VOTERS
Versatile Onboard Traffic Embedded Roaming Sensors

## Versatile Onboard Traffic-Embedded Roaming Sensors

# Framework for continuous network-wide health monitoring of roadways and bridge decks

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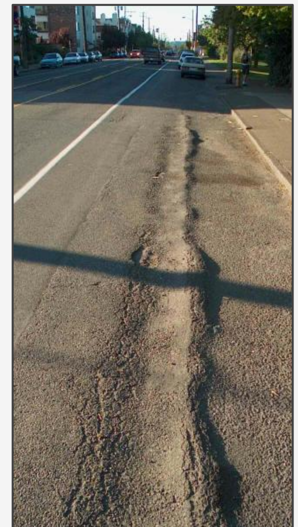
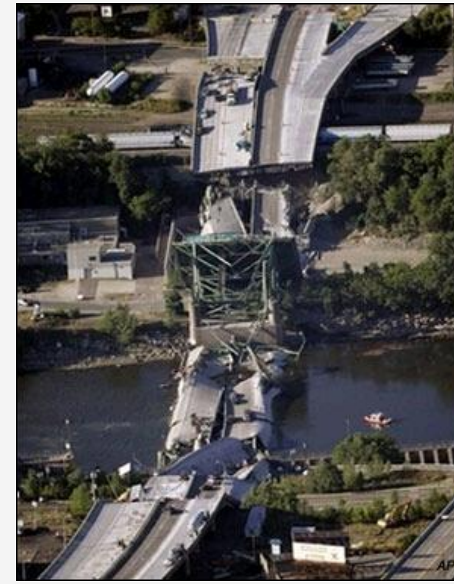
# Infrastructure Maintenance Problem


www.infrastructurereportcard.org





# Importance of Road Inspection

## Condition of US roads is poor (unsafe)

**Personal experience (local roads)**

**Professional organizations**

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS


## Road inspections are needed for improvement

1. Spot and quantify all damage in a network
   — *Can't fix it if don't know a problem exists*
2. Map inspection results-Periotic Data
3. Prioritize repair needs
   — *Not enough resources to fix everything at once*
   — *Do not have current updated PCI and condition*

# Current Methods

## Urban Roads:

- Time-consuming
- Traffic blockage
- Manual labor
- Periodic
- Expensive
- Subjective
- No Subsurface features


- Speed effect
- Interstate highway only
- Tedious processing
- Expensive technology
- Experts Required
- No Subsurface features

# VOTERS Vision

Versatile Onboard Traffic Embedded Roaming Sensors

**Use Vehicles of Opportunity (VOOs) as inspection data collection platforms**

- VOOs roam around a city going about their usual business
- Autonomous VOTERS Sensor System mounted on VOOs
- Wireless connection to Control Center


- **Vehicles of Opportunity** collect Sensor Data containing Surface and *Subsurface* Roadway and Bridge Deck Condition Information at ***Traffic Speed***
- Accurately register all data **geographically** and in time
- Data or Results are transferred to a **Control and Visualization Center** for further analysis, visualization, and decision making

# VOTERS Test Vehicle

# VOTERS

Versatile Onboard Traffic Embedded Roaming Sensors

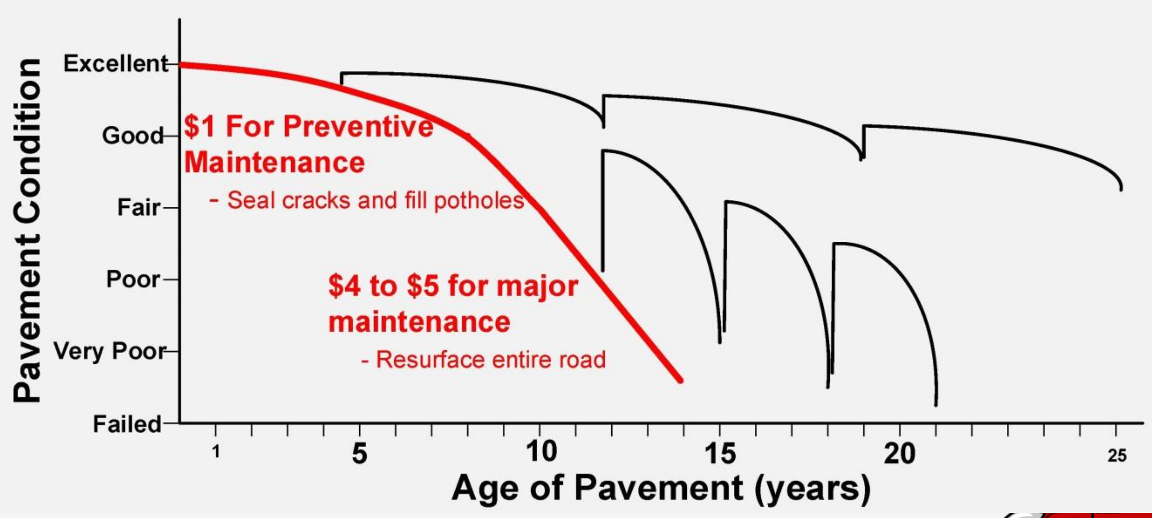
- **Continuous network-wide and performance based maintenance strategy**
  - Monitoring of conditions at short time intervals using multiple VOOs in traffic to **cover long distance**
  - Vehicles assess road conditions at **driving speed**
  - Account for severe weather effects
  - Road assessment once a year or per request
  - Surface and subsurface condition assessment
  - Serve interstate highway, urban roadways and airport
  - Maintain road in excellent condition with less fund

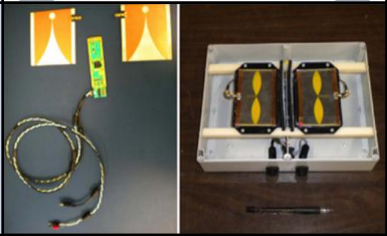
# VOTERS Paradigm Shift

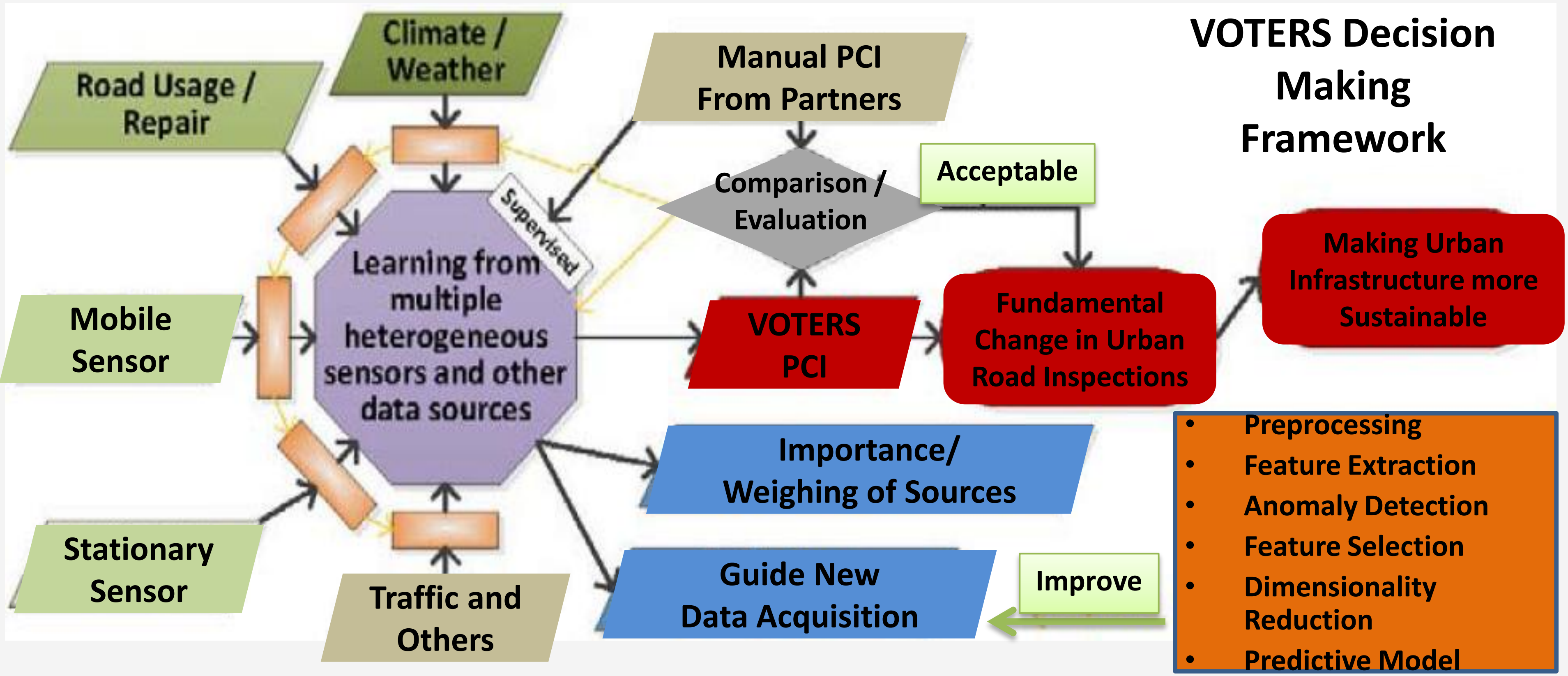
Versatile Onboard Traffic Embedded Roaming Sensors

## The VOTERS project provides a framework to shift from periodical localized inspections to continuous network-wide health monitoring of roadways and bridge decks

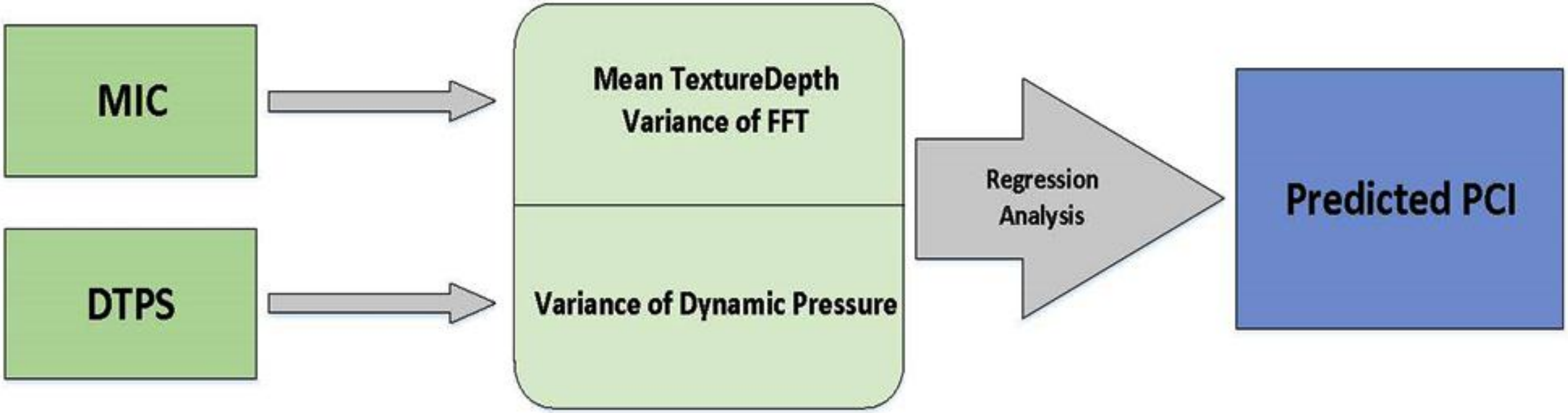
- Make the Right Repairs
- In the Right Place
- At the Right Time
- Long term saving

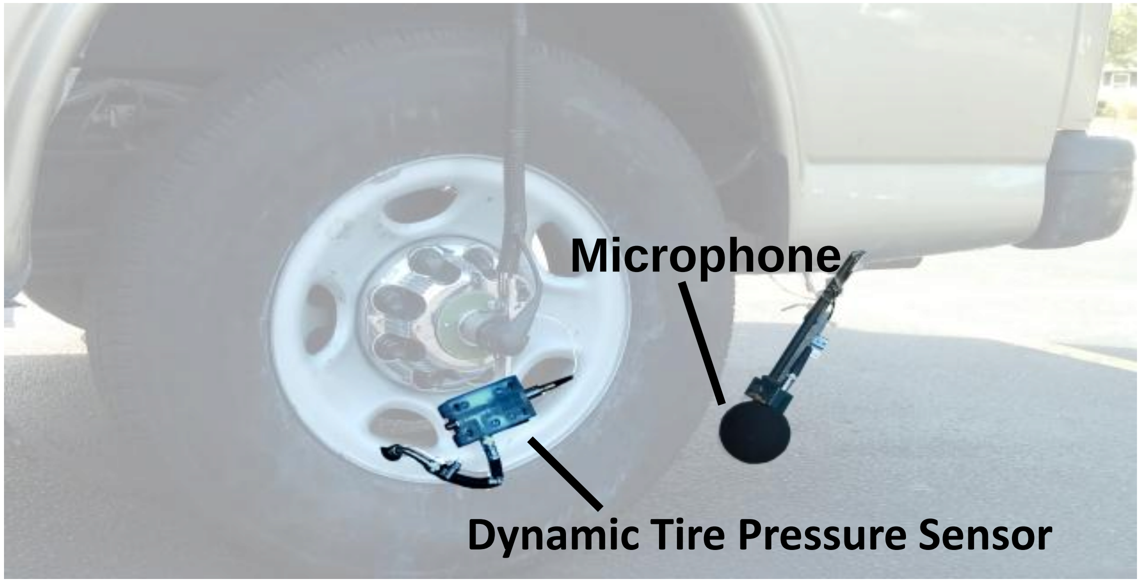


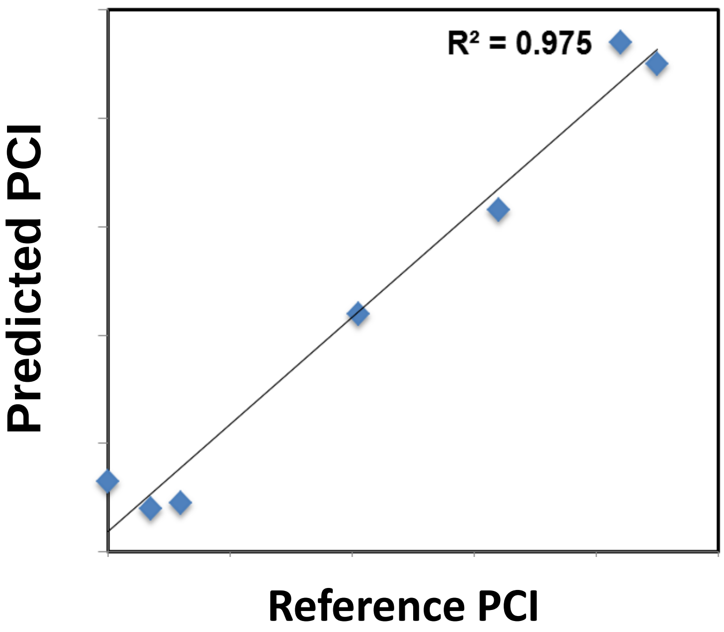
| Technology | Measurements | Specifications | Picture |
|---|---|---|---|
| **VOTERS Microphone**<br>Acoustic measurement of the tire noise | • Friction<br>• Raveling<br>• Bleeding<br>• Mean Texture Depth (MTD)<br>• Polished Aggregate | • Sensor height: ½ - 3 inch<br>• Sampling Rate: 2 - 200 KHz<br>• Sensitivity: 44 - 52 mv/Pa |  |
| **Dynamic Tire Pressure Sensor (DTPS)**<br>Acoustic measurement of the dynamic pressure from the tire/road interaction | • Roughness<br>• Road Profile<br>• Road Height Variations<br>• International Roughness Index (IRI) | • Frequency: 0.5 Hz - 20 KHz<br>• Sampling Rate: 2 - 200 KHz<br>• Dynamic Pressure: 0 - 1 psi |  |
| **VOTERS Camera**<br>Color Video acquisition and automated analysis system | • Crack Density<br>• Patch Density<br>• Potholes<br>• Shoving<br>• Rutting<br>• Feature Identification | • Resolution: 2.82 Megapixel<br>• Speed: Gigabit Ethernet |  |
| **Millimeter-Wave Radar**<br>Measurement of road surface condition | • Rutting depth<br>• Bleeding<br>• Moisture<br>• Ice<br>• Wetness<br>• Feature identification | • Operation: 24 GHz<br>• Arrays: 5 channels |  |
| **Ground Penetrating Radar**<br>Measurement of road subsurface characteristics | • Rebar Corrosion of Bridge Decks<br>• Layer Depth<br>• Vertical Profile<br>• Subsurface Feature Identification (delamination, potholes, etc.)<br>• Subsurface Moisture | • Frequency: 0.8 - 5 GHz<br>• Data rate: 1000 trace/sec<br>• Low cost<br>• Low power<br>• Small |  |
| **Mobile Acoustic Subsurface System**<br>Measurement of road subsurface characteristics | • Delamination of Bridge Decks<br>• Asphalt Pavement Layer Depth<br>• Subsurface Distress<br>• Modulus Elasticity of Layer | • Sensor Height: ½ - 3 inch<br>• Sampling rate: 200 KHz<br>• Sensing depth: 1 m |  |




- Heterogeneous data sources (green),
- Analyzes data source individually (light orange)
- Fusing the data (purple)
- VOTERS PCI equivalent (red) compare to traditionally collected PCI data sets (gray).
- A favorable comparison would fundamentally change the way urban road inspections will be performed
- Enable urban infrastructure more sustainable (red).
- PCI predicting model (orange)

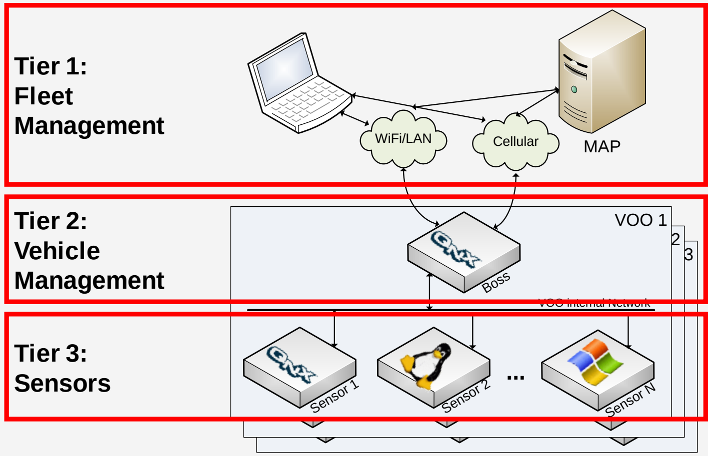

MIC
DTPS
Mean TextureDepth
Variance of FFT
Variance of Dynamic Pressure
Regression
Analysis
Predicted PCI

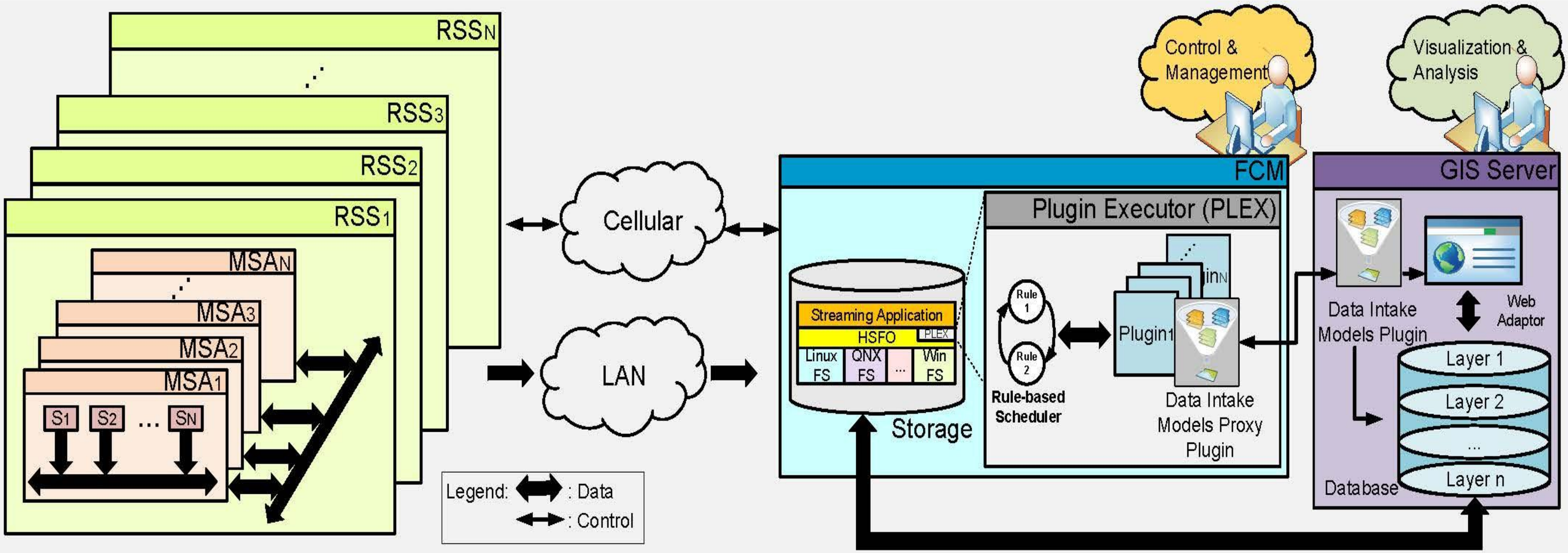

Microphone
Dynamic Tire Pressure Sensor


$R^2 = 0.975$
Predicted PCI
Reference PCI

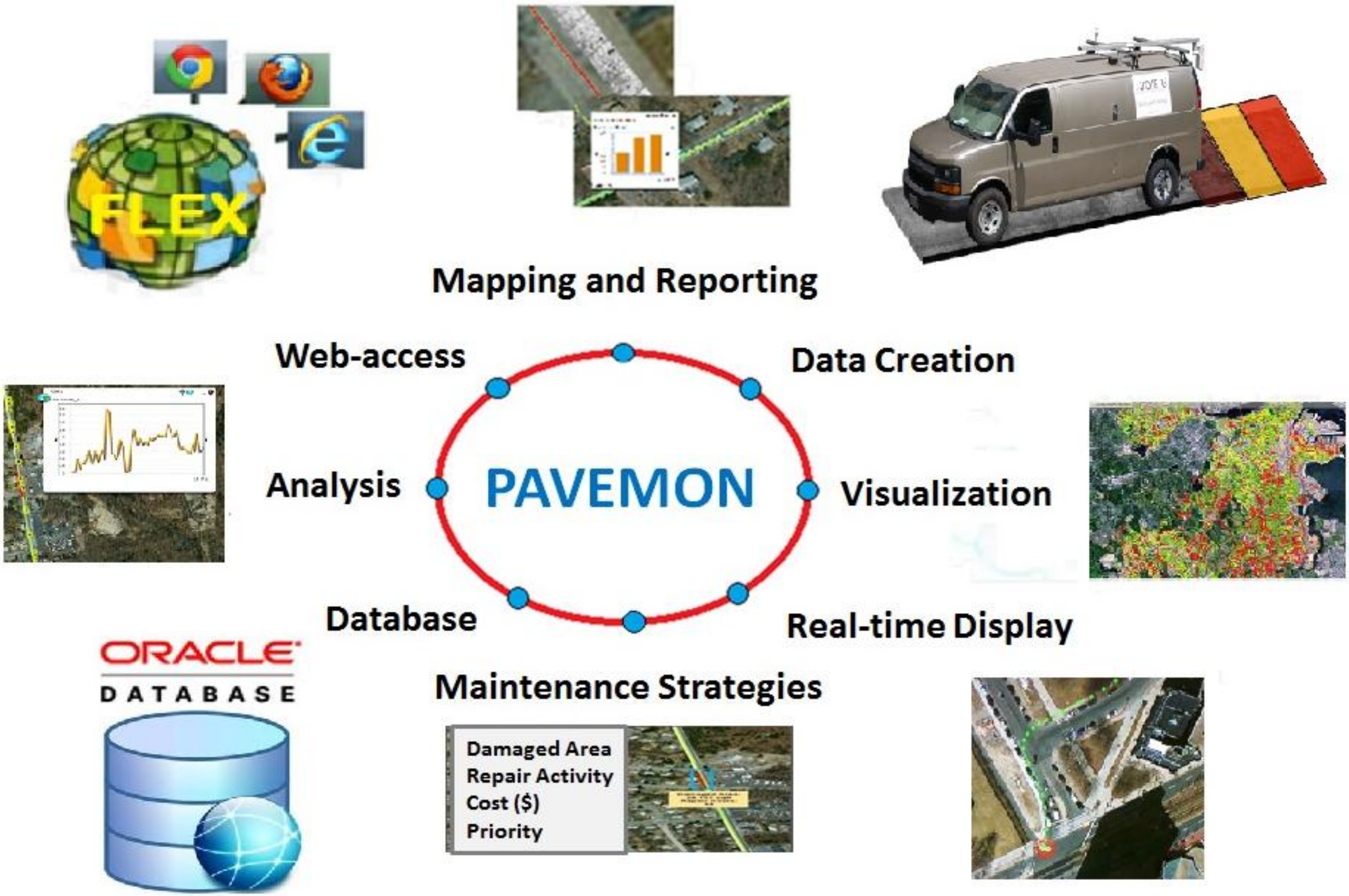
# System Integration

- Automatic VOTERS software package building with multiple build hosts
- Automatic software distribution from a centralized managing server
- Automatic system start-up/stop in the VOO.
- A centralized command center in the VOO to distribute packages to all subsystems



# VOTERS PAVEment MONitoring System



# Versatile Onboard Traffic-Embedded Roaming Sensors

# Technology Examples

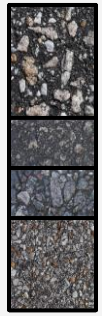
This work was performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9012

# Acoustic Sensor

## Purpose

- Road Mean Texture Depth (*MTD*)
- Pavement Condition Rating (Raveling/Bleeding)
- Friction Coefficient

| MTD (mm) | Mix Type |
|---|---|
| 3.0 – 2.2 | OGFC |
| 2.2 – 1.6 | Novachip |
| 1.6 – 1.0 | SMA |
| 1.0 – 0.2 | Superpave |



NCAT (Interstate Highway)

## Hardware

Microphone

- Sensor Location: driver side, rear tire
- Sensor Height: 1/2 to 3 inch
- Sampling Rate: 2 – 200 kHz
- Sensitivity: 44 – 52 mV/Pa

## Processing Flowchart

**Collect data** → Sound generated by tire/road interaction *plus other noise (engine, wind, etc)*

↓

**FFT** → Frequency spectrum

↓

**PCA** → Extract road texture information from large variation with respect to frequency

↓

**PCA energy ($e$)** → Integration of the first PC over the frequency ranged between 140 to 700 Hz

↓

**Fundamental Equation** → $MTD = 0.2 + 1.55e_n + 0.44\,v_n + 0.76\,e_n v_n$

**PCA** – Principal Component Analysis
PC – Principal Component
$e_n$ – normalized PCA energy, 0~1
$v_n$ – normalized velocity, 0~1

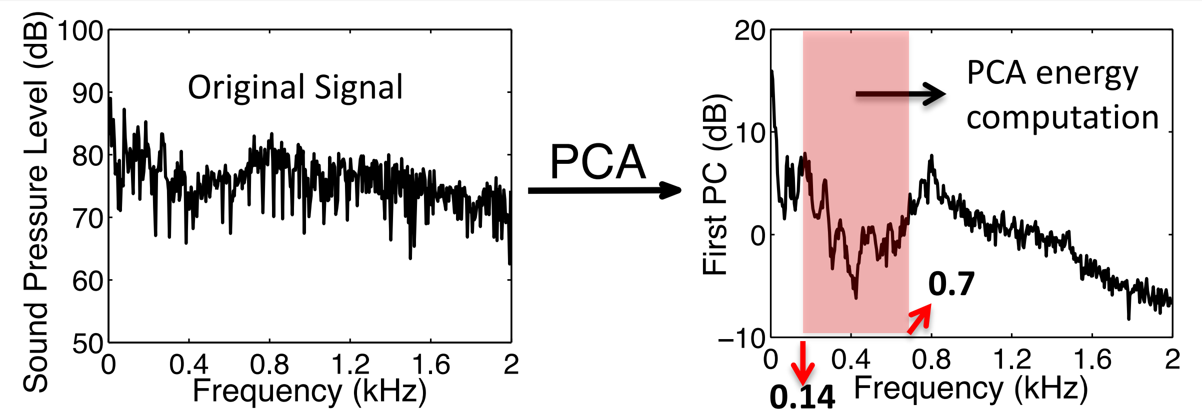
# Acoustic Sensor

## Experiment Description

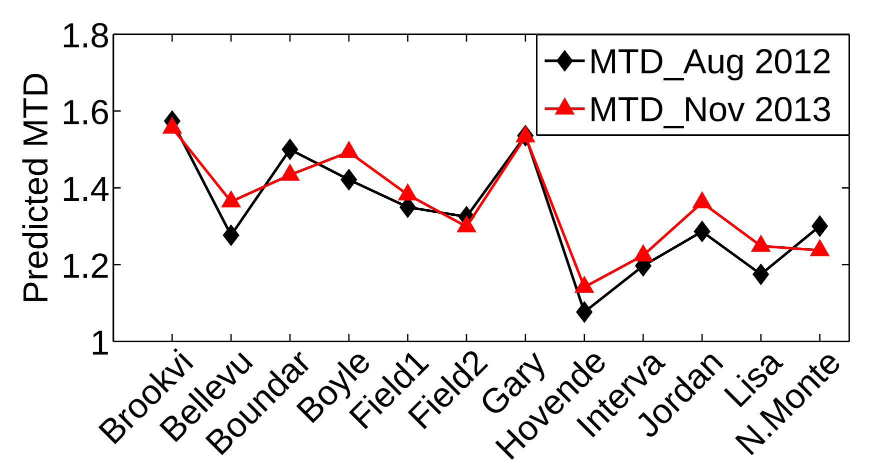
Drive vehicle over urban road at speed of 20 ~ 50 mph to determine MTD *every second*

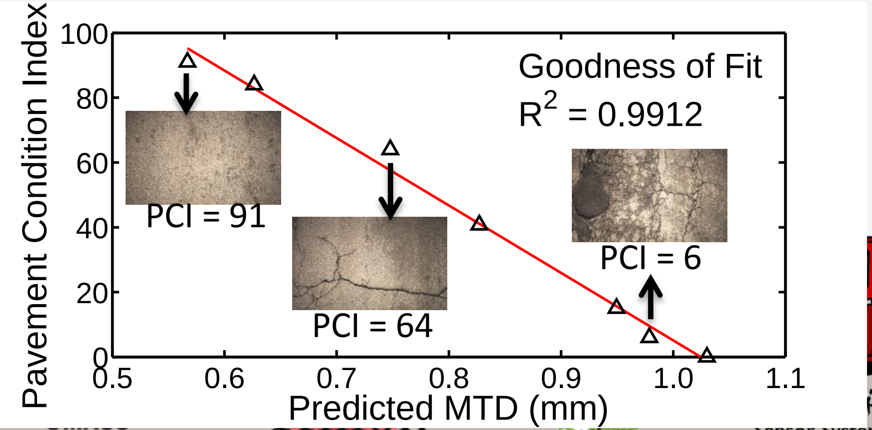
## Results

- PCA Treatment




- MTD Prediction for City of Brockton




## Conclusions

- MTD is estimated for ***highway*** **with 83.6% accuracy**
- **VOTERS MTD is inversely proportion to PCI and repeatable for urban roads**

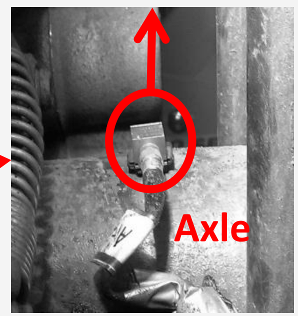
# IRI Measurement Using DTPS

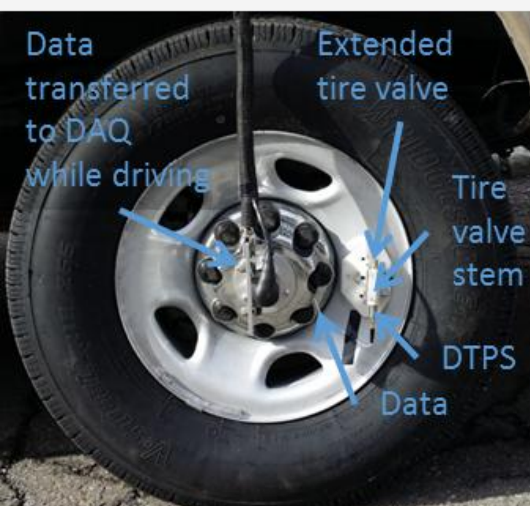
## Purpose

- Road Profile Measurement
- International Roughness Index Assessment

## Hardware


### Accelerometer




$$h_{road} = F^{-1}\left\{\frac{P_{dtps}}{G_r} - \frac{A_{axle}G_a}{G_r}\right\}$$

$h_{road}$: road profile (cm)
$P_{dtps}$: dynamic tire pressure (psi)
$A_{axle}$: Axle acceleration (g)
$F^{-1}$: inverse Fourier Transform
$G_a, G_r$: transfer function

## Processing Flowchart

**Collect data** → DTPS and Acceleration Subtract DC gain

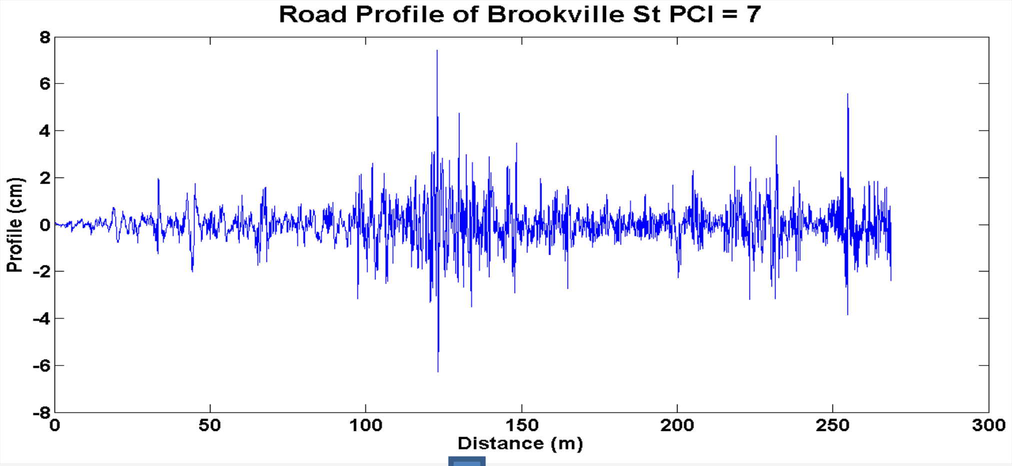
**FFT** → Frequency spectrum

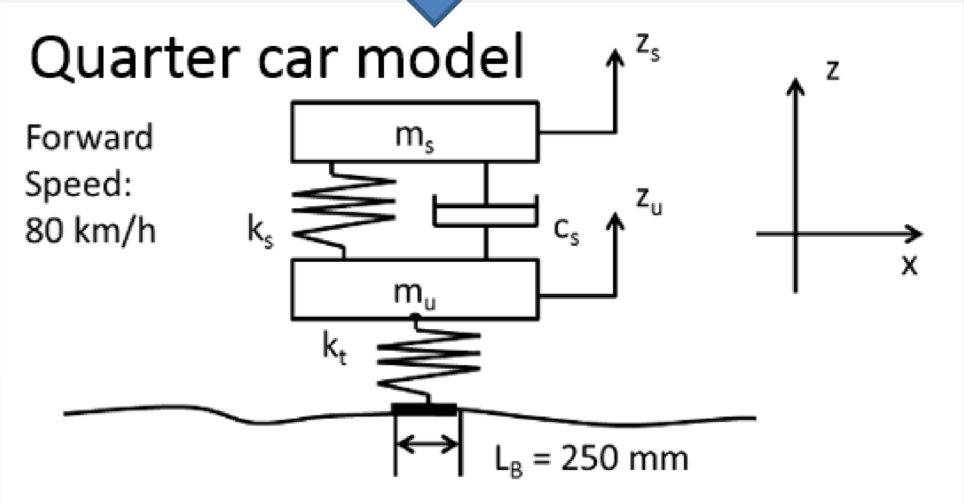
**Transfer Function** → Calculate dynamic tire pressure due to road profile

**iFFT** → Road Profile

**IRI** → **Quarter Car Model Applied based on ASTM standard E1926-08**

# IRI Derived by DTPS Road Profile




$$|R| = \frac{1}{L}\int_0^{\frac{L}{v}} |\bar{Z}_s - \bar{Z}_u|\,dt$$

$Z_s = the\ height\ of\ sprung\ mass$

$Z_u = the\ height\ of\ unsprung\ mass$

$L = distance\ traveld\ in\ m\ (> 160m)$

$v = 22.2\ m/s\ \ (80\ km/h)$

$\bar{Z}_s = \frac{dZ_s}{dt}\ in\ m/s$

$\bar{Z}_u = \frac{dZ_u}{dt}\ in\ m/s$

IRI = 11.3 m/km

# IRI Measurement Using DTPS

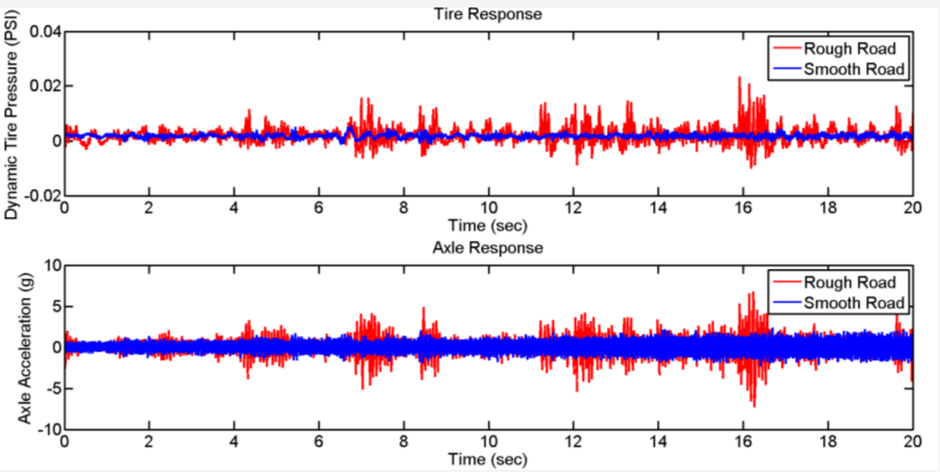
## Experiment Description

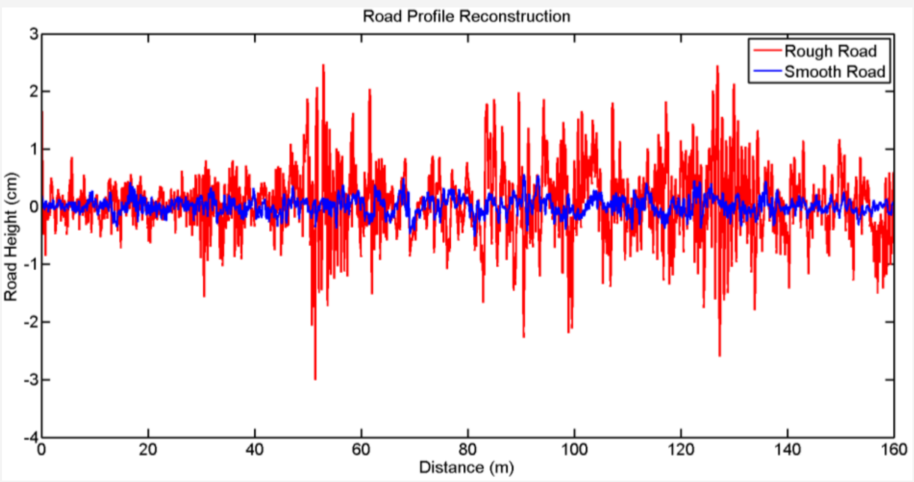
- Survey roads in the city of Brockton, MA
- Urban roads with PCI values
- Surface images taken every 1.3 meter
- Riders' feedbacks recorded

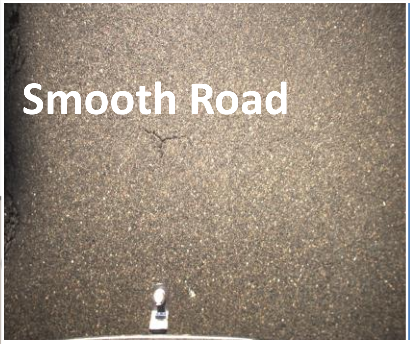
## Conclusions

- **Road profile can be measured using DTPS**
- **IRI results coincide with**
  - **PCI values based on ASTM standard**
  - **Riders' feedback**
  - **Images taken with the camera**

## Results



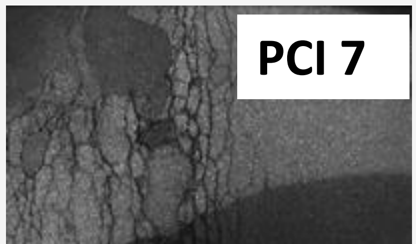

**IRI = 2.6 m/km**
**PCI = 91**
**Good**
**Comfortable**

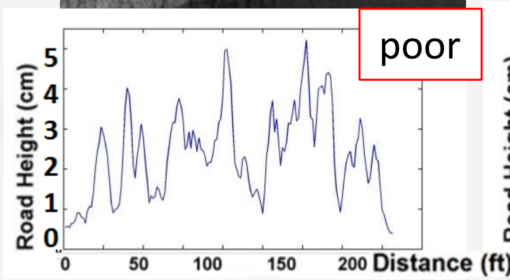

**IRI = 9.5 m/km**
**PCI = 7**
**Failed**
**Bumpy**

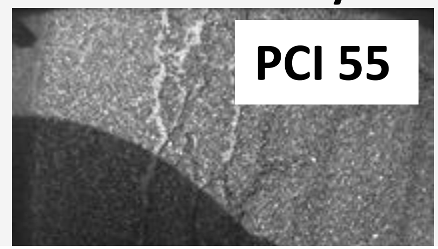
# Measuring Road Profile by Dynamic Tire Pressure Sensing (DTPS)

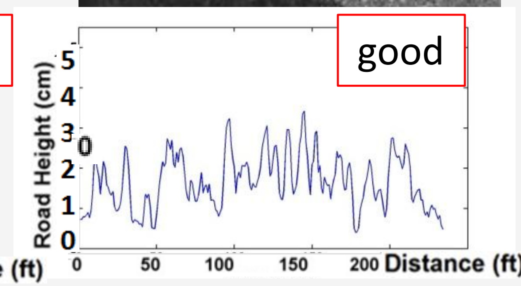
- **DTPS measures dynamic response of the tire-road interaction.**
- **DTPS is independent to driving speed.**
- **Axle accelerometer used for eliminating pressures caused by axle motion.**

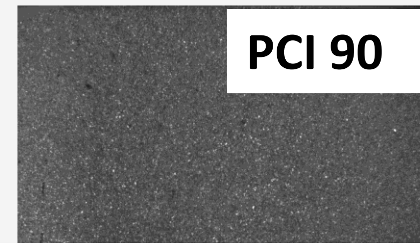
$$P_{total} = P_{road} + P_{axle}$$

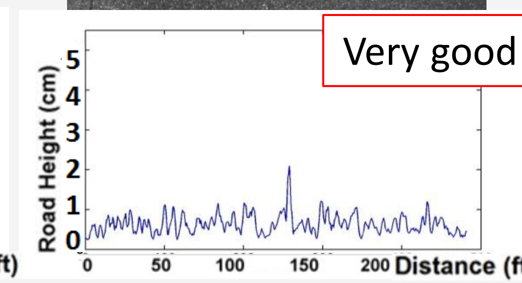



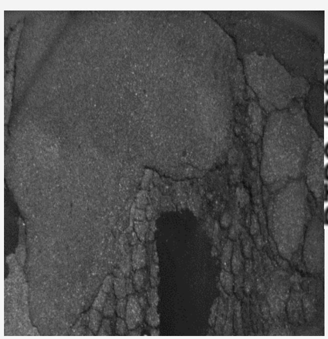



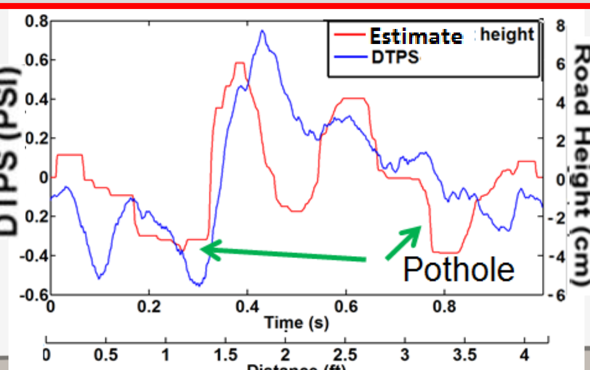



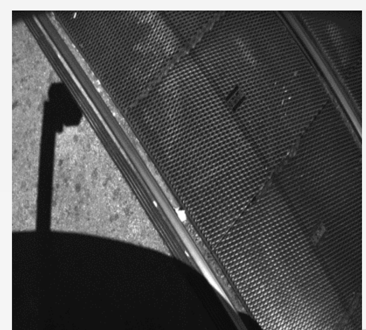



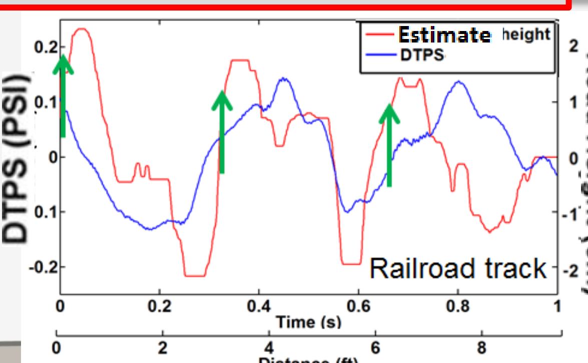




Test performed at normal driving speed --- & --- road height plot generated in real time

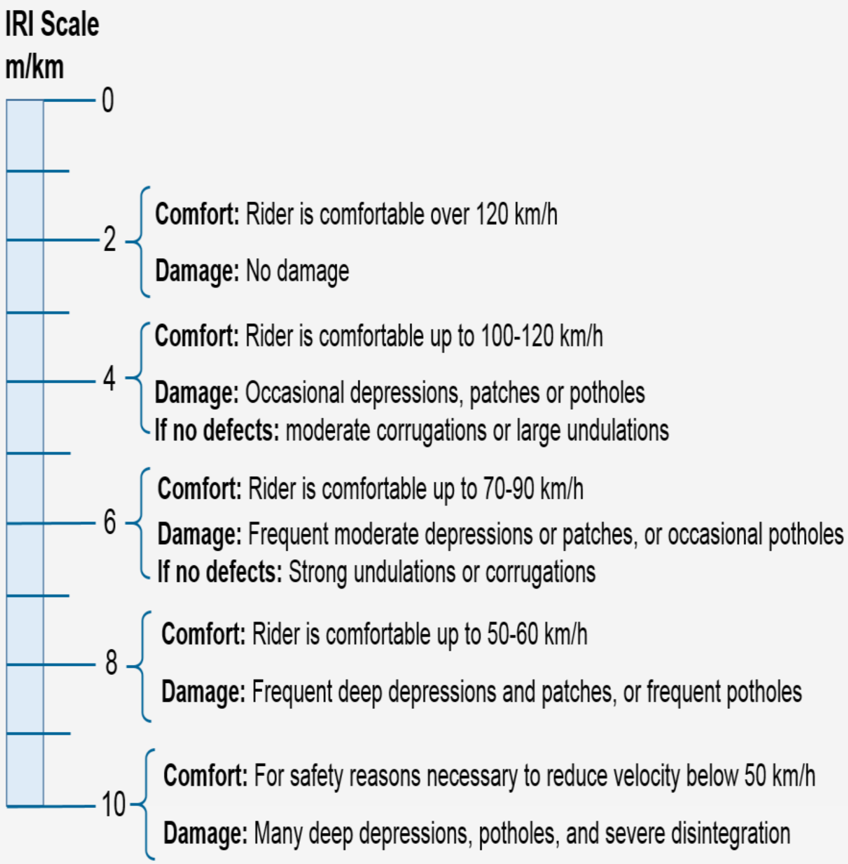






# Brockton Example

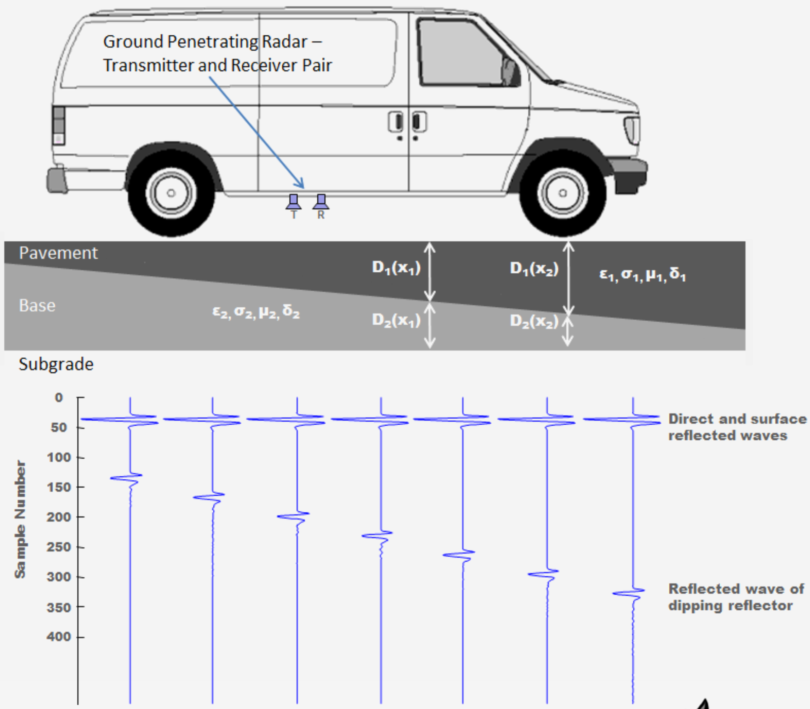



**IRI prediction of road profile from DTPS**

| | IRI m/km (Lane 1) | | | IRI m/km (Lane 2) | | |
|---|---|---|---|---|---|---|
| PCI = 90 | 3.2 | 2.5 | 3.0 | 2.6 | 2.9 | 3.0 |
| PCI = 90 | 2.3 | 3.2 | 3.5 | 3.2 | 3.9 | 2.9 |
| PCI = 55 | 7.6 | 8.6 | 8.5 | 6.8 | 7.1 | 7.5 |
| PCI = 64 | 4.9 | 4.0 | 3.6 | 5.8 | 5.0 | 5.9 |
| PCI = 12 | 12.1 | 11.0 | 12.4 | 10.2 | 9.9 | 8.8 |
| PCI = 7 | 11.3 | 9.4 | 9.3 | 9.8 | 11.9 | 11.3 |

# Subsurface Sensing with GPR

- Use vehicle-mounted mobile ESS-GPR array
- **Automation of layer and void detection**
  - **thickness $d_i$ and electromagnetic properties** of the roadway layers *i*: conductivity $\sigma_i$ and dielectric constant $\varepsilon_i$, estimates of horizontal extend of voids, focusing on the detection of pothole precursors, and voids.
- Presentation of subsurface roadway layers and other GPR detected sub-surface distresses will be included as specific data layers in the GIS system





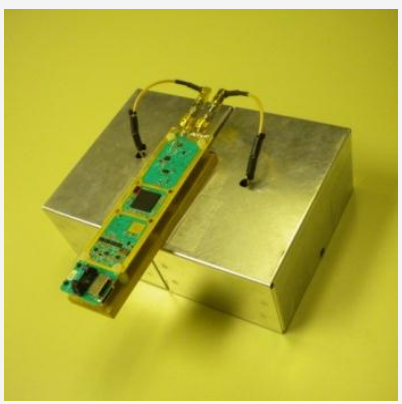
Northeastern
The University of Vermont
UMASS LOWELL
Trilion
Earth Science Systems
VOTERS Sensor Systems

# Subsurface Radar System

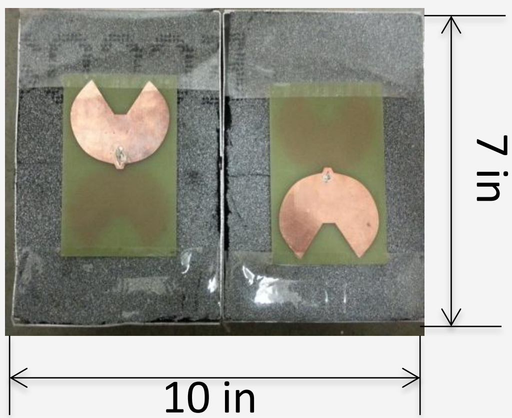
## Purpose

- Subsurface profile for pavement
- Layer thickness and dielectric constant
- Location of distress
- Correlation with modulus elasticity

## Hardware



a. Radar board by ESS




b. NEU Pacman Antennas

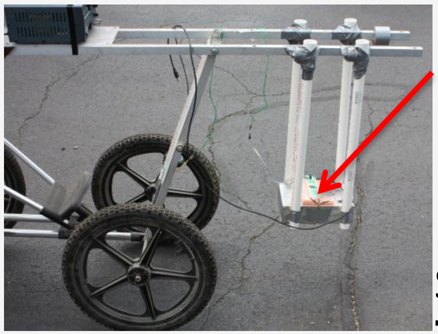
## Processing Flowchart

| | |
| --- | --- |
| **Collect data** | Reflected signal in time domain |
| **Cross correlation** | Layer Boundaries, and Traveling Time (***t***) |
| **Deconvolution** | Reflection Coefficient (***Υ***) |
| **Fundamental equations** | Dielectric constant (***ε***)<br>Phase Velocity (***v***),<br>and Thickness (***d***) |
| **Abnormity search** | **Possible locations of damage** |

# Subsurface Radar System

## Experiment Description

Move radar over pavement road at 5 mph in air-couple to identify pavement layer and possible locations of damage.



**Radar system**
Height to ground : 1 ft

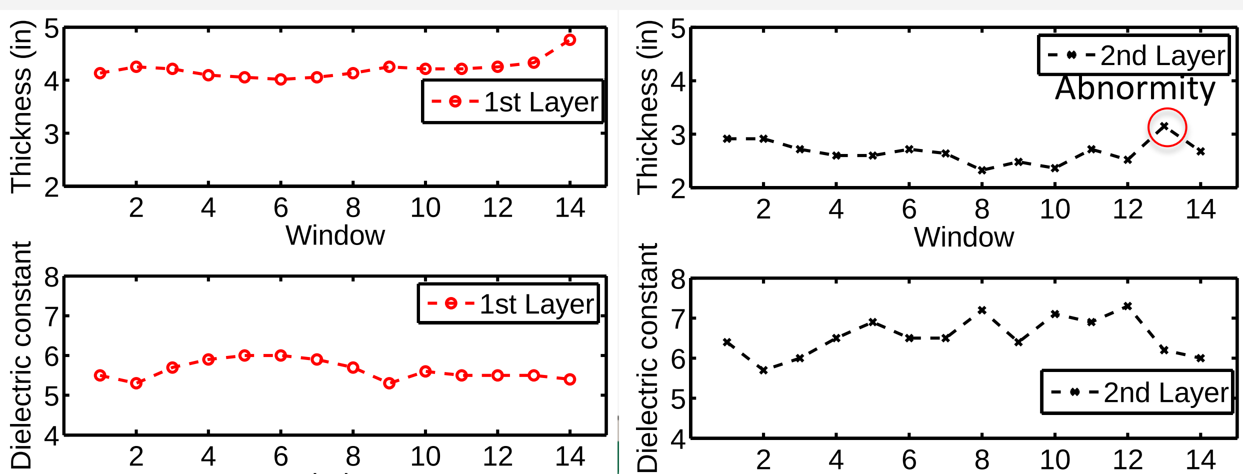
Scan direction →

Test Specifications:

- Frequency : 2 GHz
- Sampling rate : 32 psec
- Resolution : 30 traces/ft
- Penetrating depth in subsurface: ~2 ft

## Results

Data Source: Pavement road between Snell and Library, Northeastern Univ., Boston, MA




Average Layer Properties in Each Window [Window Length: 3.28 ft (1 m)]

## Conclusions

- Layer thickness and dielectric constant can be identified.
- Distress can be identified, such as prepothole and delamination.

# Air-coupled Radar for Pavement

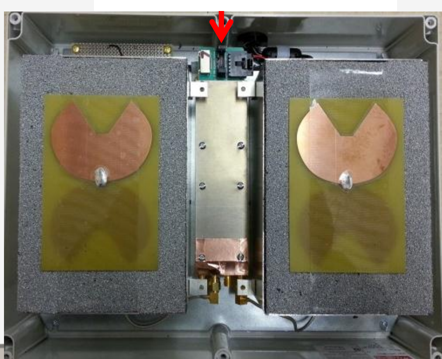
## Hardware

Specifications

- Frequency : 2 GHz
- Sampling rate : 32 ps
- Resolution : 1 trace/ms


ESS Gen3 radar
(Overview)

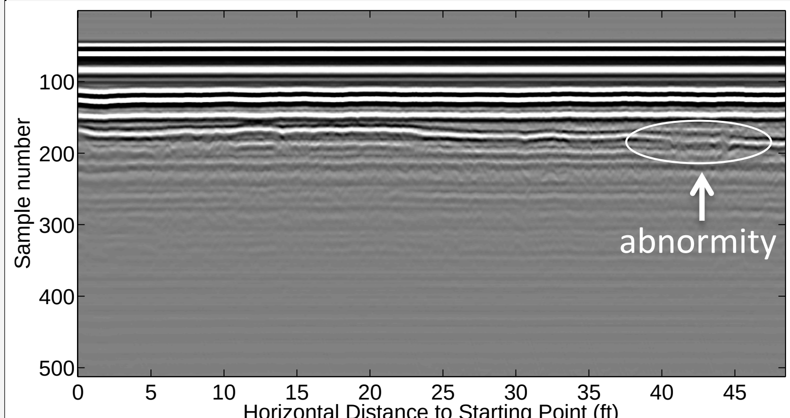
*Radar board*



ESS Gen3 radar
(Inside box)

## Layer Identification Results

Data Source: **Asphalt pavement** on campus




Raw data image

**Collect data** → Reflected signal in time domain

↓

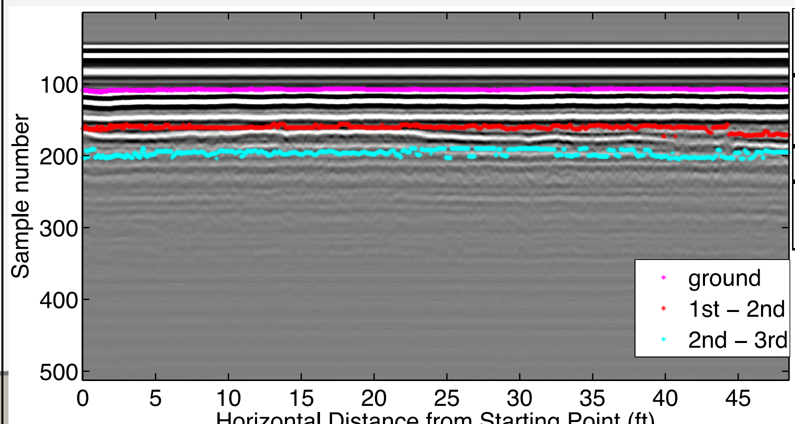
**Cross correlation** → Layer boundary, and traveling time (***t***)

↓

**Deconvolution** → Reflection Coefficient (***Υ***)

↓

**Fundamental equations** → Dielectric constant (***ε***), Velocity ***(v)***, Thickness (***d***)




Layer tracking on radar image

| Pavement Profile | Layers | Depth (in) | Dielectric Constant (No Dim.) |
|---|---|---|---|
| | Asphalt Concrete | 4~6 | 4.4~6.4 |
| | Compacted gravel | 3~4 | 6.6~11.5 |
| | Subgrade (natrual soil) | INF | – |

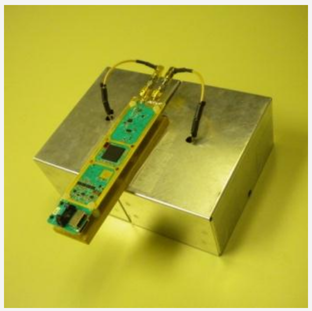
Table 1. Pavement Profile

# Corrosion Analysis using Air-coupled GPR

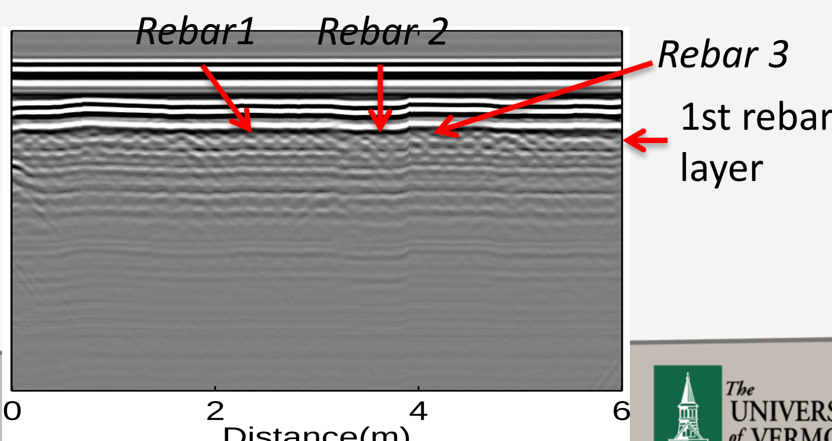
## Purpose

- Determine the level of rebar corrosion using air-coupled GPR

## Hardware

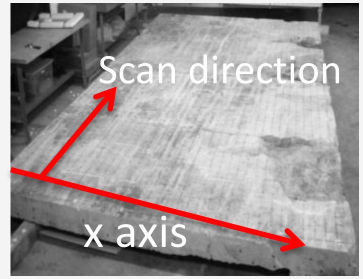

Radar by ESS (2GHz)

Experiment setup (Air-coupled)



B-scan along x=4ft

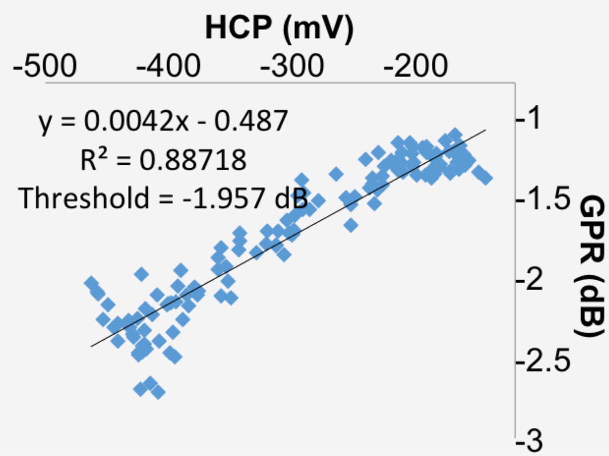
## Experimental Results



Test bed – Sawcut bridge decks


Chandler Rd. bridge (Andover, MA)


Hopkins St. bridge (Wakefield, MA)



Ground-coupled GPR *vs.* HCP

**Threshold of GPR:**
<-1.957dB→Corroded
>-1.957dB→Healthy

**Air-coupled** Results
*Rebar 1*: -1.65dB→Healthy
*Rebar 2*: -3.69dB→Corroded
*Rebar 3*: -0.38dB→Healthy

## Indications

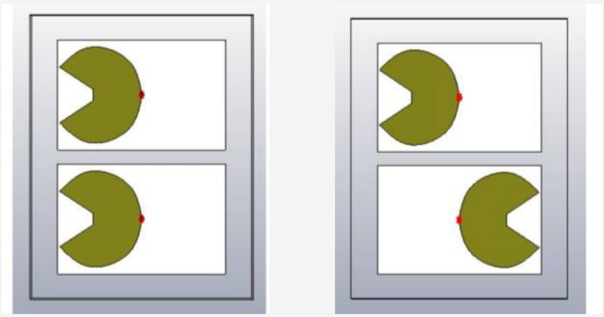
**Rebar corrosion level can be derived by GPR amplitude.**

# Antenna Array Configuration

## Purpose

- To improve performance of GPR by antenna array

## Hardware



Parallel Anti-Parallel

**Fig 1**. Pacman antenna array as receivers

One-Two (One Tx with Array as Rx's

One-One (One Tx with One Rx)

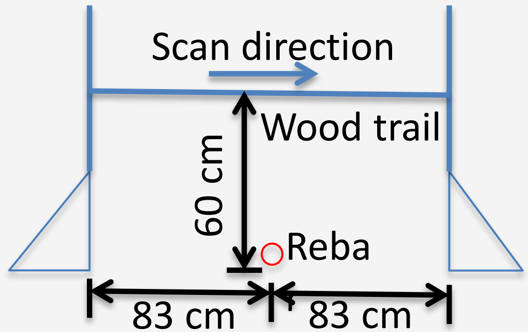
**Fig 2**. One-two and One-one connections

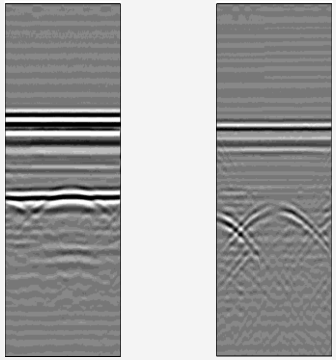
## Experimental Results

Test Specifications:

- Frequency : 2 GHz; Resolution : 30 traces/ft
- Sampling rate : 32 psec

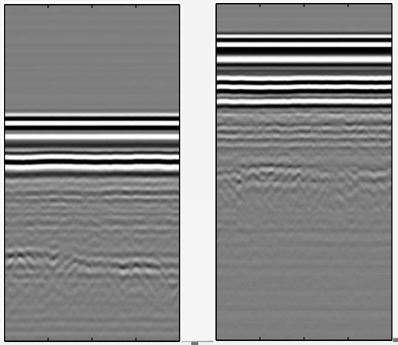
a. Rebar on the ground



Parallel Anti-Parallel

b. Test on pavement road in air-couple



One-Two (Parallel) One-One

## Conclusions

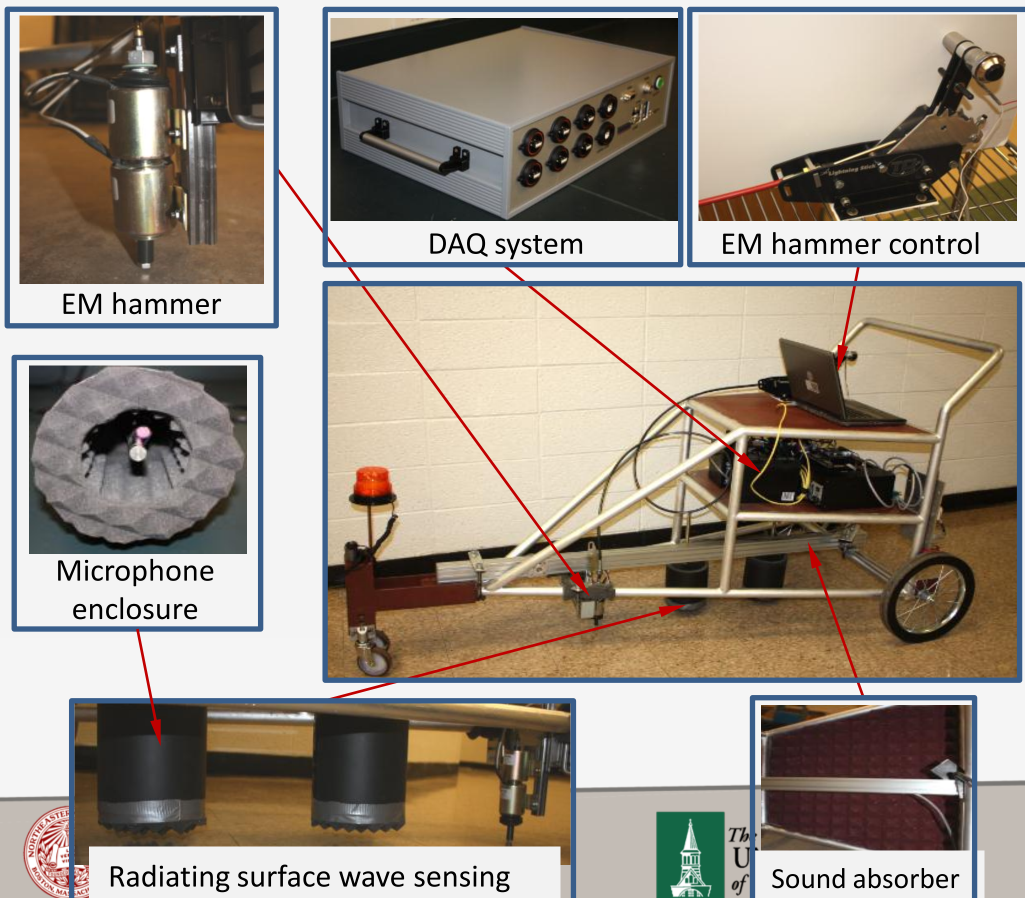
- **Parallel: increases the gain → better identification of sub-layer**
- **Anti-Parallel: removes horizontal layer reflection → better at objects identification (e.g., rebar)**

# Mobile Acoustic Subsurface Sensing (MASS) System for Pavement

## Objectives

- Subsurface profile assessment
- Non-contact mobile sensing by acoustics at walking speed

## Hardware




## Processing Flowchart

**Collect data** → Acoustic signal of radiating surface wave by microphone array

↓

**Windowing and filtering** → Hanning window to filter the radiating surface wave

↓

**FFT and Transfer Function** → Frequency domain analysis

↓

**Dispersion Curve** → Dispersion curve calculation

↓

**Inversion analysis** → Subsurface profile and parameters

# Mobile Acoustic Subsurface Sensing (MASS) System for Pavement

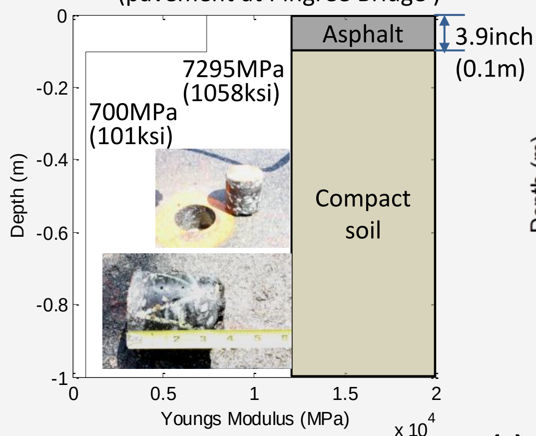
## Prototype Results

(a). asphalt pavement; (b). concrete bridge deck and (c). Parking lot

## Results

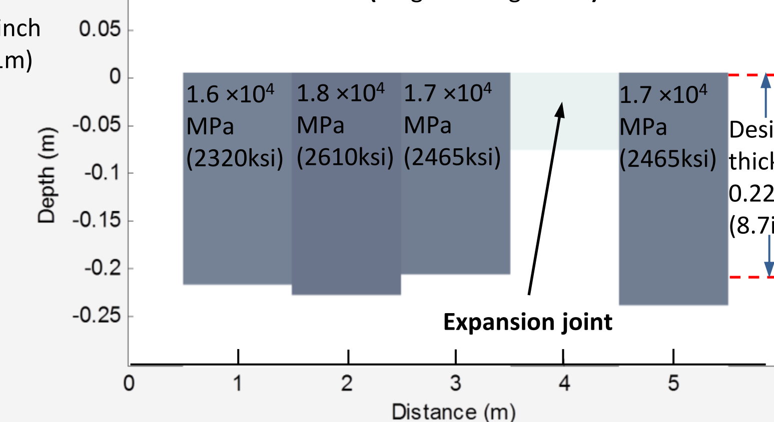
**(a). Asphalt Pavement**

(pavement at Pingree Bridge )



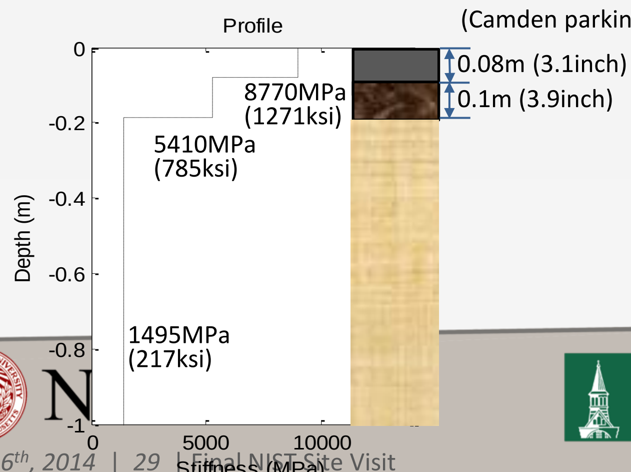

**(b). Concrete Bridge Deck**

**(**Pingree bridge deck**)**




**(c). Parking Lot**

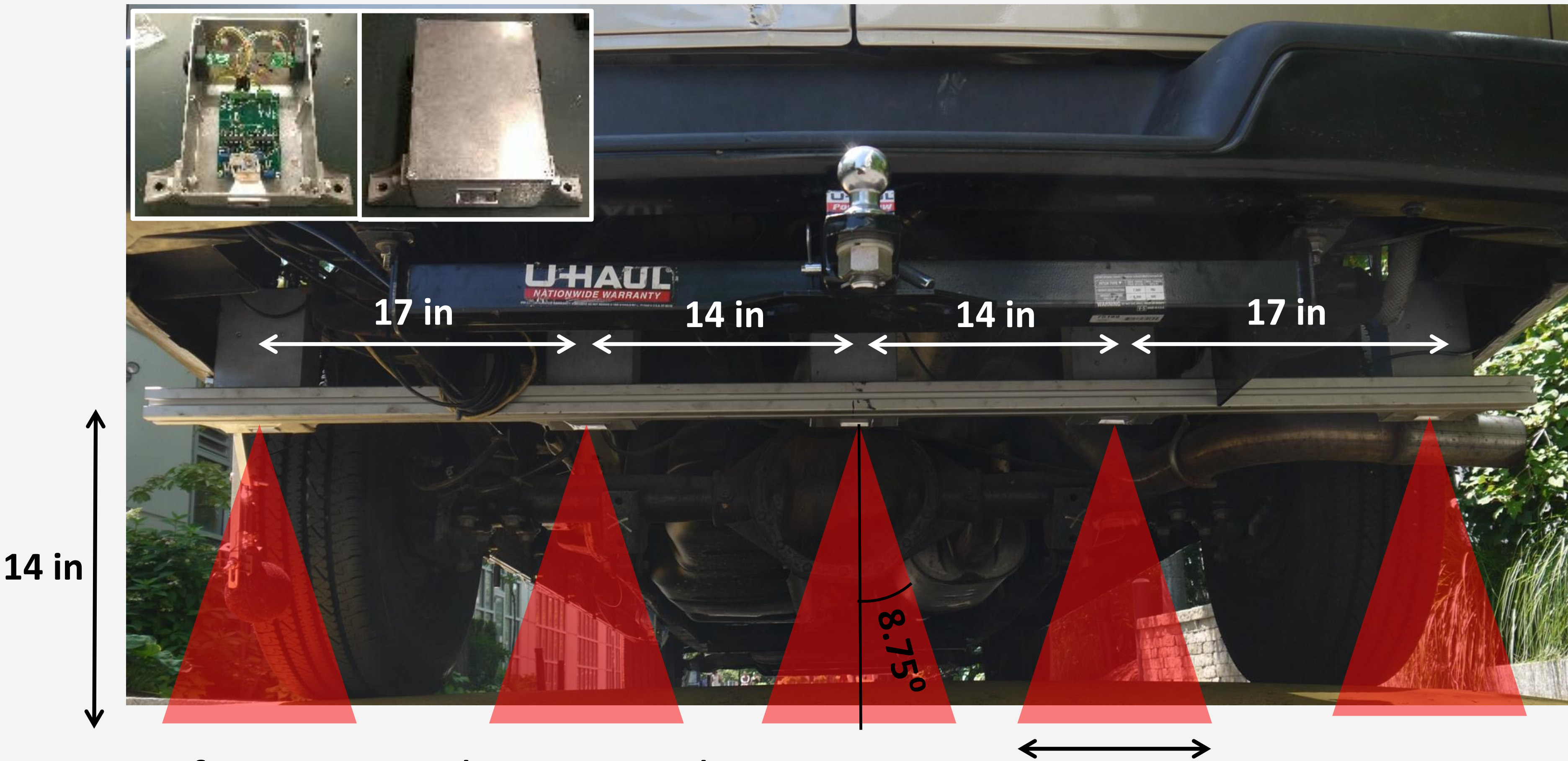
(Camden parking lot, NEU)




## Conclusions

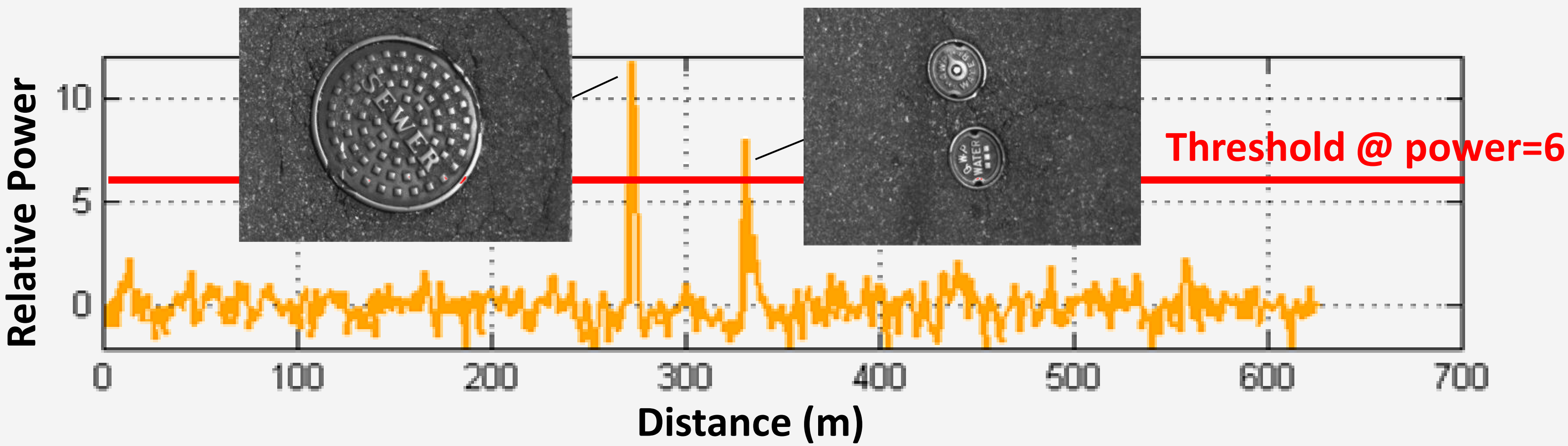
- Integrated hardware & software prototype for non-contact and mobile acoustic sensing
- Determine layer depth and Modulus of Elasticity

# 24 GHz Millimeter-Wave Radar Array

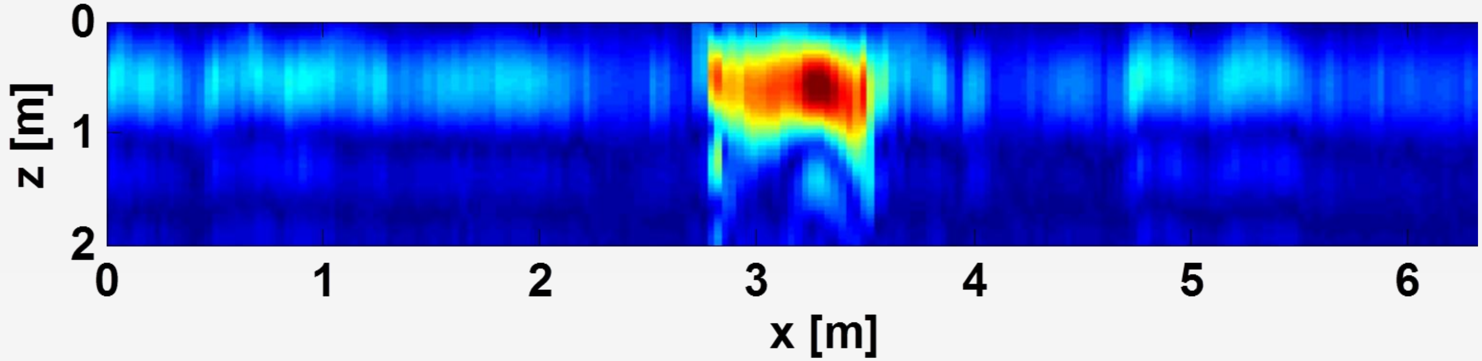



- Surface material
- Road profile
- Potholes
- Patches
- Rutting
- Roughness

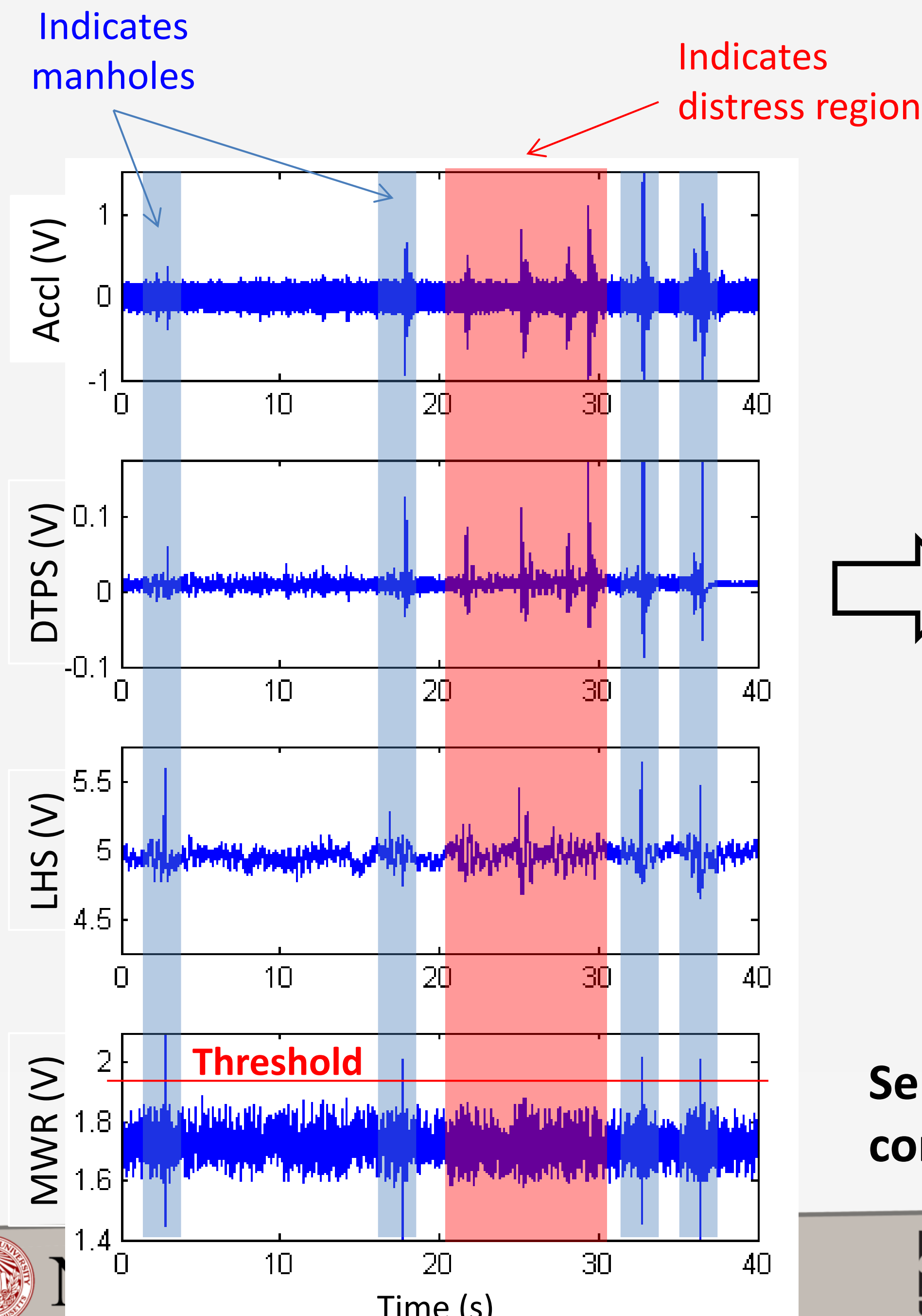
# Material Characterization Example

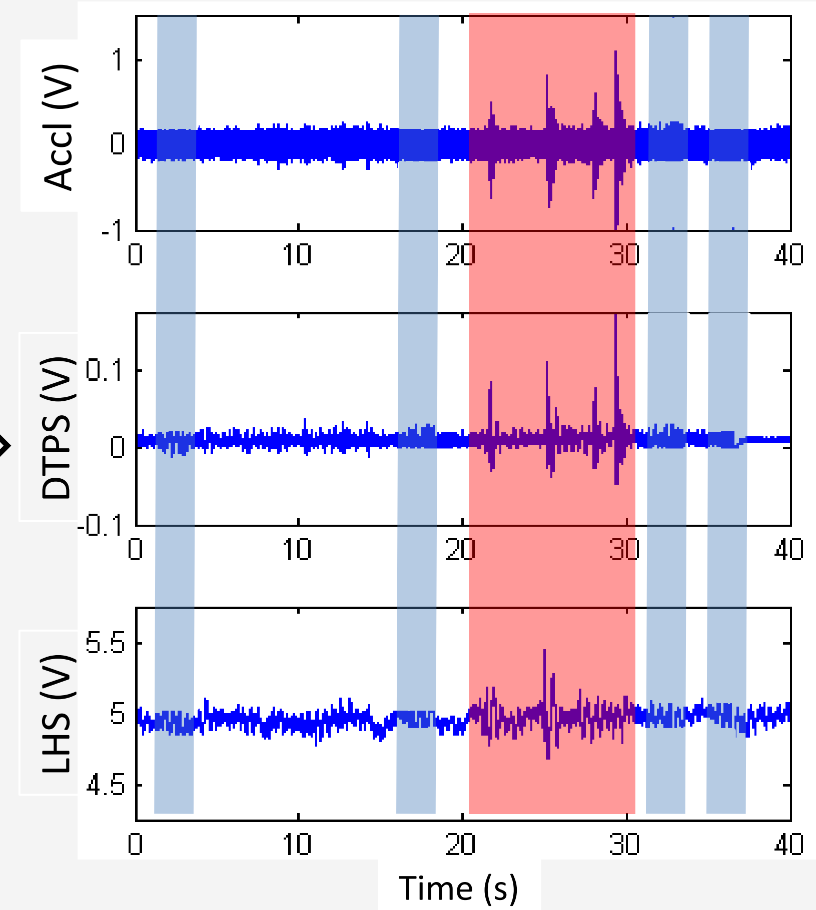



Crossing a metal plate – Range Representation

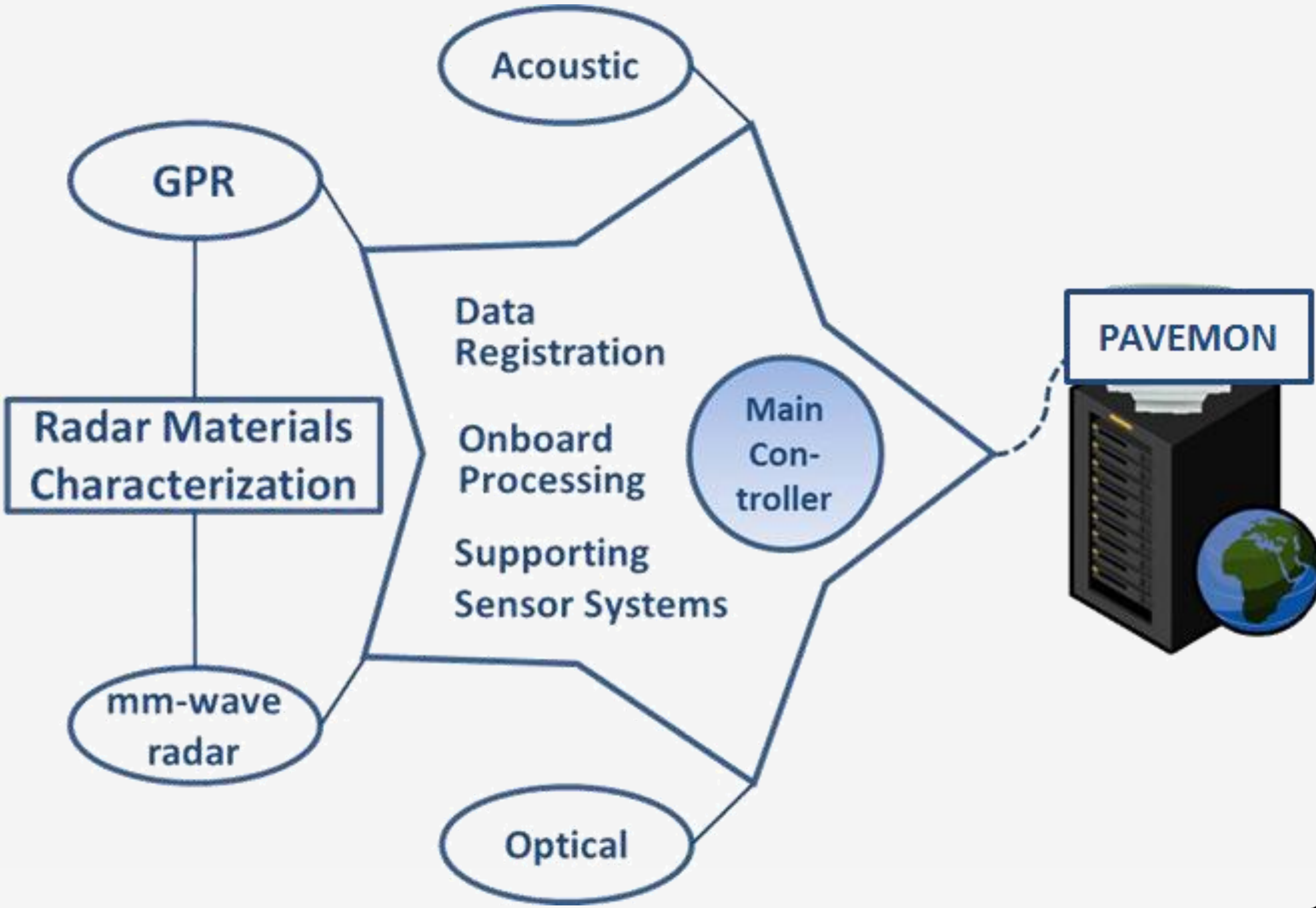


# Filter out non-PCI events

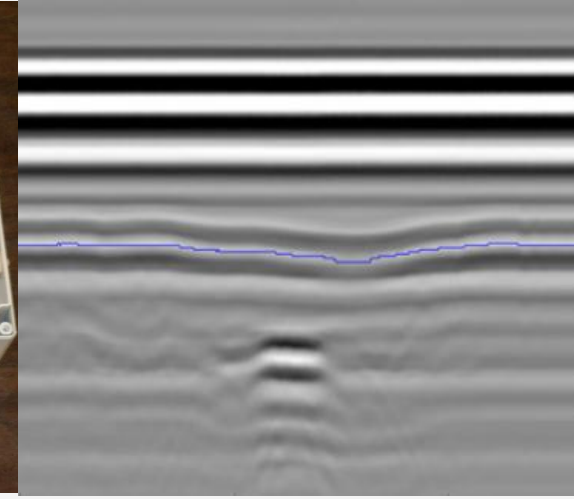



**Sensors confirm and complement each other**


Acoustic
GPR
Radar Materials Characterization
mm-wave radar
Optical
Data Registration
Onboard Processing
Supporting Sensor Systems
Main Con-troller
PAVEMON

# ESS Gen3 GPR



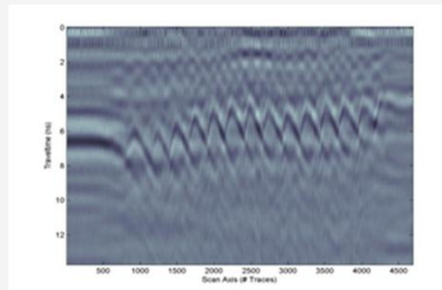
- Frequency Range: 2-5 GHz
- Novel 100 GHz 1 bit sampler
- Dynamic Range: 105 dB
- Fast acquisition speed: 1000 traces/sec
- Power: 7W at 5 VDC
- Array Acquisition: Up to 16 Tx & 16 Rx channels
- Simultaneous multi-offset acquisition
- Diversity in frequency, polarization and geometry
- Custom antennas suitable for ground-coupling and air-coupling
- Wheel encoder interface
- Dimensions: 300x230x85 mm
- Acquisition Software (Windows, Linux, others)
- HDF5 open format data storage for large datasets with many free readers

VOTERS
Versatile Onboard Traffic Embedded Roaming Sensors

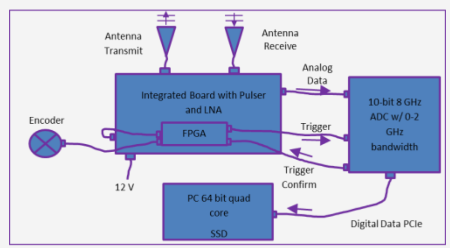
# High Speed Low-Cost, Small Size GPR

D Huston, T Xia, A Venkatachalam, D Burns, Y Zhang, X Xu
University of Vermont, Burlington, VT

- Innovative digital ground penetrating radar system using full waveform digitization of radar signals
- Enables reduced radiated emissions, FCC 02-48 compliance path for highway speed imaging of bridge deck reinforcing bars
- Image quality comparable to commercial systems using conventional subsampling.
- Waveform sampling ASIC technology [1] demonstrated for low-cost multichannel scalable system

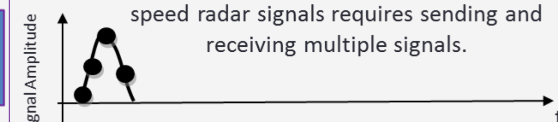



B-scan of rebar mesh


System schematic


Standard method of subsampling high speed radar signals requires sending and receiving multiple signals.




Full waveform sampling of high speed radar signals allows sending and receiving fewer signals. N.B. short duration duty cycle followed by long idle time

This work was performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9012

[1]Univ of Chicago H Frisch, E Oberla

Northeastern | The University of Vermont | UMASS LOWELL | Trilion | Earth Science Systems | VOTERS Sensor Systems

# SOPRA

## Surface Optical Profilometry Roadway Analysis

### SOPRA Video

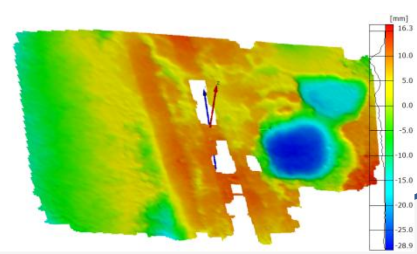
**GOALS:**
- Streaming Video data collection, 100% coverage.
- Optimal imaging for precise analytical analysis

**STATUS:**
- Fully operational
- Automated Data Collection
- Automated Data Upload
- Automated Publication

### SOPRA 3D

**GOALS:**
- Streaming 3D video data collection, 100% coverage
- Pulsed illumination
- 0.2mm resolution

**STATUS:**
- Prototype has run on VOO.



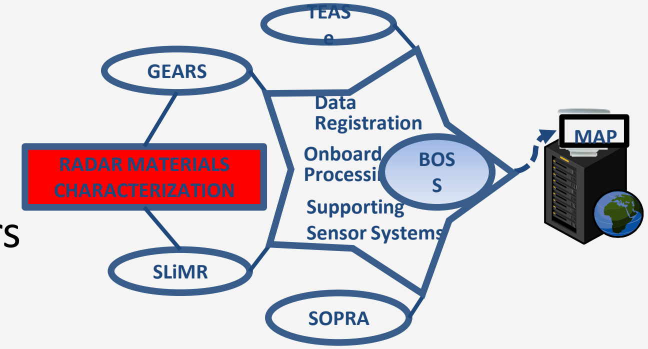
### SOPRA Analytics

**GOALS:**
- Post-processing of SOPRA video images for:
- Road surface visual measurement
- Video registration

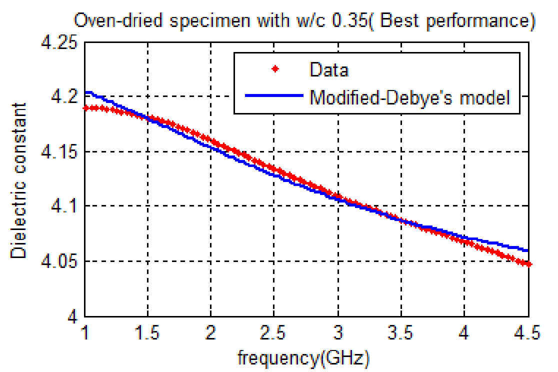
**STATUS:**
- Preliminary 3D data analysis, crack detection, anomaly determination and sizing

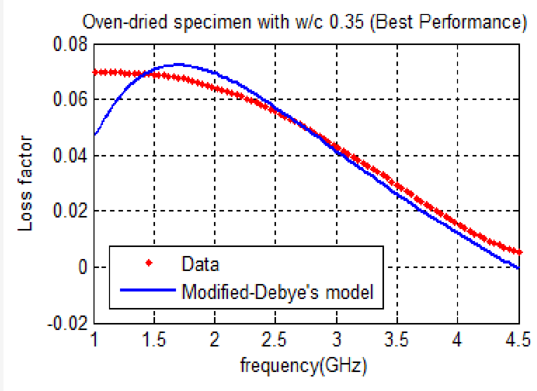
# Radar Materials Characterization

- Major Accomplishment at end of Year 5
  - Experimental dielectric data of construction materials including concrete and asphalt.
  - An inverse algorithm for predicting material parameters




- Dielectric model of cement paste



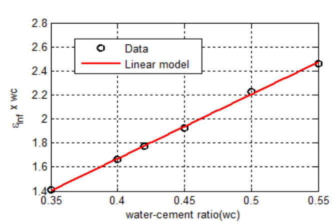



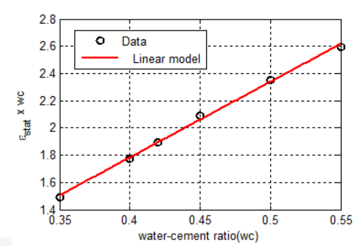

$$\varepsilon_r'^{(m)} = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\omega\tau)^2} - C_1$$

$$\varepsilon_r''^{(m)} = \frac{\omega\tau(\varepsilon_s - \varepsilon_\infty)}{1 + (\omega\tau)^2 - C_3} - C_2$$

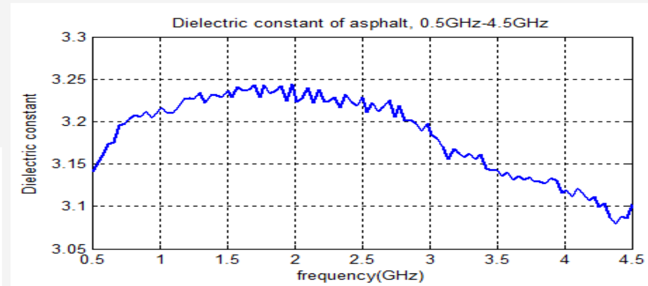
[$C_1$ = (water-to-cement ratio)/10]

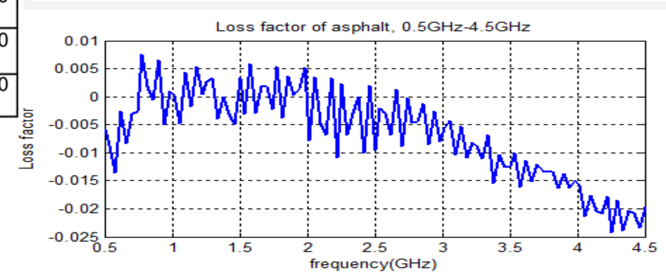
| Specimen | $\varepsilon_\infty$ | $\varepsilon_s$ | $\tau$(ns) | $C_1$ | $C_2$ | $C_3$ |
|---|---|---|---|---|---|---|
| CP35 | 4.0200 | 4.2648 | 0.3367 | 0.0350 | 0.6738 | 0.1420 |
| CP40 | 4.1522 | 4.4395 | 0.3172 | 0.0400 | 0.4945 | 0.0991 |
| CP45 | 4.2823 | 4.6423 | 0.3434 | 0.0450 | 0.3465 | 0.0650 |
| CP50 | 4.4485 | 4.7002 | 0.32737 | 0.0500 | 0.6500 | 0.1710 |
| CP55 | 4.4758 | 4.7182 | 0.30437 | 0.0550 | 0.6726 | 0.1660 |




- Dielectric data of asphalt pavement

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# The VOTERS Team

VOTERS

Versatile Onboard Traffic Embedded Roaming Sensors

This work was performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology (NIST), Technology Innovation Program (TIP), Cooperative Agreement Number 70NANB9H9012

# Thank you!

www.neu.edu/VOTERS

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**Supporting Organizations**