

INSPIRE University Transportation Center Webinar

Microwave Materials Characterization and Imaging for Structural Health Monitoring

March 15, 2018



R. Zoughi

Applied Microwave Nondestructive Testing Lab. (*amntl*)
Electrical and Computer Engineering Department
Missouri University of Science and Technology (S&T)
(Formerly University of Missouri-Rolla)
Rolla, MO 65409
zoughi@mst.edu
http://amntl.mst.edu/
(573) 341-4656

Outline

- Why microwaves.
- Microwave materials characterization.
- Contributions to SHM.
- Examples of cement-based materials characterization.
- Chloride permeation and ASR.
- Holographical imaging and steel rebar corrosion detection.
- 3D real-time microwave imaging principles & "Microwave Camera".

Why μ- & mm-Wave NDT&E

- Limitation associated with "standard" techniques.
- These signals penetrate into dielectric materials, and composites.
- Sensitive to dielectric property variation:
  - ✓ abrupt (boundaries)
  - ✓ local (inclusions)
  - ✓ gradual (gradient in material change).
- Polarization, frequency, measurement parameter (near-field vs. far-field) & probe type diversity-degrees of freedom.
- Correlation of microwave properties to physical, chemical and mechanical properties.

Why μ- & mm-Wave NDT&E

- Coherent properties – magnitude & phase.
- Large available bandwidth.
- Life-cycle inspection possibilities.
- Electromagnetic modeling (analytical, numerical and empirical).
- On-line and real-time inspection.
- Operation in industrial environments.
- Little to no need for operator expertise.
- Relatively inexpensive.

amntl

MISSOURI S&T

μ- & mm-Wave Spectra

X-Band
8.2-12.4

Ku-Band
12-18

K-Band
18-26.5

Ka-Band	Q-Band	V-Band	W-Band	D-Band
26.5-40	33-50.5	50-75	75-110	110-170

Microwave Characterization of Cement-Based Materials

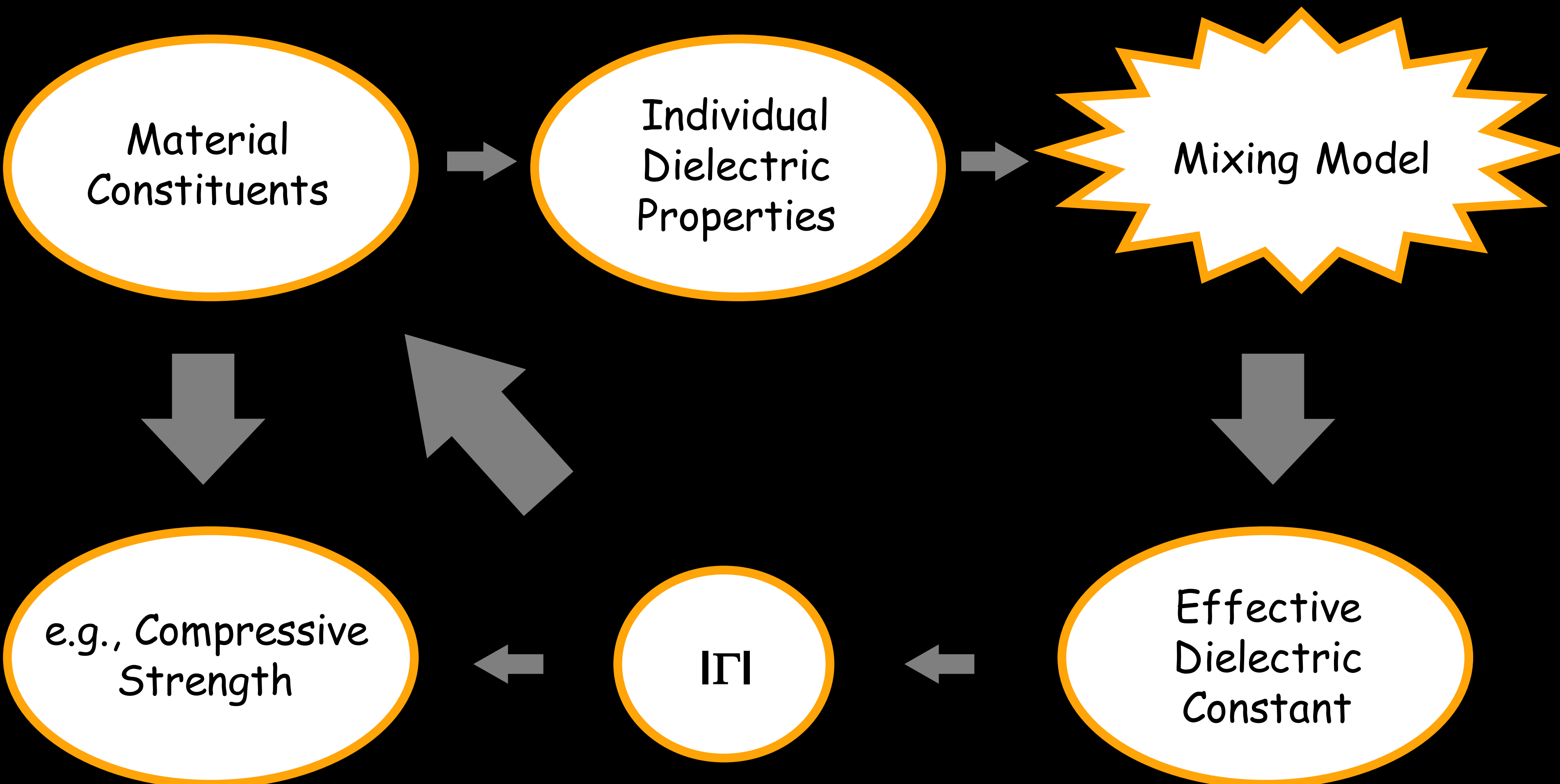
Microwaves & Materials

- Interaction of materials with microwave signals is macroscopically described by the complex dielectric constant - $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$
- It describes the ability of a material to store and absorb microwave energy.
- It depends on material chemistry, mixture content, etc. – e.g. bound vs. free water.
- It can be measured in many different ways.
- Microwave signal properties are directly influenced by this parameter.

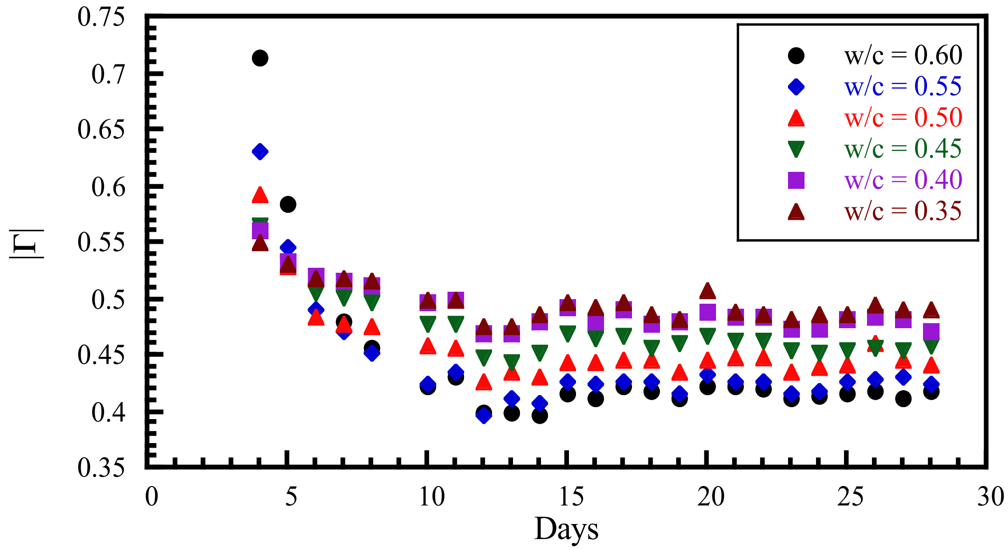
Contributions

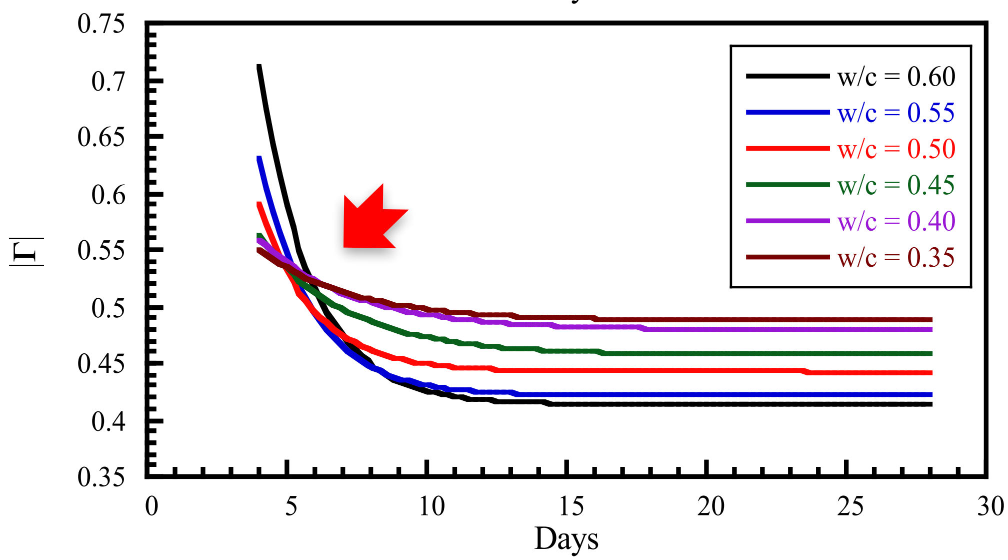
- **NDT applications for SHM:**
  - ✓ Concrete materials characterization (w/c, s/c, ca/c) & correlation with compressive strength
  - ✓ Chloride permeation assessment
  - ✓ ASR development, evolution & assessment
  - ✓ Steel fiber density assessment
  - ✓ Steel rebar corrosion detection & imaging
  - ✓ Glass rebar detection & imaging
  - ✓ CFRP-strengthened member inspection & imaging
- **EM modeling.**

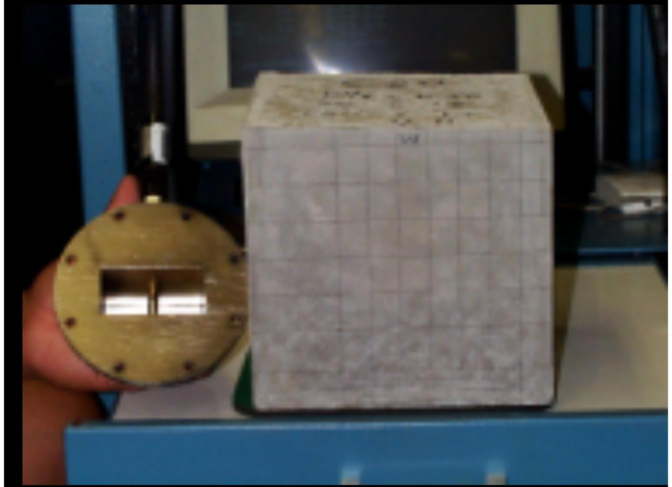
Correlation to Materials



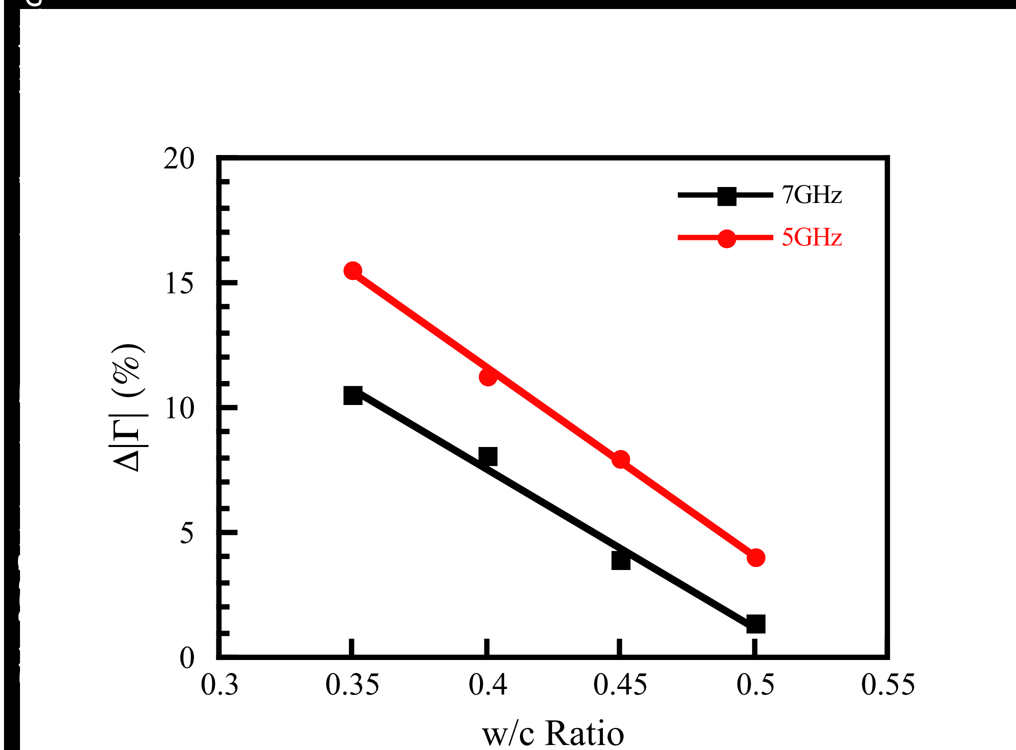
Hardened Paste @ 3 GHz vs. w/c

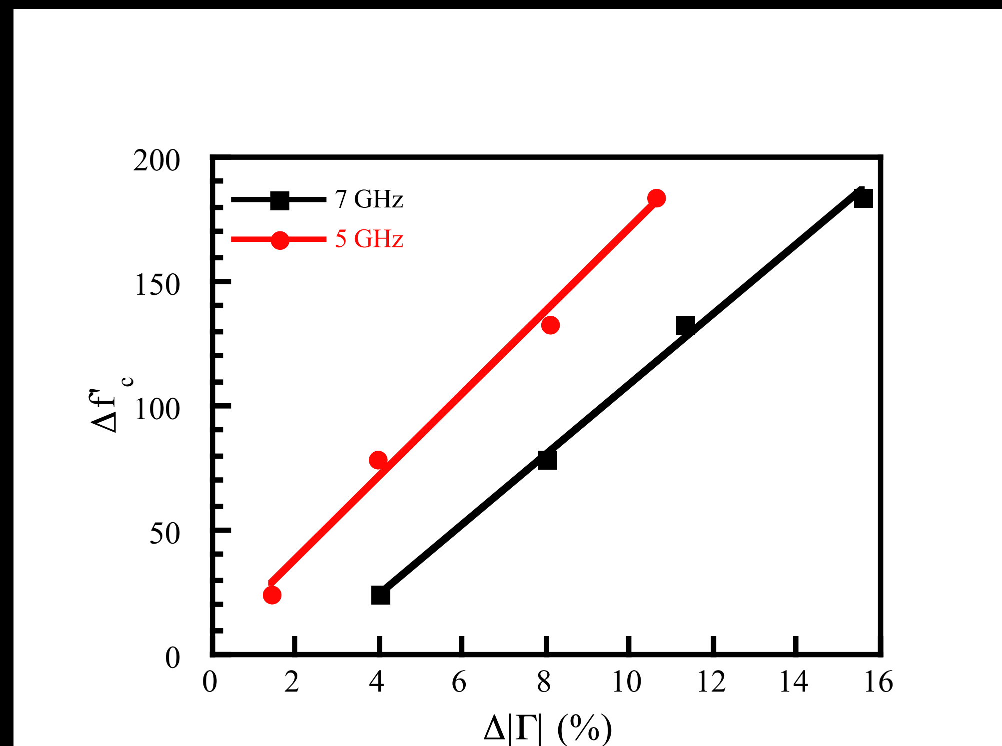




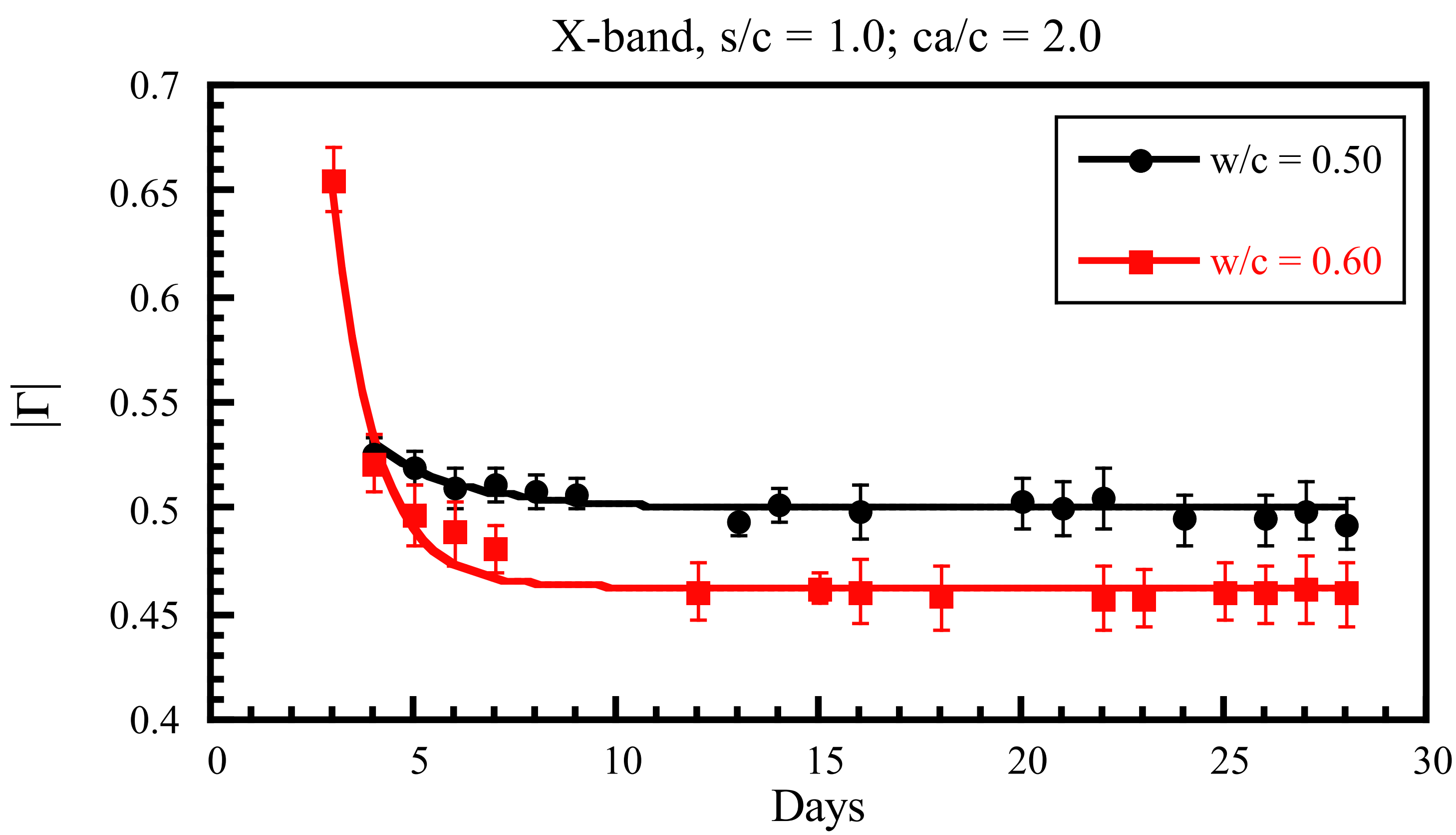


Cement Paste |Γ| vs. w/c & C.S.





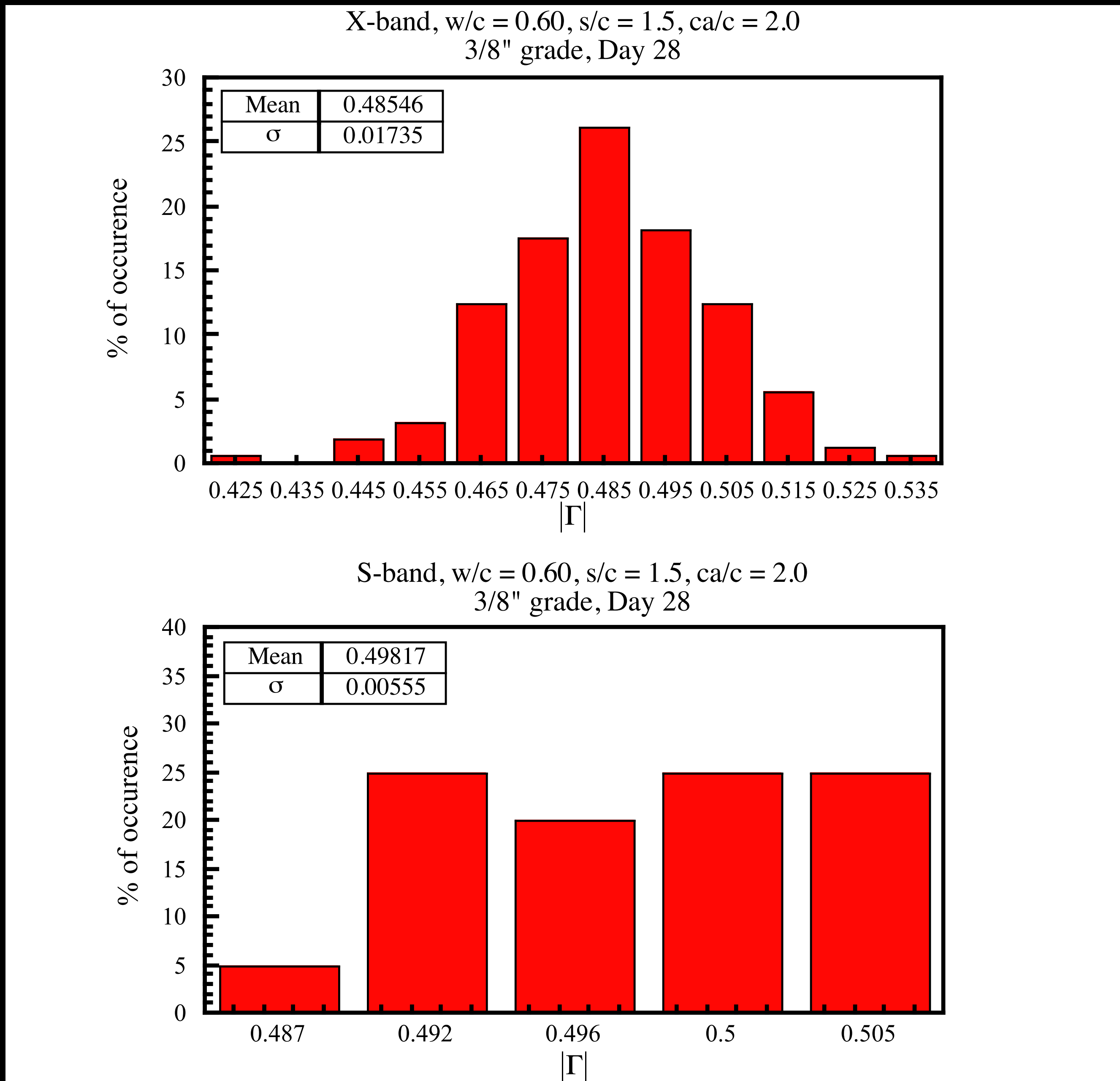
Concrete @ 10 GHz



INSPIRE University Transportation Center Webinar

MISSOURI S&T

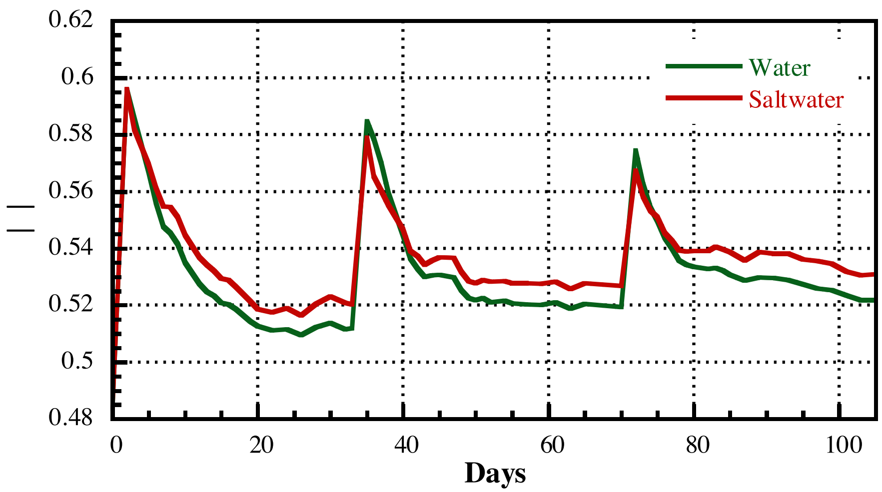
Hardened Concrete @ 10 & 3 GHz

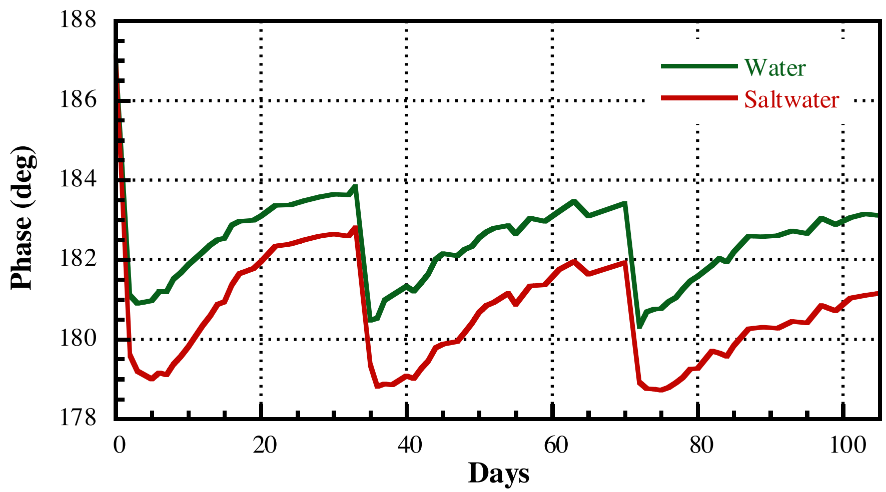


INSPIRE University Transportation Center Webinar

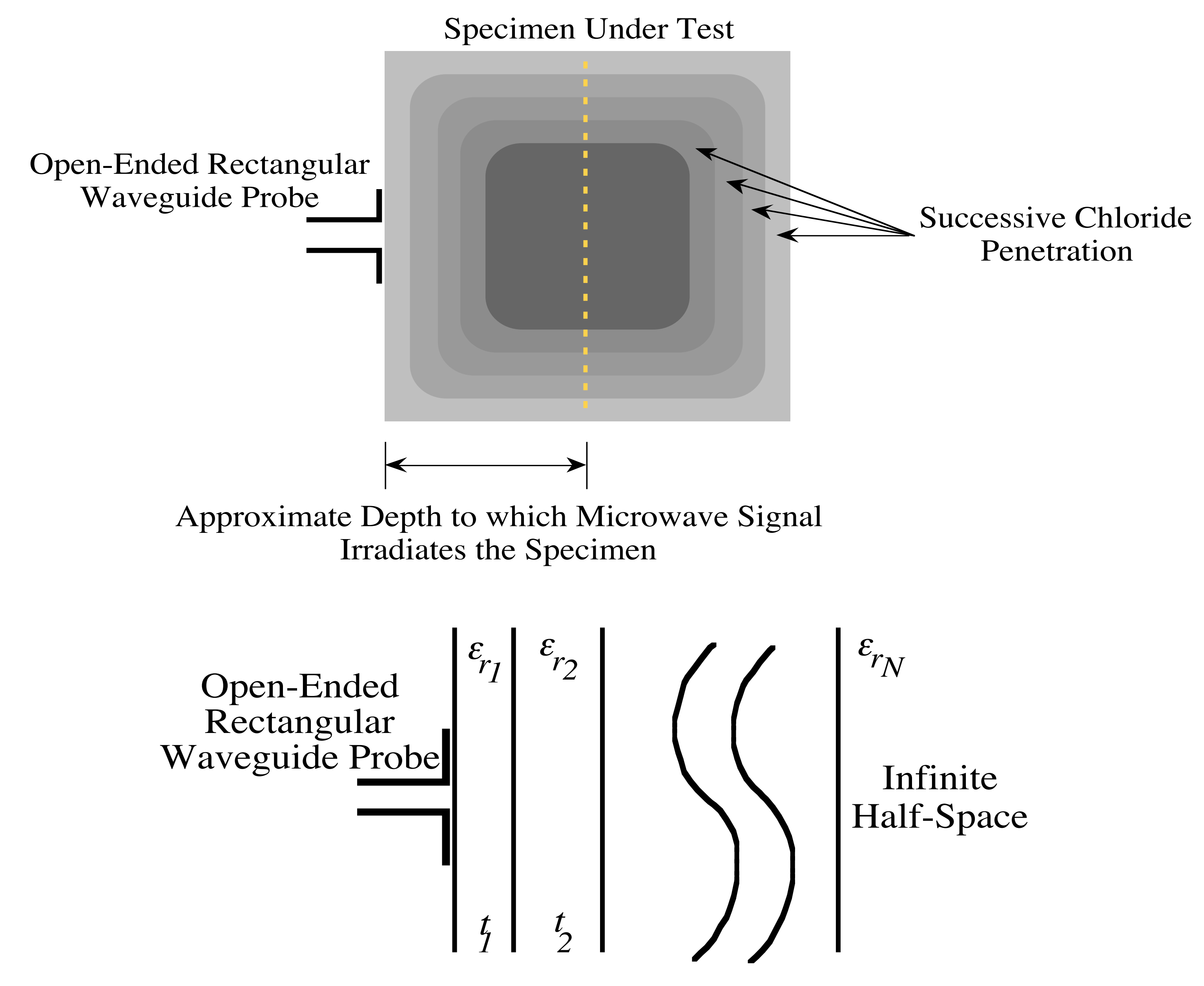
MISSOURI S&T

Salt Water Permeation in Mortar @ 3 GHz





Salt Water Permeation in Mortar @ 3 GHz



INSPIRE University Transportation Center Webinar

MISSOURI S&T

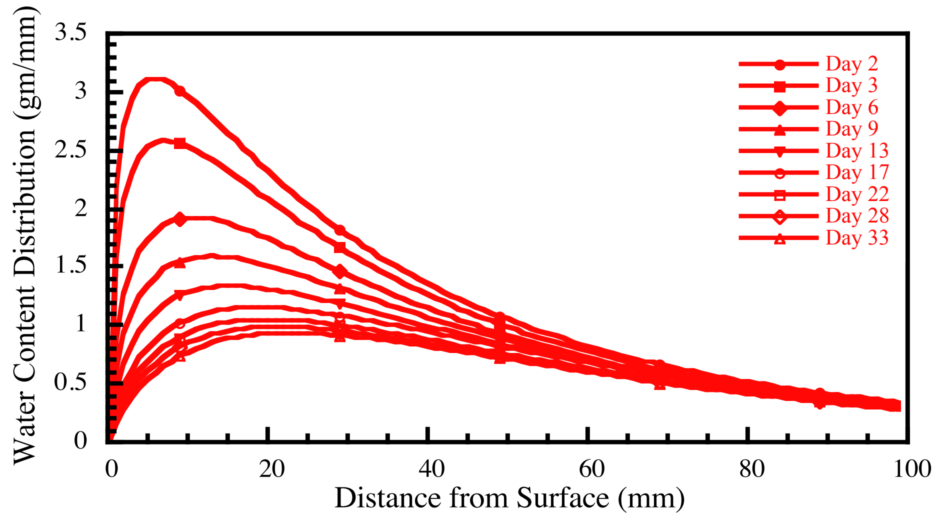
Modeling Process

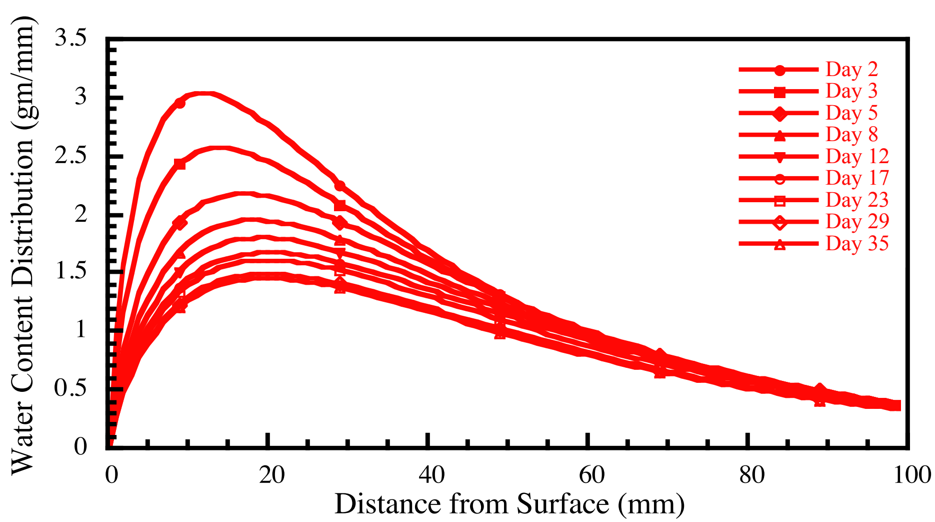
- The general equation for the temporal water/saltwater distribution is given by:

$$SWCD(t) = k_4 \left(\frac{t}{k_1}\right)^{k_2} e^{\left[-k_3\left(\frac{t}{k_1}\right)^{k_2}\right]}$$

where k1, k2, k3 are empirical factors and k4 is the amplitude of the distribution function for each day.

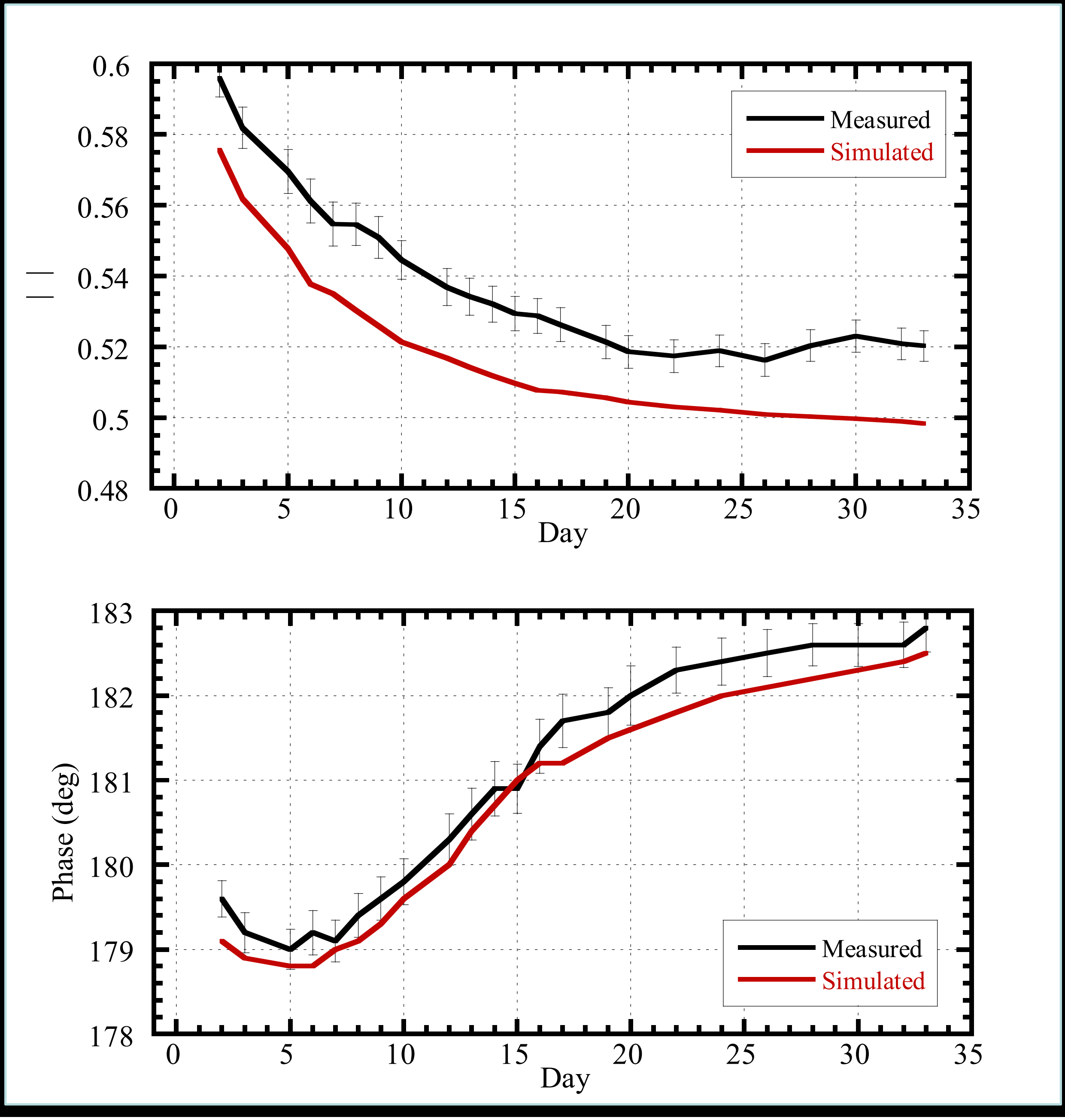
Salt Water Permeation in Mortar @ 3 GHz





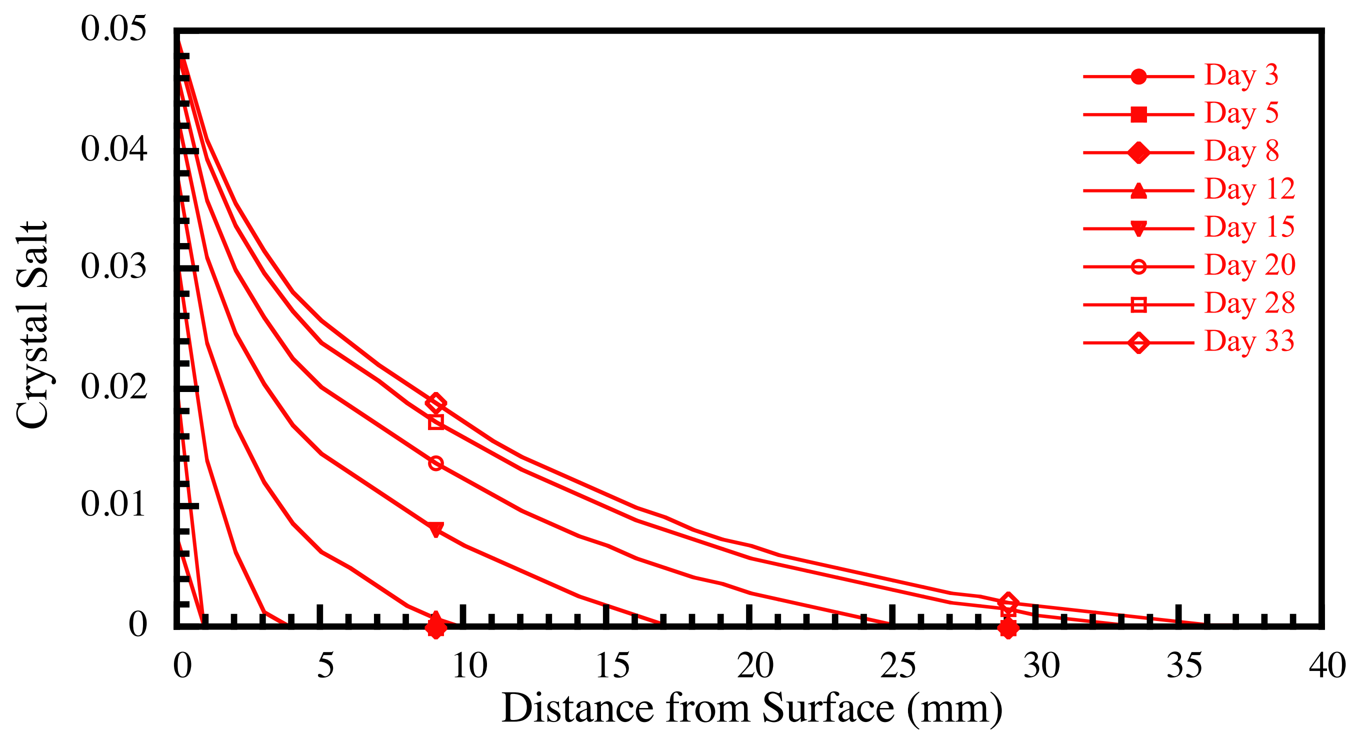
MISSOURI S&T

Cycle 1 @ 3 GHz



0.6
0.58
0.56
0.54
0.52
0.5
0.48
0 5 10 15 20 25 30 35
Day
Measured
Simulated
183
182
181
180
179
178
Phase (deg)
0 5 10 15 20 25 30 35
Day
Measured
Simulated

Salt Water Permeation in Mortar @ 3 GHz



INSPIRE University Transportation Center Webinar

MISSOURI S&T

Alkali-Silica Reaction (ASR)

Alkali-Silica Reaction - ASR

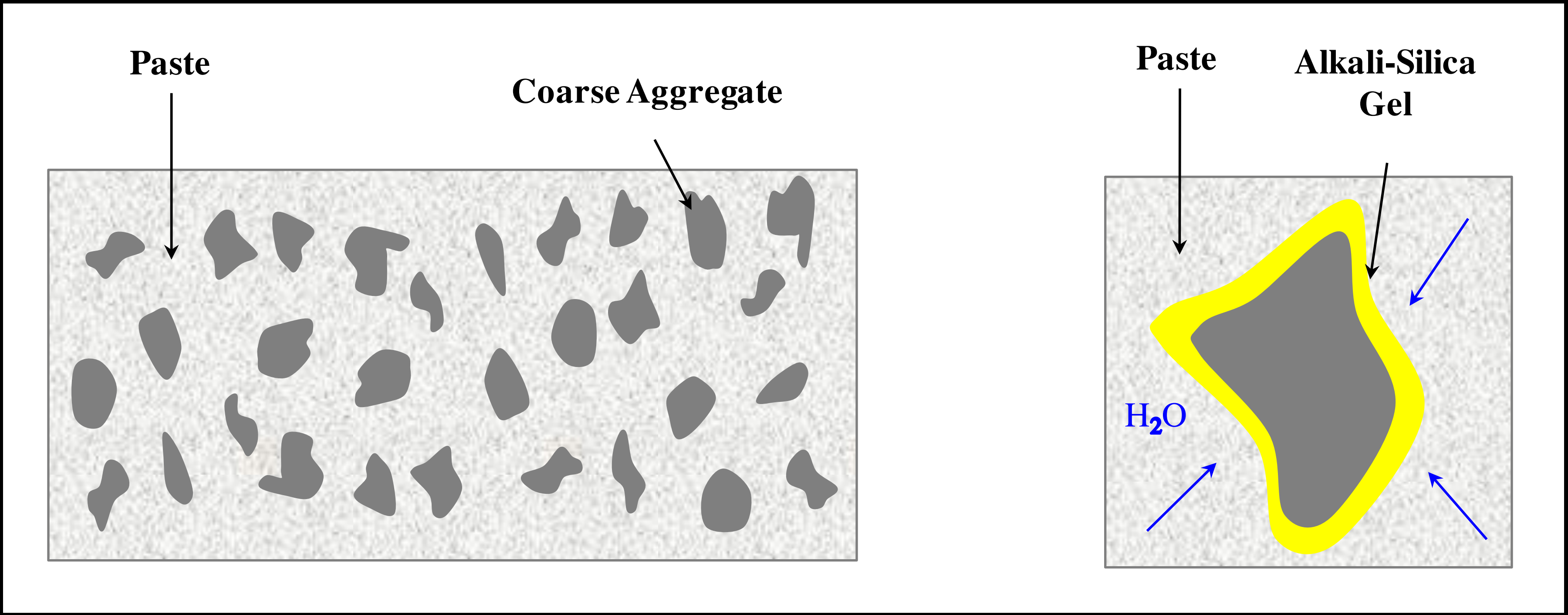
- Reaction between the alkalies (Na & K) in portland cement and certain siliceous minerals (opaline chert, strained quartz, and acidic volcanic glass) in some aggregates.
- Products of reaction may cause abnormal expansion and cracking of concrete in service.

Cracking Near Joints

Oriented Cracking

ASR

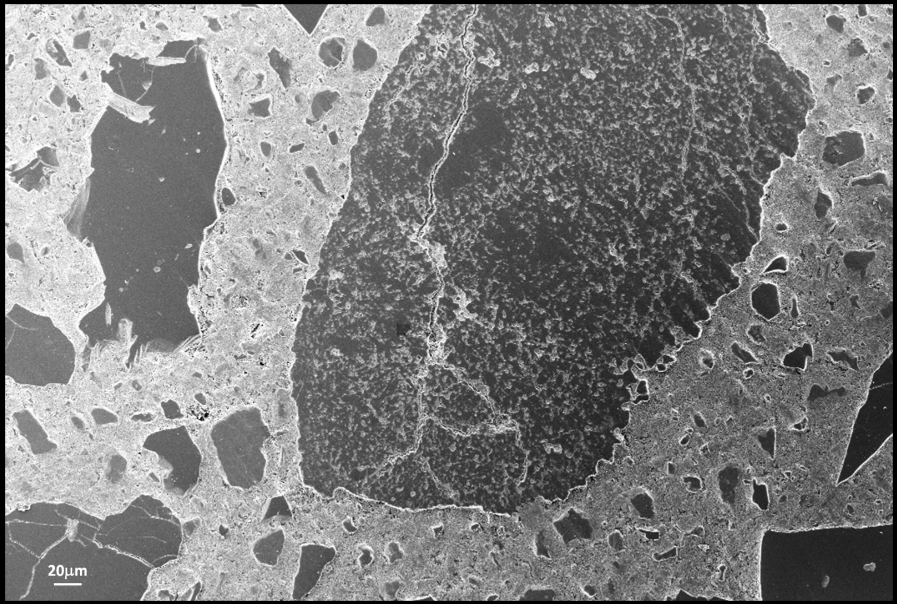
- ASR gel tends to form and accumulate in reaction rims around reactive aggregates.
- Over time, ASR gel imbibes water from its surroundings and swells ➩ expansion & cracking.

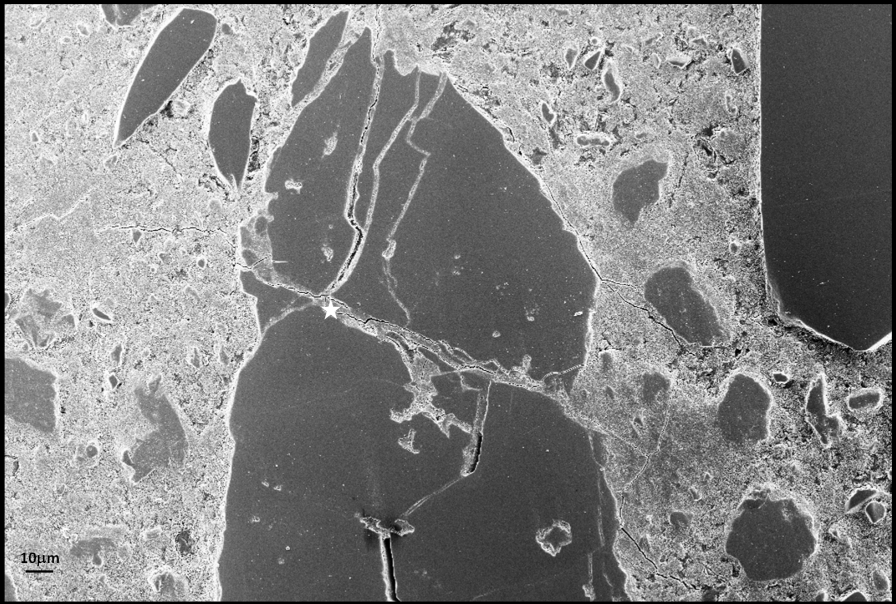


Sources of Alkali

- Portland cement
- Other cementing materials
  - ✓ Fly ash
  - ✓ Slag
  - ✓ Silica fume
- Chemical admixtures
- Wash water (if used)
- Aggregates
- External sources
  - ✓ Seawater
  - ✓ Deicing chemicals

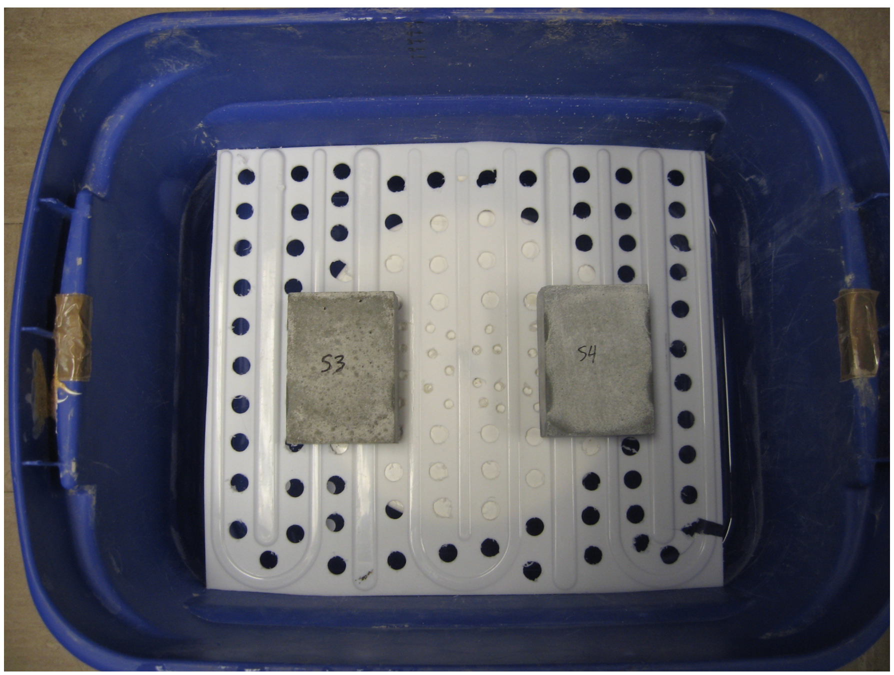
SEM Micrographs



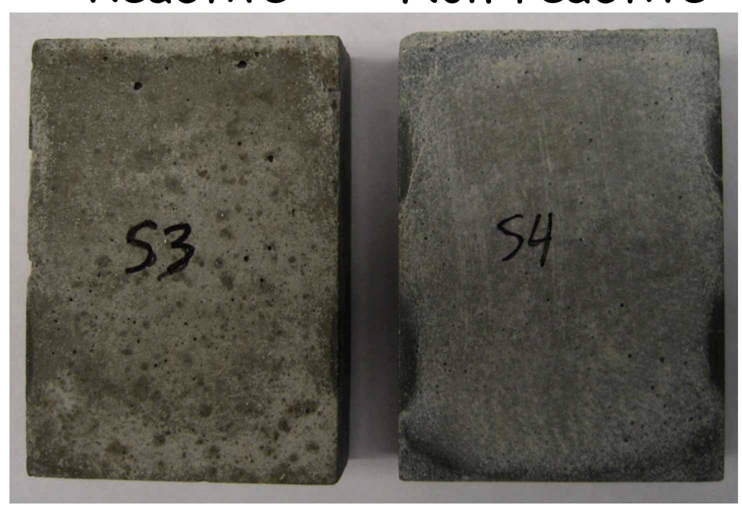


Sample Preparation

- Samples demolded ~24 hours after mixing.
- S-parameter measurements were conducted at S-band (2.6-3.95 GHz).
- After measurement, they were placed in an ambient humidity of ~99%.



Reactive Non-reactive



Sample Preparation

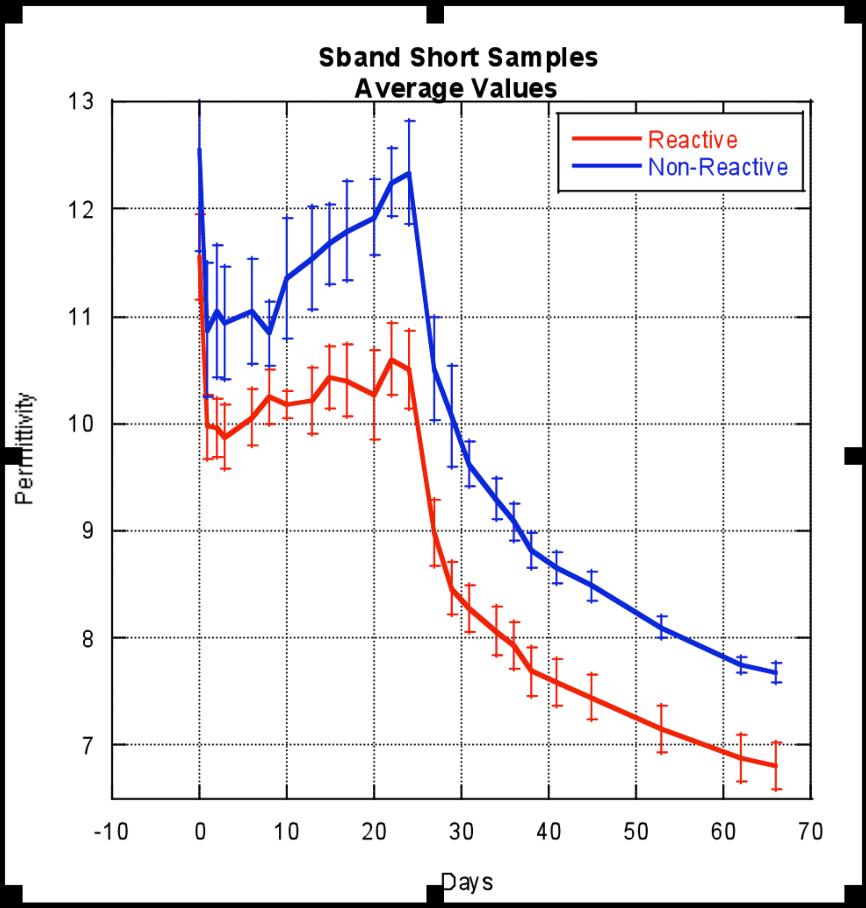
- Container was stored in an oven at a constant temperature of 38^{o}C.
- Initially the samples were placed in the oven ~15 hours after demolding.
- Every 2-3 days the samples were removed from the oven, measured and immediately put back.
- Mass of each sample was measured as well.
- After 22 days samples were placed in room conditions till day 36 when a set of final measurements was conducted.

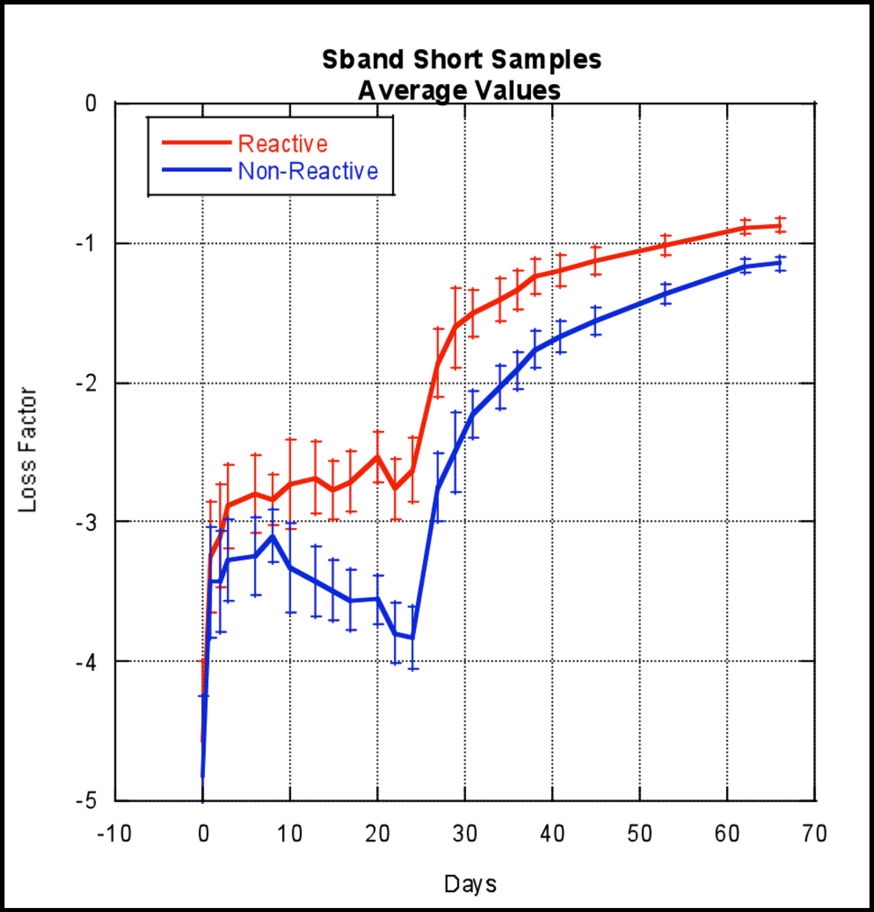
Measurement Setup

- **Transmission coefficient, $|S_{21}|$, indicates signal attenuation through sample.**
- **Higher $|S_{21}|$ (in dB) means less attenuation and vice versa.**

MISSOURI S&T

Measurements – S-Band

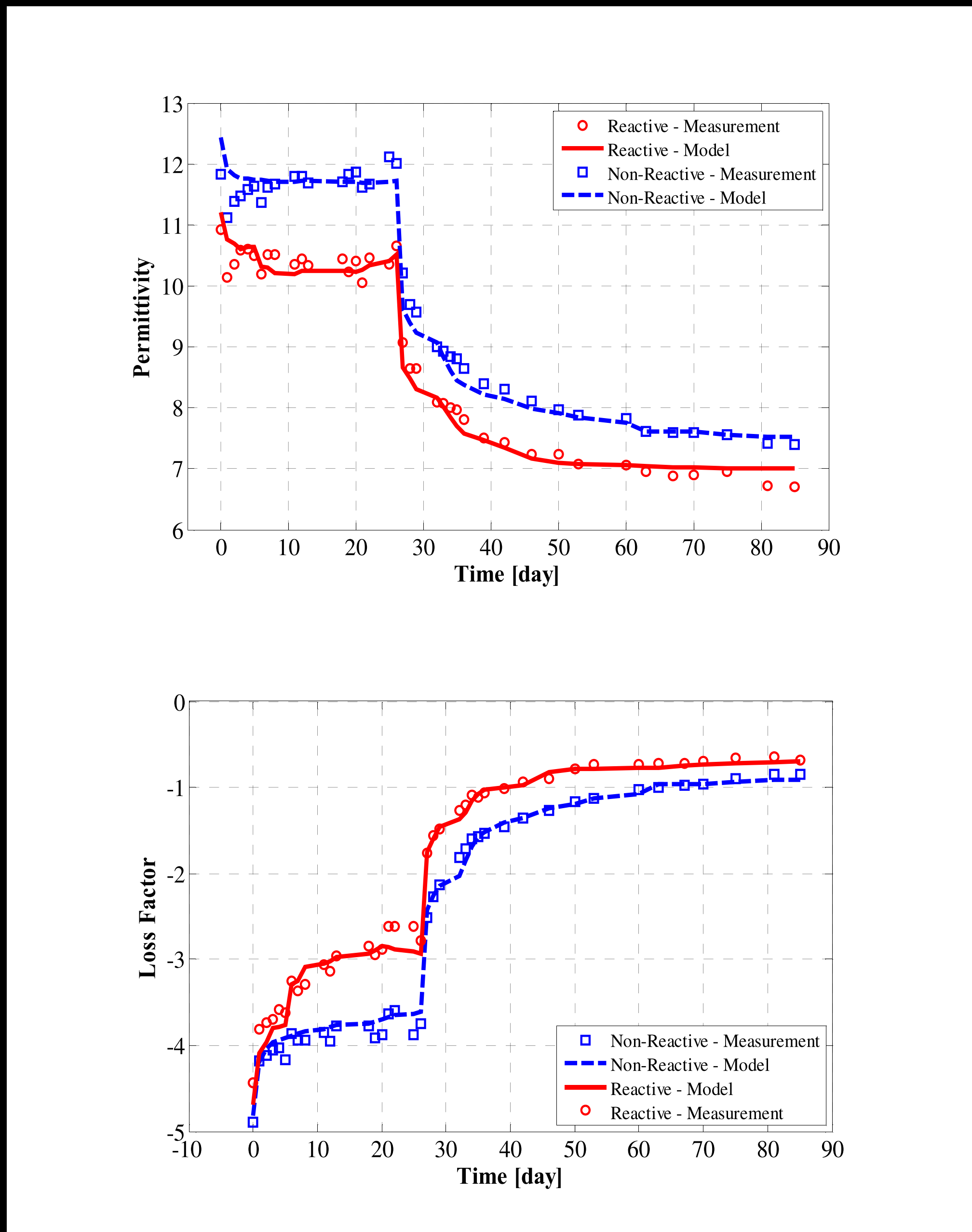




INSPIRE University Transportation Center Webinar

Missouri S&T

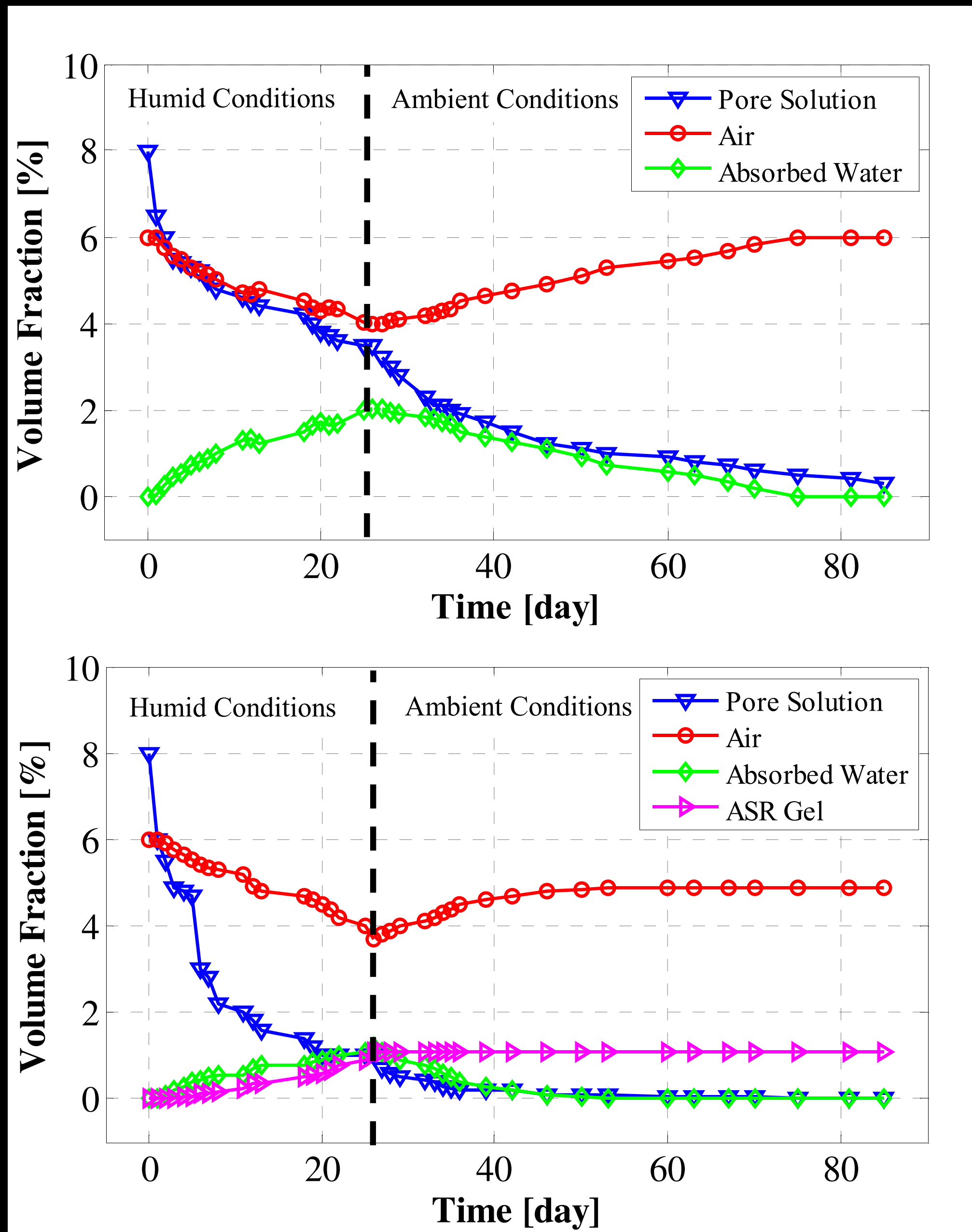
Modeling Results vs. Measurements



Semi-Empirical Effective Dielectric Constant Model

MISSOURI S&T

Semi-Empirical Modeling Results

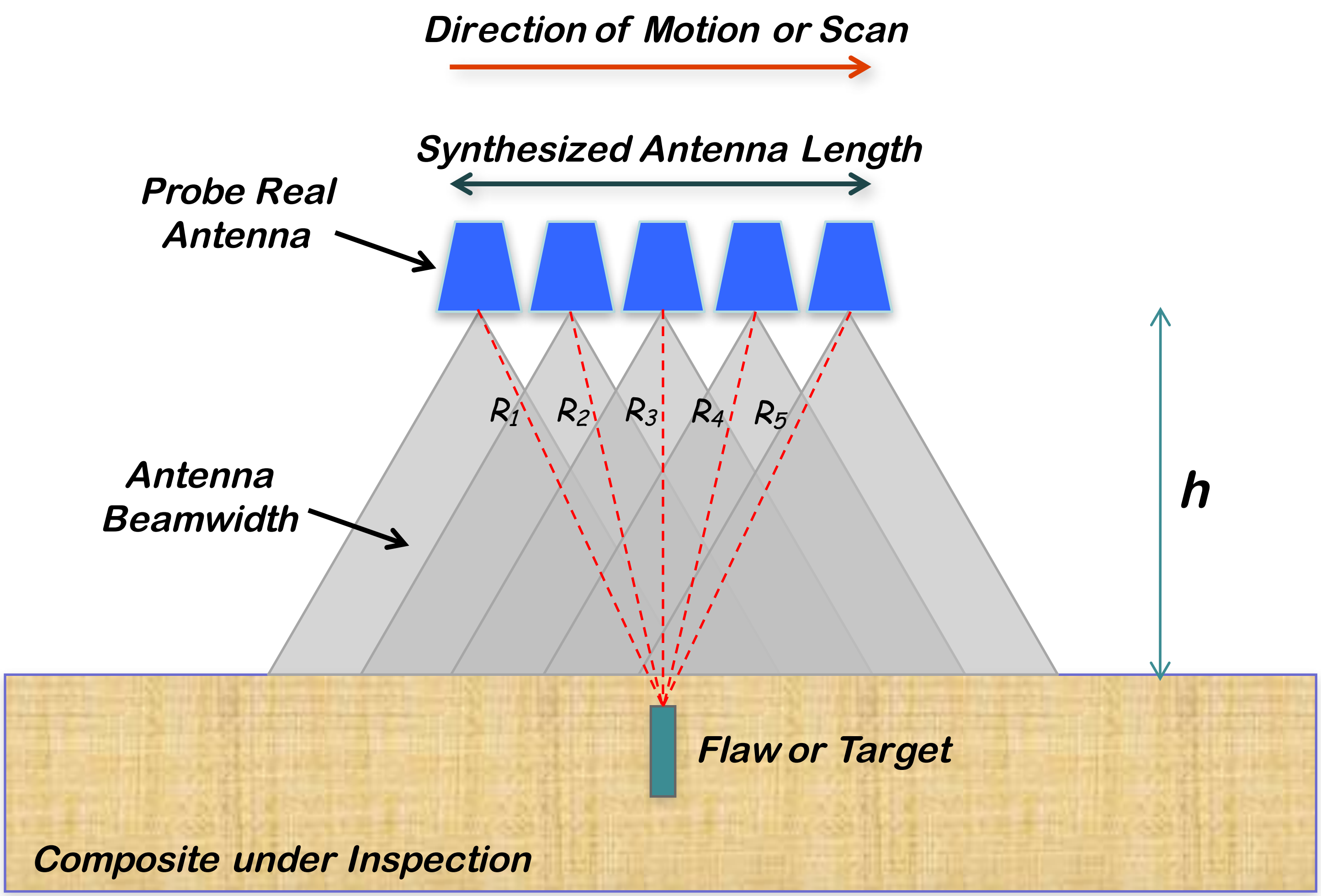


Nonreactive

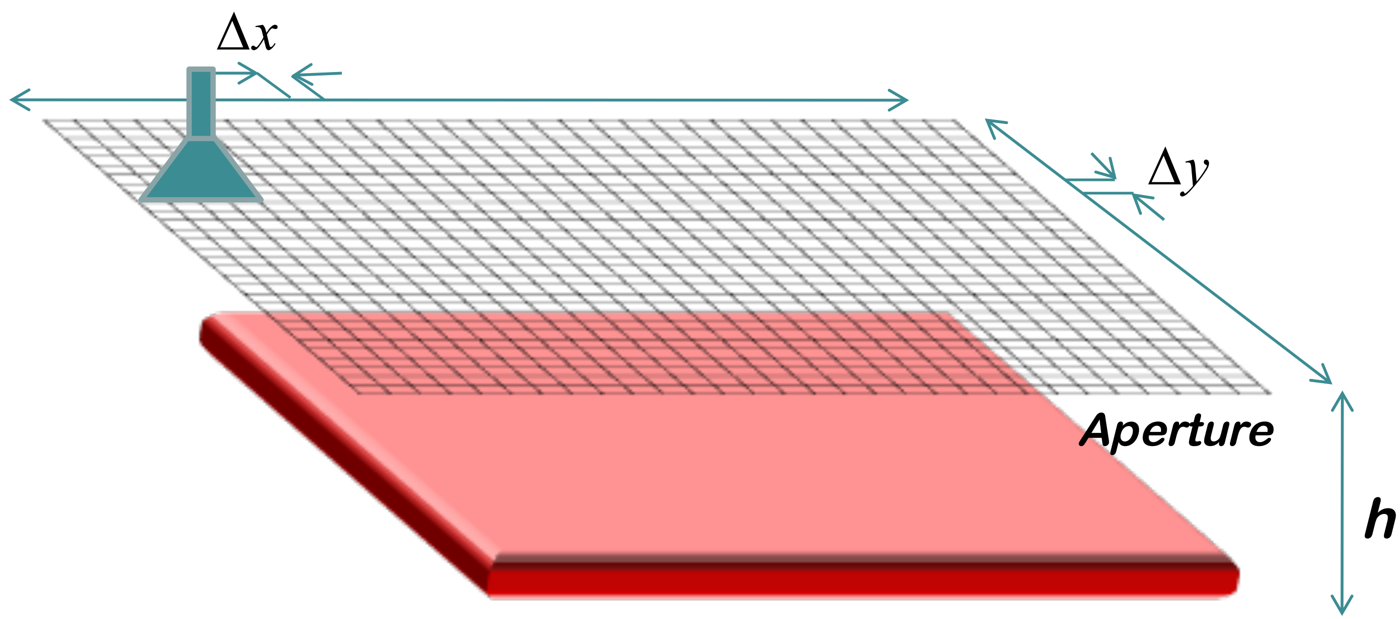
Reactive

Wideband Synthetic Aperture Focused Imaging Technique

Synthetic Aperture Focusing



SAR 2D Measurement



Microwave 3D Imaging

- Swept-frequency approach can be used to produce images with high range-resolution (i.e., depth) with reasonable penetration depth.
- This results in high-resolution 3D images with capability of producing image slices at various depths.
- Coherent summation over frequencies is possible, which improves the signal-to-noise (SNR) ratio associated with an image.

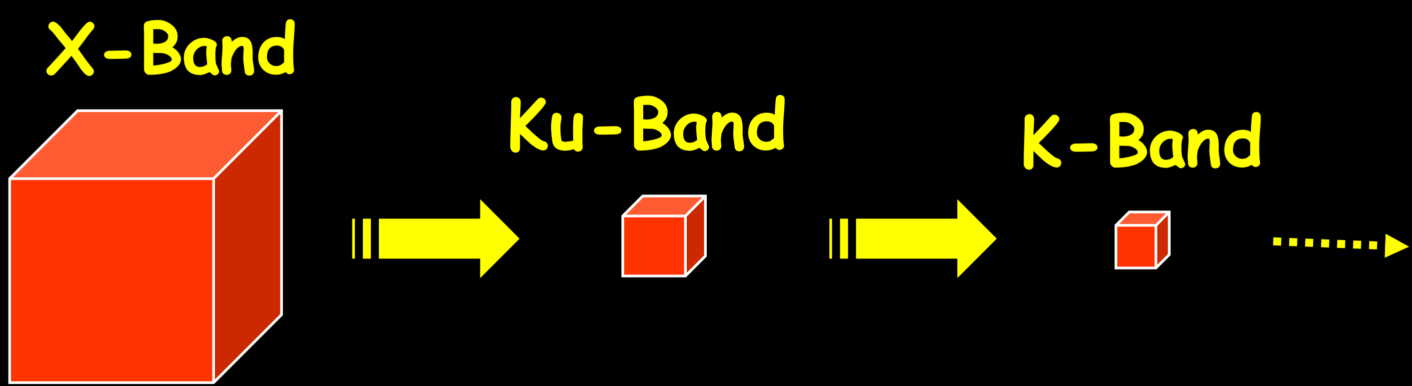
Microwave 3D Imaging

Frequency Band, Bandwidth (B) and Range-Resolution (RR)

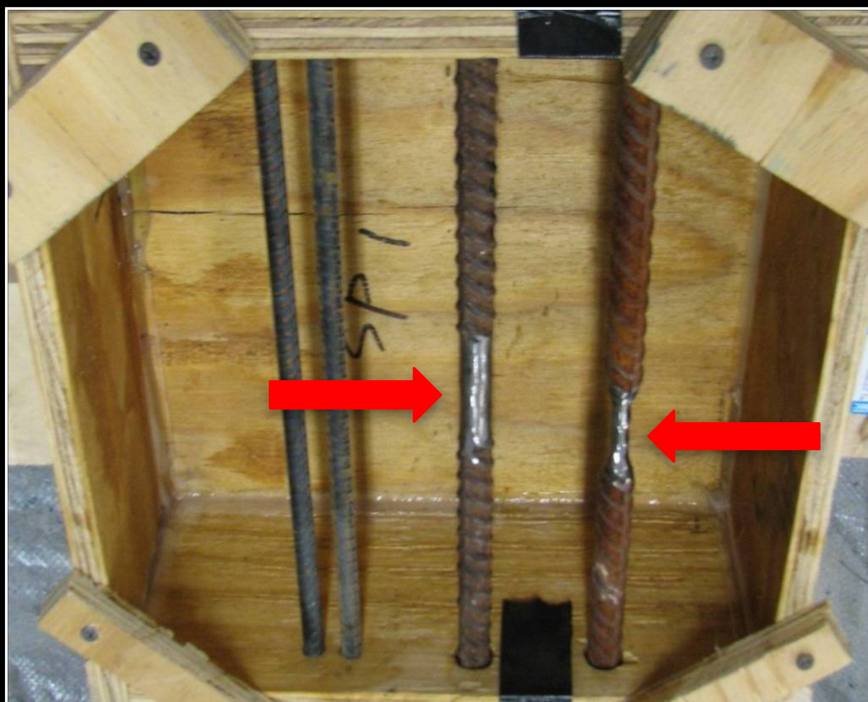
X-band (8.2 GHz - 12.4 GHz): B = 4.2 GHz, RR~16 mm

Ku-band (12.4 GHz – 18 GHz): B = 5.6 GHz, RR~12 mm

K-band (18 GHz – 26.5 GHz): B = 8.5 GHz, RR~8 mm



Sample #1



12" by 12" by 5"

(305 mm by 305 mm by 127 mm)

MISSOURI S&T

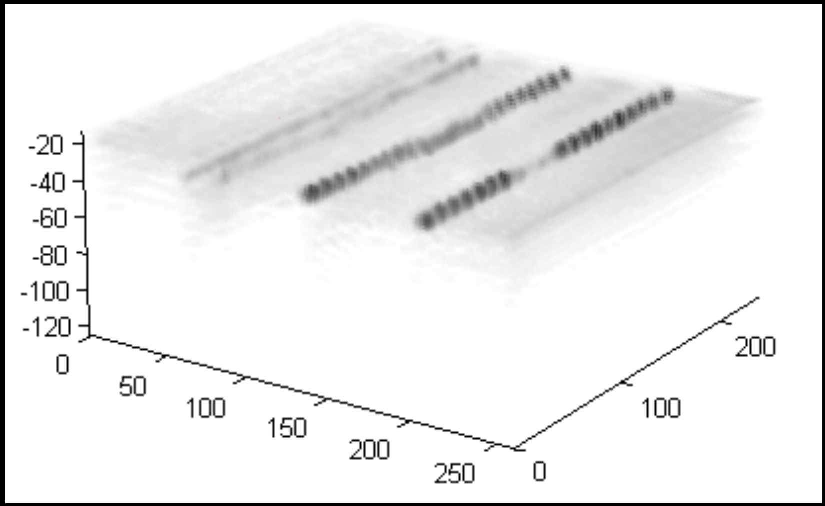
Sample #1

Shallow

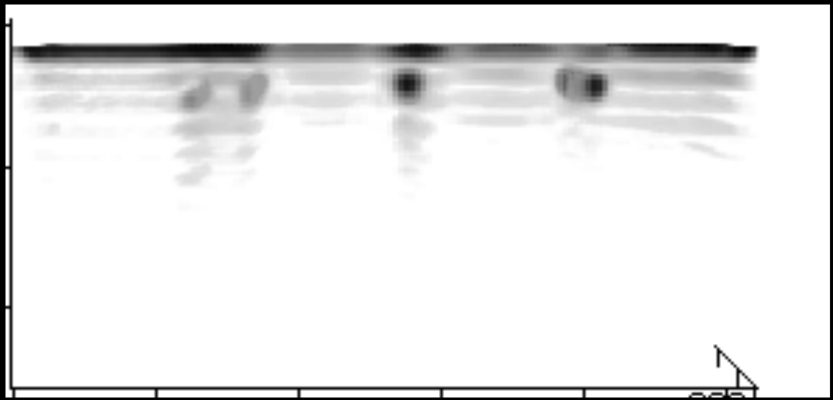
Deep

Results - Sample #1

3D Image @ Ku-band

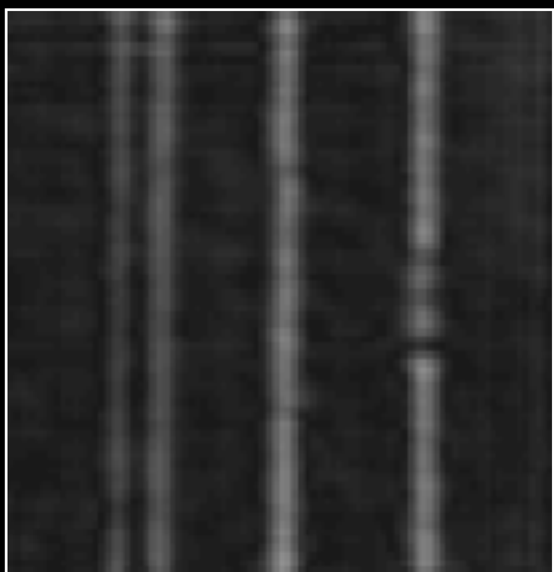


General View

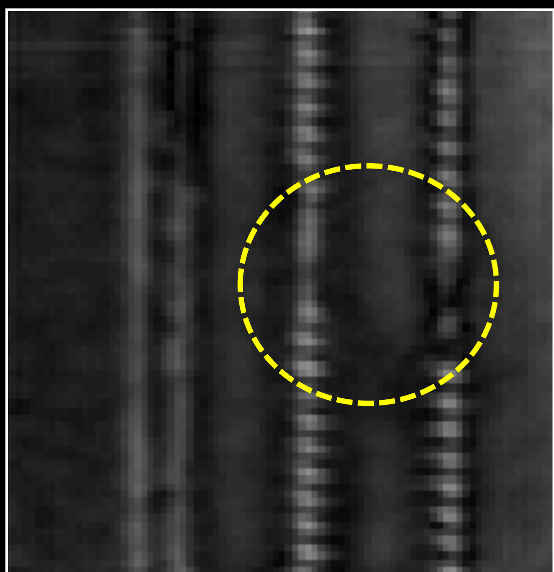


Side View

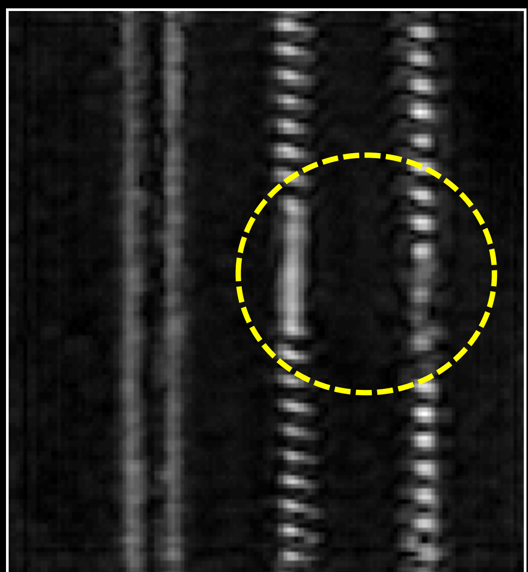
Results - Sample #1



X-band



Ku-band

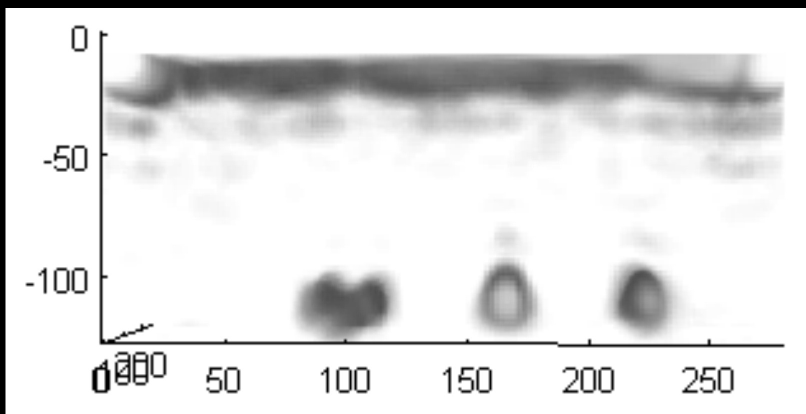


K-band

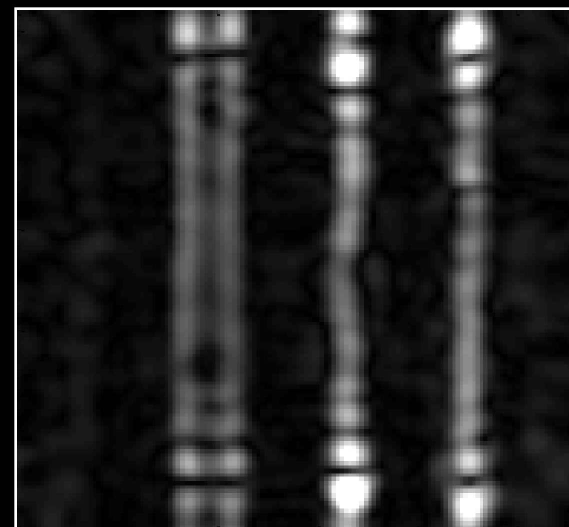
MISSOURI S&T

Results - Sample #1

X-band



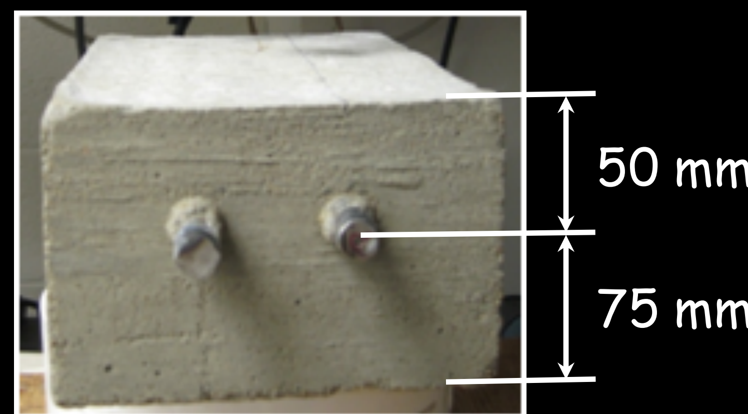
Side View



Hologram Slice

Sample #2

Grinded Area Filled with Rust

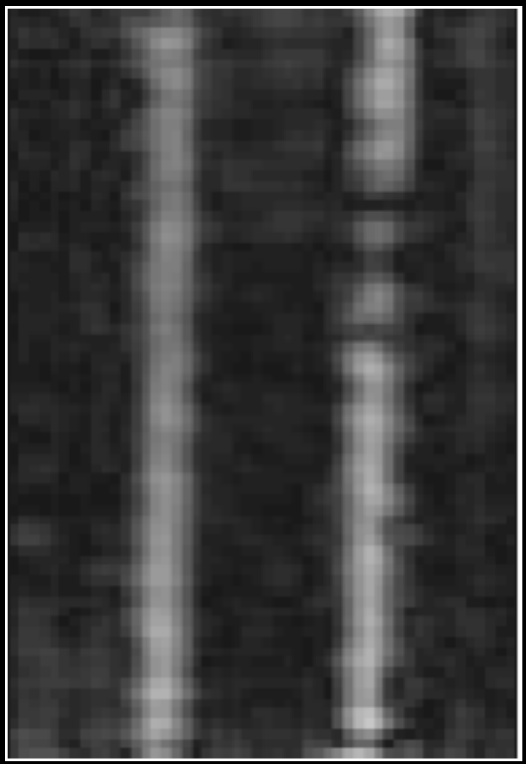


12" by 7.5" by 5"

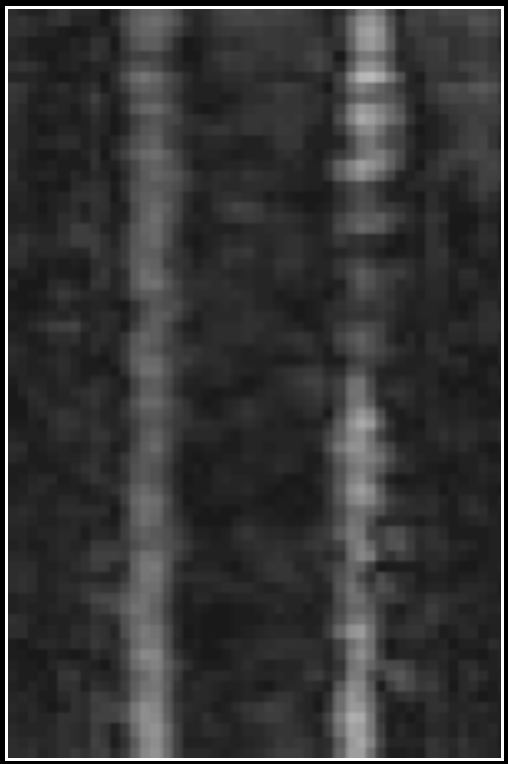
(305 mm by 190 mm by 125 mm)

Results - Sample #2

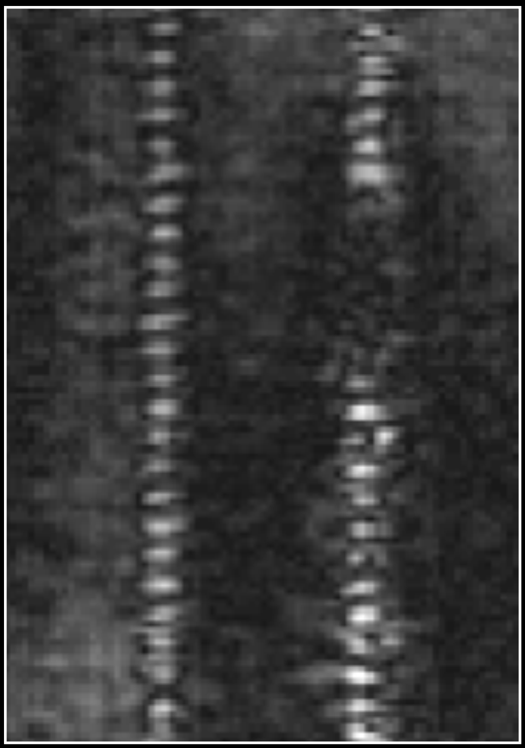
Hologram Slices



X-band



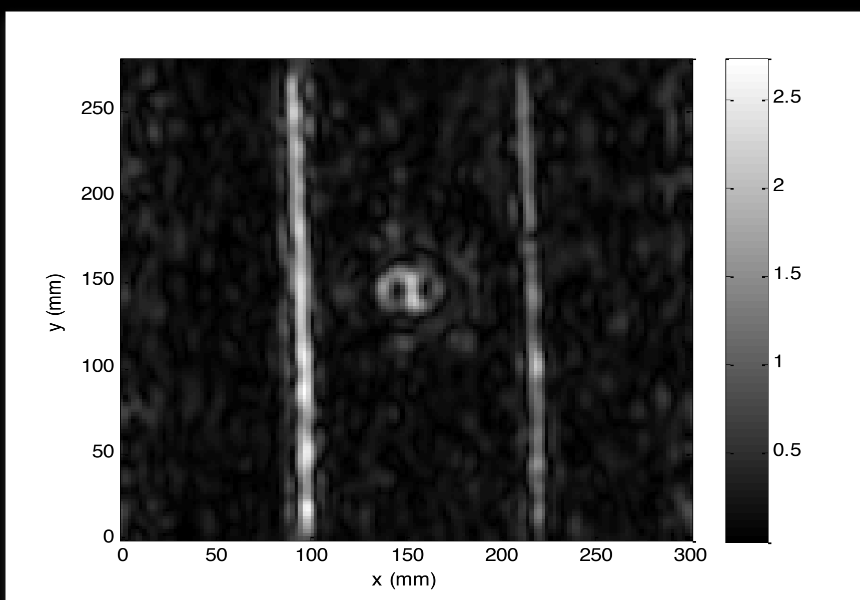
Ku-band

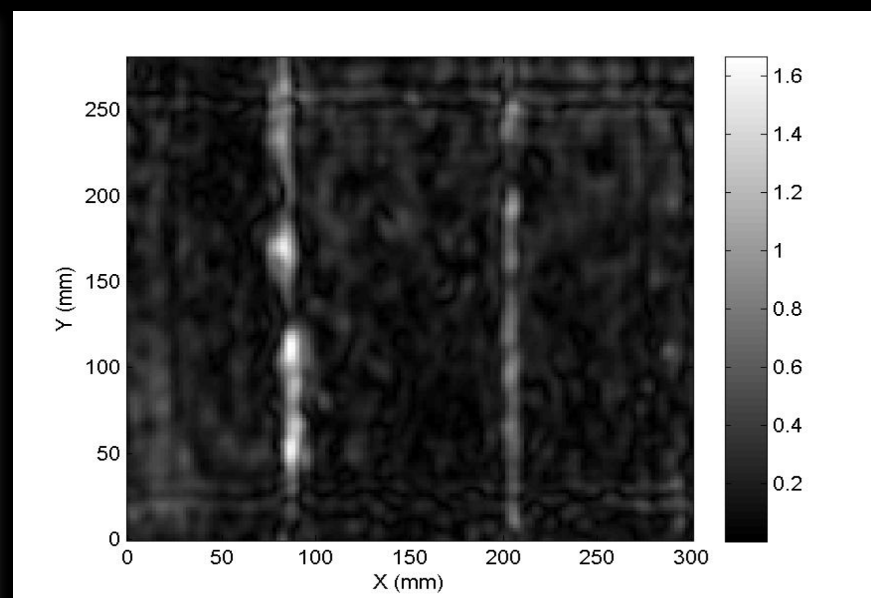


K-band

Corroded Rebar in Concrete

Un-Corroded | **Corroded**





INSPIRE University Transportation Center Webinar

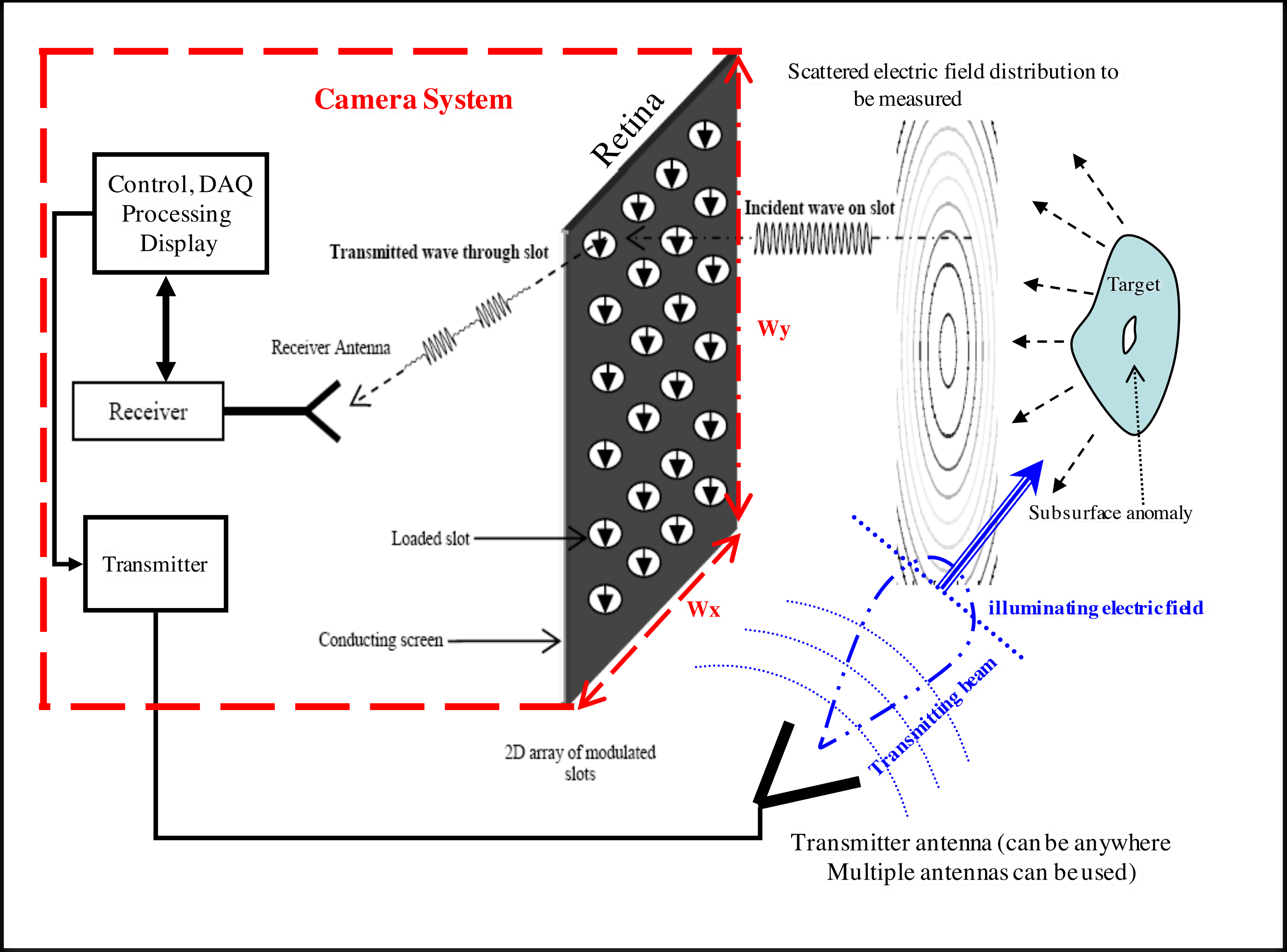
MISSOURI S&T

Real-Time Techqniues

http://amntl.mst.edu/

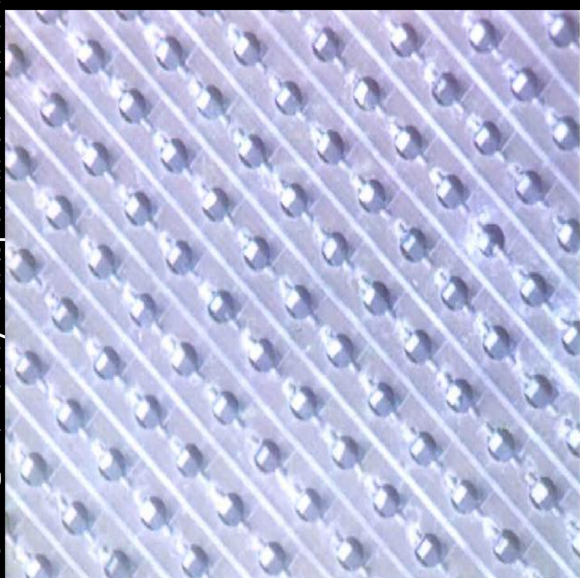
MISSOURI S&T

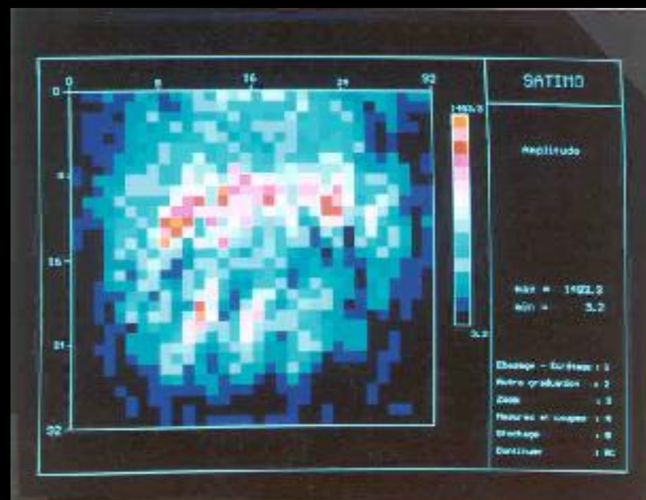
Basic Schematic

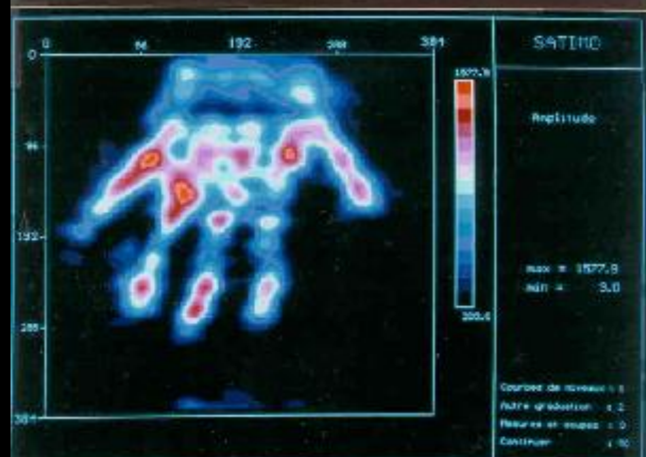


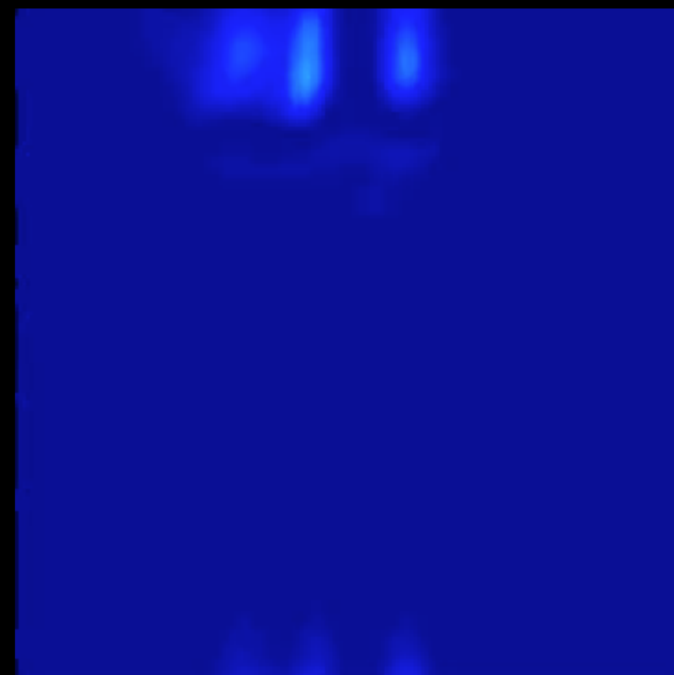
Retina

Courtesy: Professor Bolomey @ Supelec









Real-Time Imaging System

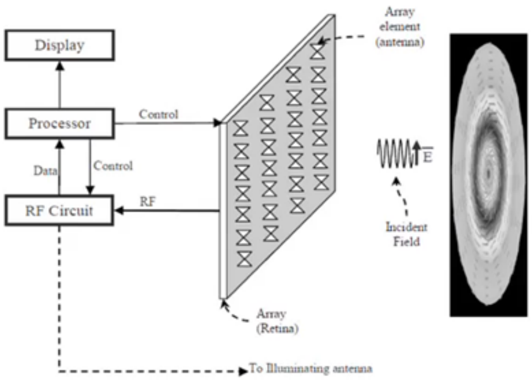
A REAL-TIME MICROWAVE CAMERA at 24 GHz (K-Band)

Objective

- Design and build a *real-time* microwave imaging system (i.e., camera)

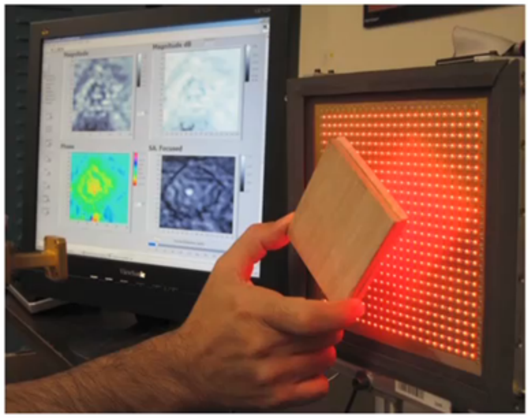
Overview

- Microwave imaging offers tremendous potential in many applications:
  - Inspection of low-loss composites, radomes, etc.
  - Detection and evaluation of corrosion under paint
  - Medical imaging
  - Security, contraband detection
- Raster scanning is slow and requires bulky mechanical systems
- A *real-time* and *portable* imaging system can be extremely useful for rapid nondestructive testing of large structures



Specification

- Aperture Size: 6″ × 6″
- Spatial Resolution : ~0.25″
- Coherent E-Field measurement
- Frequency: 24 GHz
- Dynamic range: 70 dB
- Frame rate: 30 fps
- Real-time focusing



Acknowledgment - This work was partially supported by NASA Marshall Space Flight Center (MSFC), Huntsville, AL

From interactive poster presented at the QNDE 2009 Conference.

Ghasr, M.T., *et al.*, "Portable Real-Time Microwave Camera at 24 GHz", *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 1114-1125, February 2012.

3D Real-Time Camera

Thank You.

Acknowledgment

Students, research associates, colleagues at various institutions and agencies, and funding support from various federal, state and commercial entities.

Acknowledgement

- **This webinar was funded by the INSPIRE University Transportation Center (UTC).**
  - ➢ **Financial support for INSPIRE UTC projects is provided by the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) under Grant No. 69A3551747126 through INSPIRE University Transportation Center (http://inspire-utc.mst.edu) at Missouri University of Science and Technology. The views, opinions, findings and conclusions reflected in this publication are solely those of the authors and do not represent the official policy or position of the USDOT/OST-R, or any State or other entity.**

Related Publications

Bois, K., A. Benally and R. Zoughi, "An Exact MultiMode Solution for the Reflection Properties of an Open-Ended Rectangular Waveguide Radiating into a Dielectric Half-Space: Forward and Inverse Problems," IEEE Transactions on Instrumentation and Measurement, vol. 48, no. 6, pp. 1131-1140, December 1999.

Zoughi, R., S. Gray and P.S. Nowak, "Microwave Nondestructive Estimation of Cement Paste Compressive Strength," ACI Materials Journal, vol. 92, no. 1, pp. 64-70, January-February, 1995.

Bois, K.J., A.D. Benally, P.S. Nowak and R. Zoughi, "Cure-State Monitoring and Water-to-Cement Ratio Determination of Fresh Portland Cement Based Materials Using Near Field Microwave Techniques," IEEE Transactions on Instrumentation and Measurement, vol. 47, no. 3, pp. 628-637, June 1998.

Bois, K., A. Benally, P.S. Nowak and R. Zoughi, "Microwave Nondestructive Determination of Sand to Cement (s/c) Ratio in Mortar," Research in Nondestructive Evaluation, vol. 9, no. 4, pp. 227-238, 1997.

Bois, K., A. Benally and R. Zoughi, "Microwave Near-Field Reflection Property Analysis of Concrete for Material Content Determination," IEEE Transactions on Instrumentation and Measurement, vol. 49, no. 1, pp. 49-55, February 2000.

Bois, K. and R. Zoughi, "A Decision Process Implementation for Microwave Near-Field Characterization of Concrete Constituent Makeup," Special Issue of Subsurface Sensing Technologies and Applications: on Advances and Applications in Microwave and Millimeter Wave Nondestructive Evaluation, vol. 2, no. 4, pp. 363-376, October 2001.

Bois, K., A. Benally and R. Zoughi, "Near-Field Microwave Non-Invasive Determination of NaCl in Mortar," IEE proceedings - Science, Measurement and Technology, Special Issue on Non-destructive Testing and Evaluation, vol. 148, no. 4, pp. 178-182, July 2001.

Peer, S., J.T. Case, E. Gallaher, K.E. Kurtis and R. Zoughi, "Microwave reflection and Dielectric Properties of Mortar Subjected to Compression Force and Cyclically Exposed to Water and Sodium Chloride Solution," IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 1, pp. 111-118, February 2003.

Related Publications

Peer, S., K.E. Kurtis and R. Zoughi, "An Electromagnetic Model for Evaluating Temporal Water Content Distribution and Movement in Cyclically Soaked Mortar," IEEE Transactions on Instrumentation and Measurement, vol. 53, no. 2, pp. 406-415, April 2004.

Case, J.T., S. Peer, and R. Zoughi, "Microwave Reflection Properties of Concrete Periodically Exposed to Chloride Solution of 3% Salinity and Compression Force," IEEE Transactions on Instrumentation and Measurement, vol. 53, no. 4, pp. 1000-1004, August 2004.

Peer, S., K.E. Kurtis and R. Zoughi, "Evaluation of Microwave Reflection Properties of Cyclically Soaked Mortar Based on a Semi-Empirical Electromagnetic Model," IEEE Transactions on Instrumentation and Measurement, vol. 54, no. 5, pp. 2049-2060, October 2005.

Donnell, K.M., S. Hatfield, R. Zoughi and K.E. Kurtis, "Wideband Microwave Characterization of Alkali-Silica Reaction (ASR) Gel in Cement-Based Materials," Materials Letters, vol. 90, pp. 159-161, January 2013.

Donnell, K.M., R. Zoughi and K.E. Kurtis, "Demonstration of Microwave Method for Detection of Alkali–Silica Reaction (ASR) Gel in Cement-Based Materials," Cement and Concrete Research, pp. 1-7, February 2013.

Hashemi, A., M. Horst, K.M. Donnell, K.E. Kurtis and R. Zoughi, "Comparison of Alkali-Silica Reaction (ASR) Gel Behavior in Mortar at Microwave Frequencies," IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 7, pp. 1907-1915, July 2015.

Hashemi, A., M. Rashidi, K.E. Kurtis, K.M. Donnell and R. Zoughi, "Microwave Dielectric Properties Measurements of Sodium and Potassium Water Glasses," Materials Letters, vol. 169, pp. 10-12, 2016.

Hashemi, A., K.E. Kurtis, K.M. Donnell and R. Zoughi, "Empirical Multiphase Dielectric Mixing Model for Cement-Based Materials Containing Alkali-Silica Reaction (ASR) Gel," IEEE Transactions on Instrumentation and Measurement, vol. 66, no. 9, pp. 2428-2436, September 2017.

MISSOURI S&T

Related Publications

Rashidi, M., M. Knapp, A. Hashemi, J.Y. Kim, K.M. Donnell, R. Zoughi, L. Jacobs and K.E. Kurtis, "Detecting Alkali-Silica Reaction: A Multi-Physics Approach," Cement and Concrete Composites, vol. 73, pp. 123-135, October 2016.

Hashemi, A., K.M. Donnell, K.E. Kurtis, M. Knapp, and R. Zoughi, "Microwave Detection of Carbonation in Mortar Using Dielectric Property Characterization," Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 216-220, Montevideo, Uruguay, May 12-15, 2014.

Hashemi, A., K.M. Donnell, K.E. Kurtis, M. Knapp, and R. Zoughi, "Microwave Detection of Carbonation in Mortar Using Dielectric Property Characterization," Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 216-220, Montevideo, Uruguay, May 12-15, 2014.

Mehdipour, I., R. Zoughi and K. Khayat, "Feasibility of using Near-Field Microwave Reflectometry for Monitoring Autogenous Crack Healing in Cementitious Materials," Cement and Concrete Composites, vol. 85, pp. 161-173, 2018.

Mehdipour, I., M. Horst, R. Zoughi and K. Khayat, "Use of Near-Field Microwave Reflectometry to Evaluate Steel Fiber Distribution in Cement-Based Mortars," Journal of Materials in Civil Engineering (ASCE), vol. 29, no. 7 (04017029), March 2017 (DOI: 10.1061/ (ASCE)MT.1943-5533.0001850).

Ghasr, M.T., Y. LePape, D.B. Scott, and R. Zoughi, "Holographical Microwave Imaging of Corroded Steel Bars in Concrete," American Concrete Institute (ACI) Materials Journal, vol. 112, no. 1, pp. 115-124, January 2015.

Bao, Y., M.T. Ghasr, K. Ying, G. Chen and R. Zoughi, "Microwave Synthetic Aperture Radar (SAR) Imaging for Nondestructive Evaluation of Mechanically Stabilized Earth Walls," Materials Evaluation, vol. 75, no. 2, pp. 177-184, February 2017.

Akuthota, B., D. Hughes, R. Zoughi, J. Myers and T. Nanni, "Near-Field Microwave Detection of Disbond in Carbon Fiber Reinforced Polymer (CFRP) Composites Used for Strengthening Cement-Based Structures and Disbond Repair Verification," ASCE Journal of Materials in Civil Engineering, vol. 16, no. 6, pp. 540-546, December 2004.

Related Publications

Kharkovsky, S., A.C. Ryley, V. Stephen and R. Zoughi, “Dual-Polarized Near-Field Microwave Reflectometer for Non-Invasive Inspection of Carbon Fiber Reinforced Polymer (CFRP)-Strengthened Structures,” IEEE Transactions on Instrumentation and Measurement, vol. 57, no. 1, pp. 168-175, January 2008.

Nadakuduti, J., G. Chen and R. Zoughi, “Semi-Empirical Electromagnetic Modeling of Crack Detection and Sizing in Cement-Based Materials Using Near-Field Microwave Methods,” IEEE Transactions on Instrumentation and Measurement, vol. 55, no. 2, pp. 588-597, April 2006.

Mubarak, K., K.J. Bois and R. Zoughi, “A simple, Robust and On-Site Microwave Technique for Determining Water-to-Cement (w/c) Ratio of fresh Portland Cement-Based Materials,” IEEE Transactions on Instrumentation and Measurement, vol. 50, no. 5, pp. 1255-1263, October 2001.

Shalaby, W. and R. Zoughi, “Analysis of Monopole Sensors for Cement Paste Compressive Strength Estimation,” Research in Nondestructive Evaluation, vol. 7, no. 2/3, pp. 101-105, 1995.