


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Advanced Methods to Identify Asphalt Pavement Delamination (R06D)

Minnesota DOT Evaluation: Calibration and Signal Analysis

Ken Maser, Infrasense
Shongtao Dai, Research Operations Engineer
Kyle Hoegh, Research Scientist
MnDOT

Peer Exchange 2018

U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

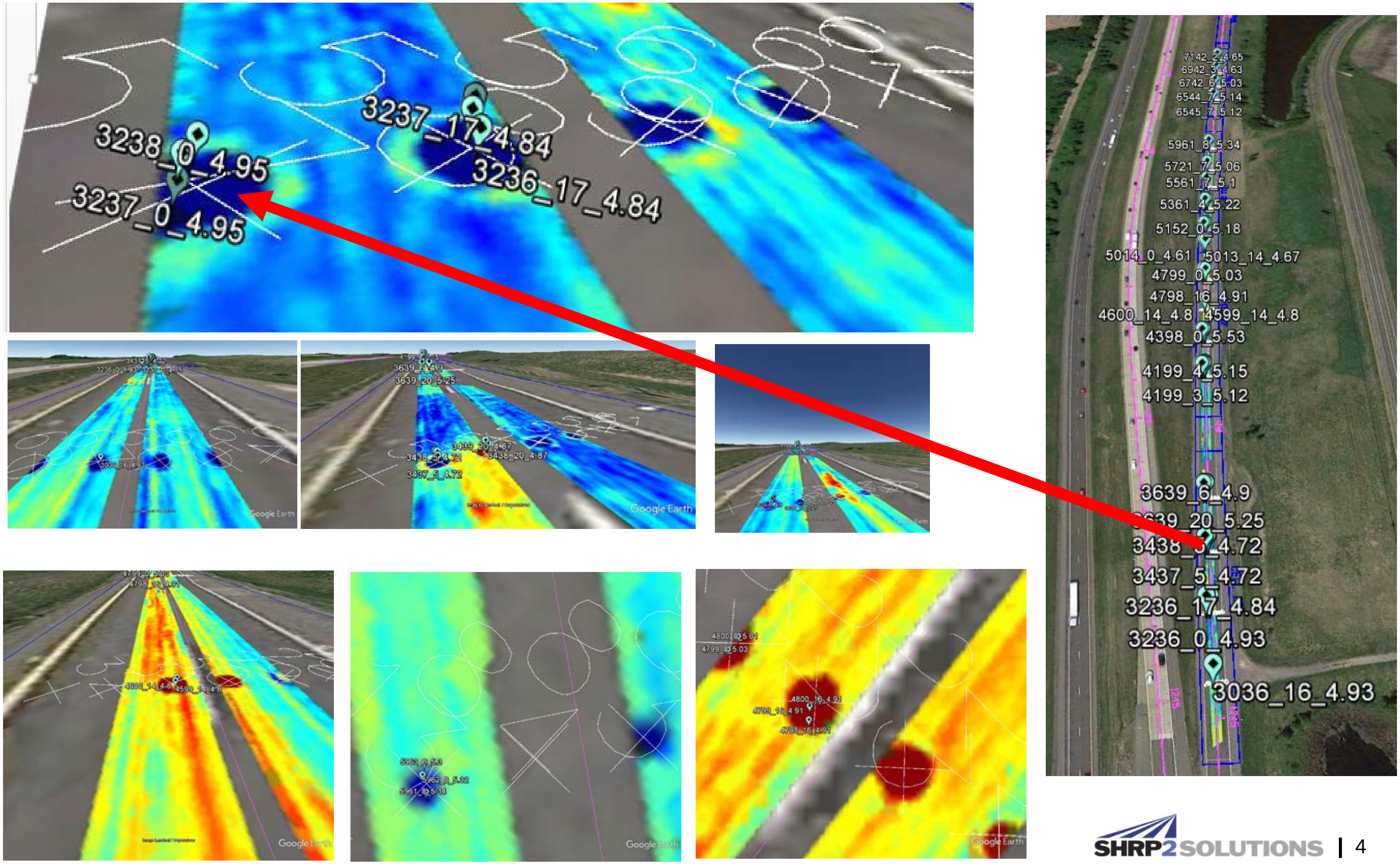
Topics

- Calibration/Validation: Kyle Hoegh
- Activity analysis and applications: Ken Maser
- Advanced Analysis: Shongtao Dai

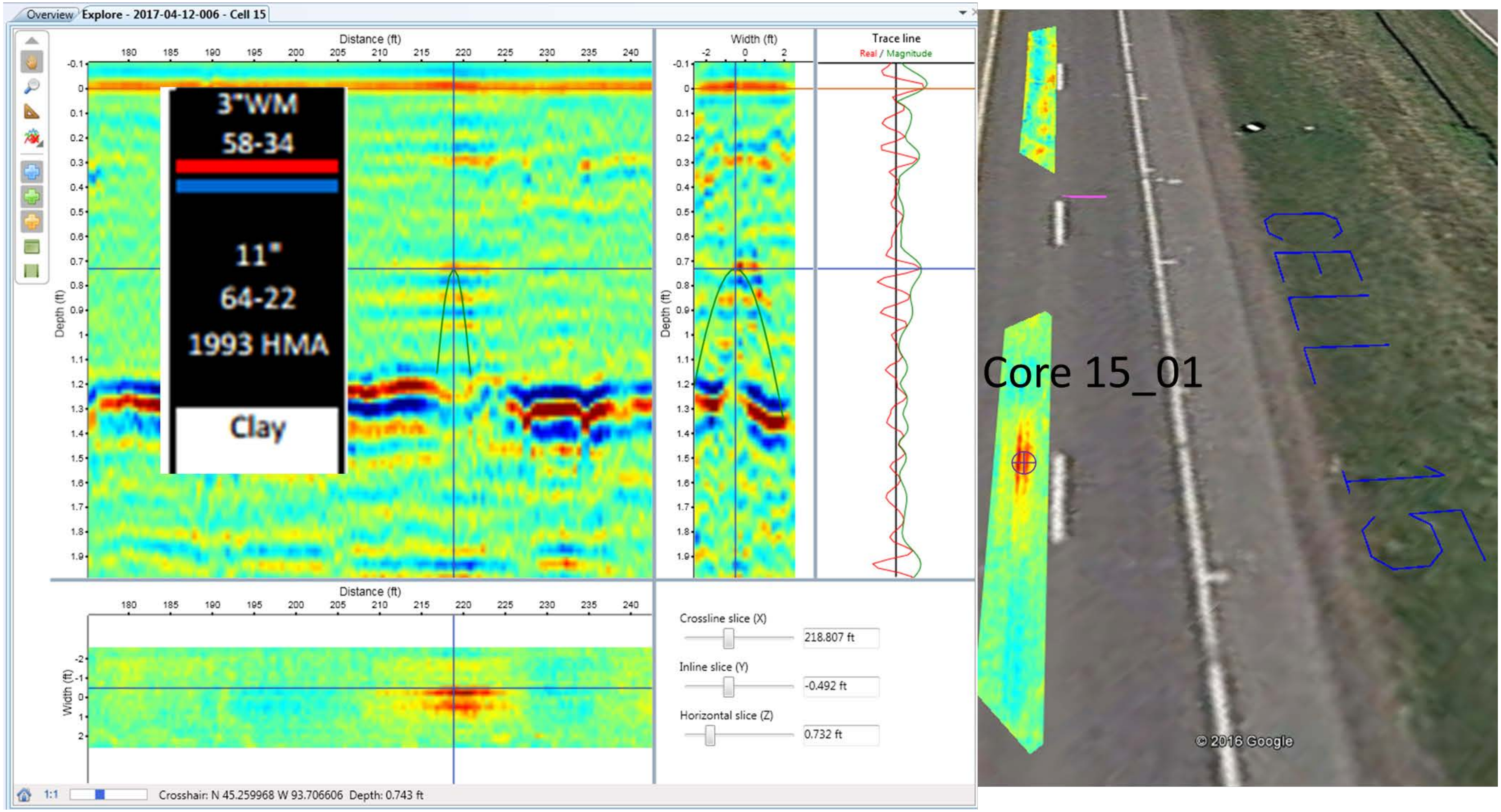
Calibration/Validation Topics

- Highway Speed GPS accuracy (MnROAD)
- Controlled Laboratory Tests (Metal Plate and HDPE plastic)
  - Sampling Rate
  - Metal Calibration
  - Air Calibration

Highway Speed GPS accuracy (MnROAD)



GPS accuracy: Implications for Implementation

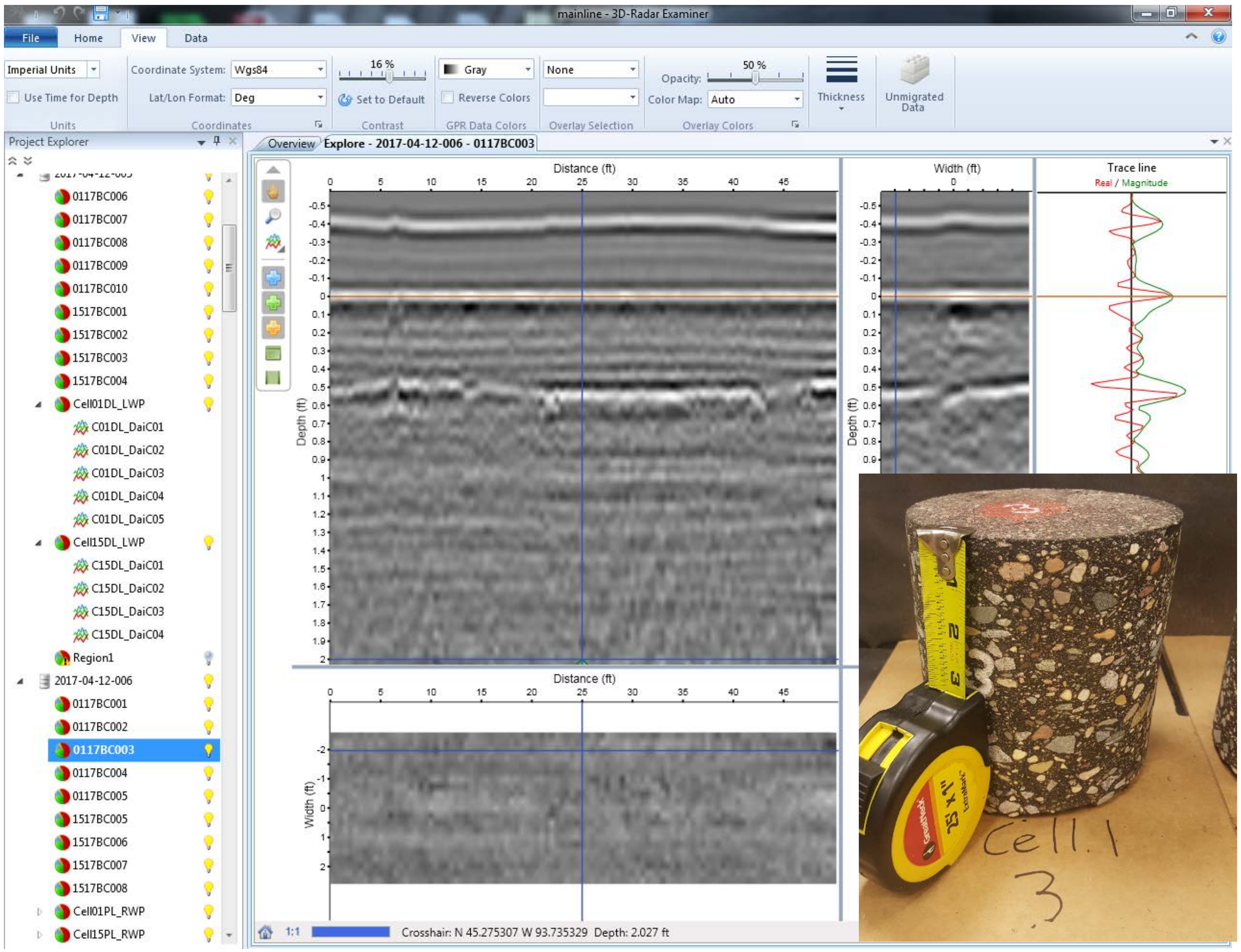


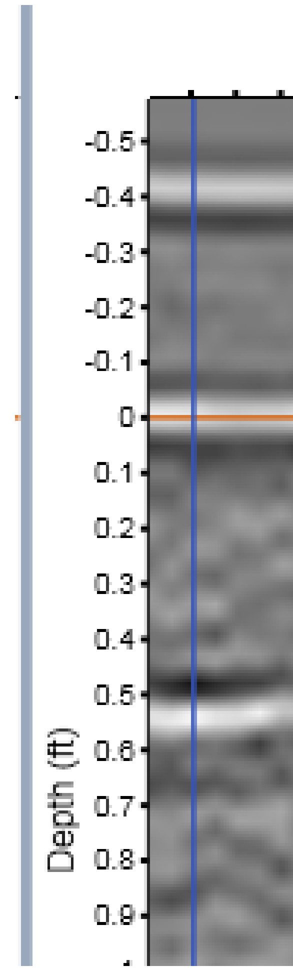
Examiner Results: MnROAD

Cell 1		
Core ID	**Core Condition**	**Qualitative GPR Signal Assessment**
1	shallow slight deter/strip	direct shallow anomaly
2	insignficant	strong backwall
3	none/sound condition	strong backwall
4	lg crack/deterioration	backwall shaddow
5	deterioration (coring caused?)	backwall shaddow/slight direct
6	slight shallow/bottom deterioration	backwall shaddow
7	shallow slight deter/delam	direct shallow anomaly
8	minimal middepth stripping	slight shaddowing
9	slight deterioration/strip	direct reflection (deeper than distress)
10	shallow slight deter/delam	banding/shaddowed backwall

Examiner Results: MnROAD Sound Pavement, Clear Signal

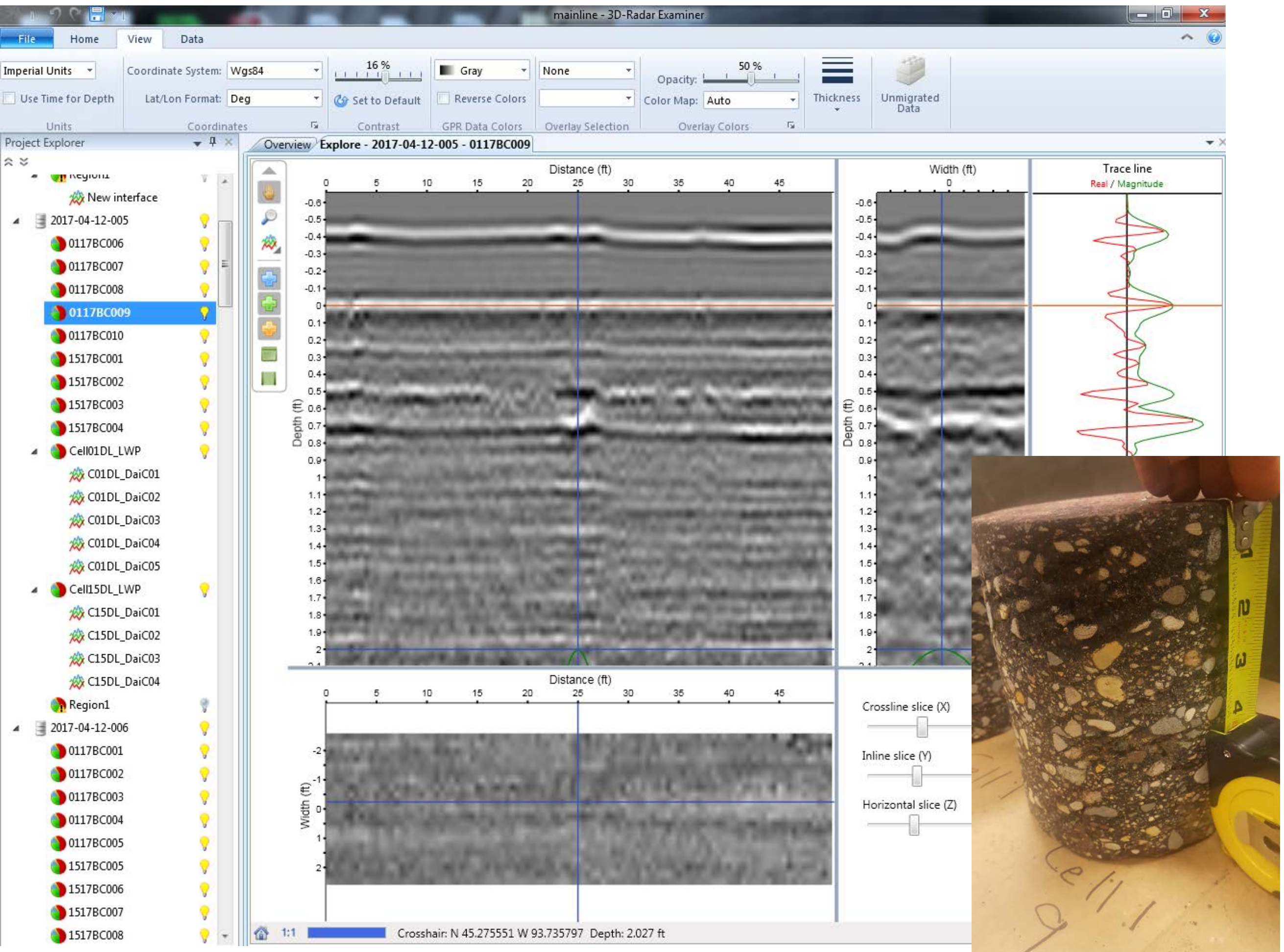
Cell 1		
Core ID	**Core Condition**	**Qualitative GPR Signal Assessment**
3	none/sound condition	strong backwall

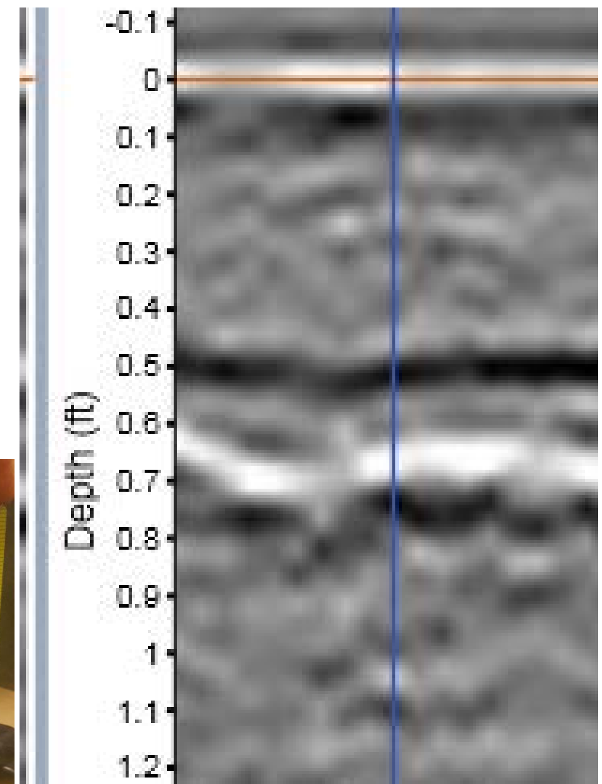




Examiner Results: MnROAD Deteriorated Pavement, Unclear

Cell 1		
Core ID	Core Condition	Qualitative GPR Signal Assessment
9	slight deterioration/strip	direct reflection (deeper than distress)

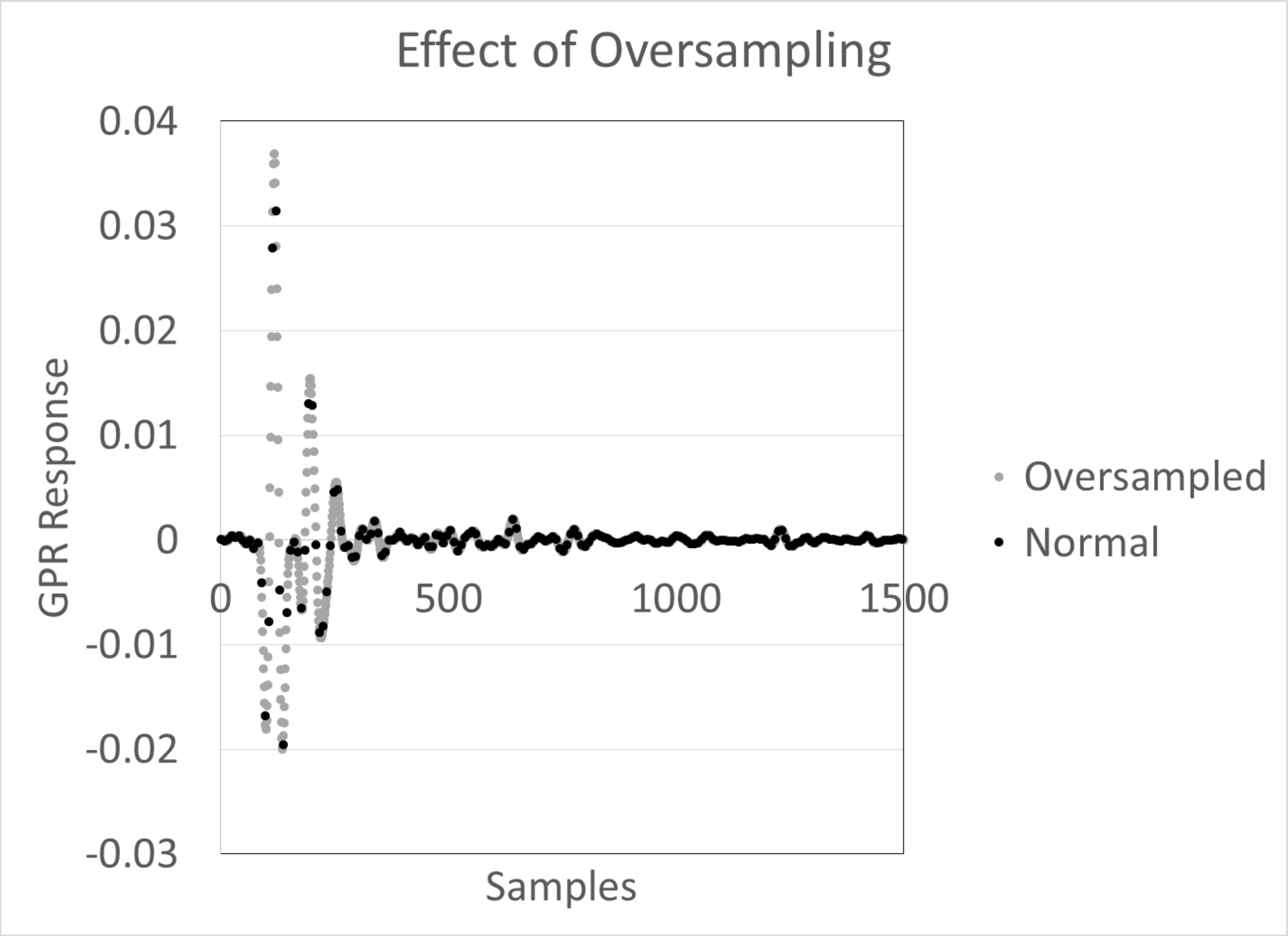




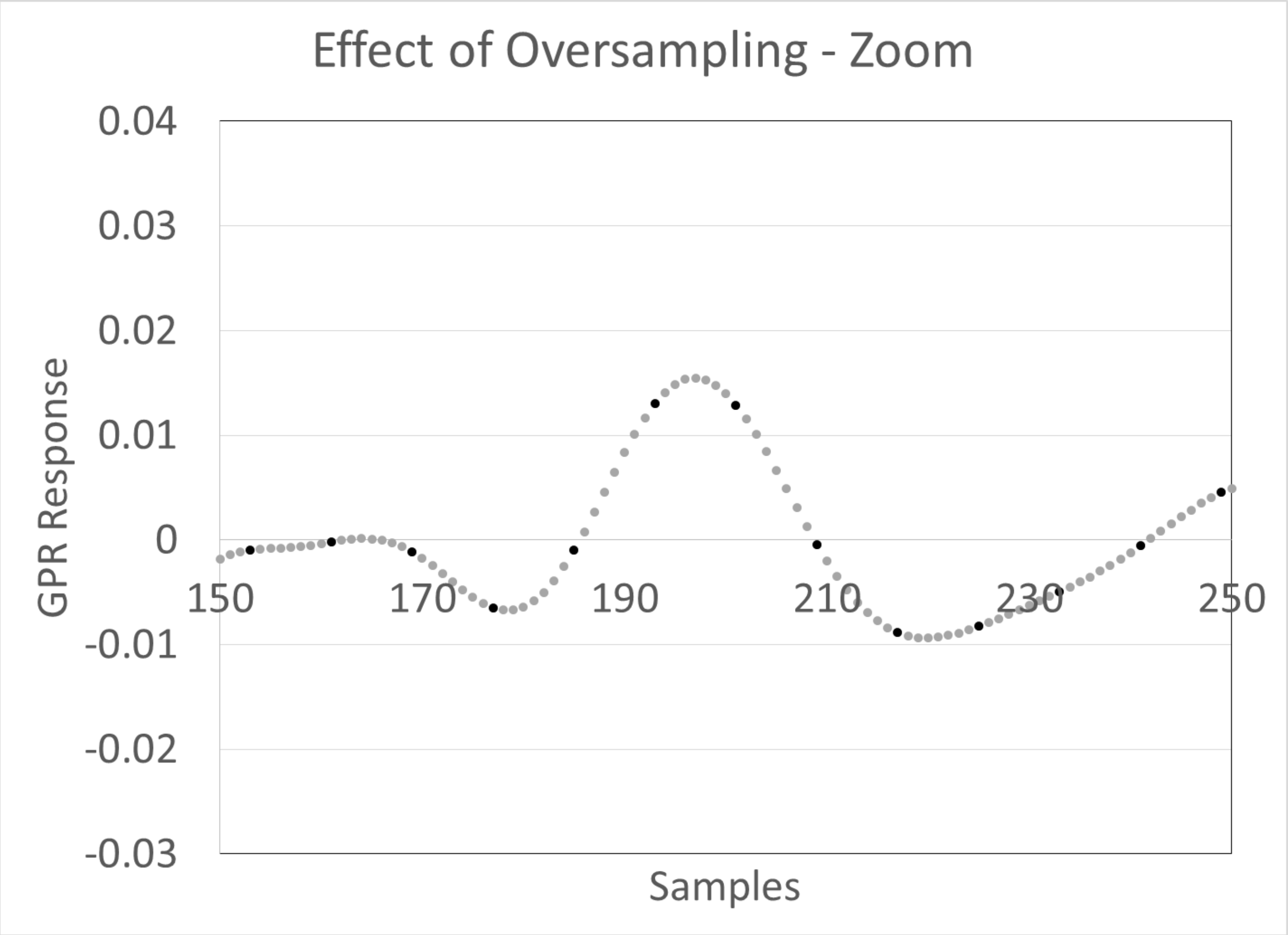
Examiner Results: MnROAD

Cell 15		
Core ID	**Core Condition**	**Qualitative GPR Signal Assessment**
1	mid-depth strip/delam	slight anomaly/shaddowed backwall
2	clear stripping	direct anomaly
3	crumbled stripping	direct anomaly
4	slight strip/deterioration	slight anomaly/shaddowed backwall
5	no significant distress	strong backwall
6	clear stripping	direct anomaly
7	clear stripping	direct anomaly
8	slight deterioration	edge of anomaly

Controlled Laboratory Tests: Sampling Rate



Controlled Laboratory Tests: Sampling Rate

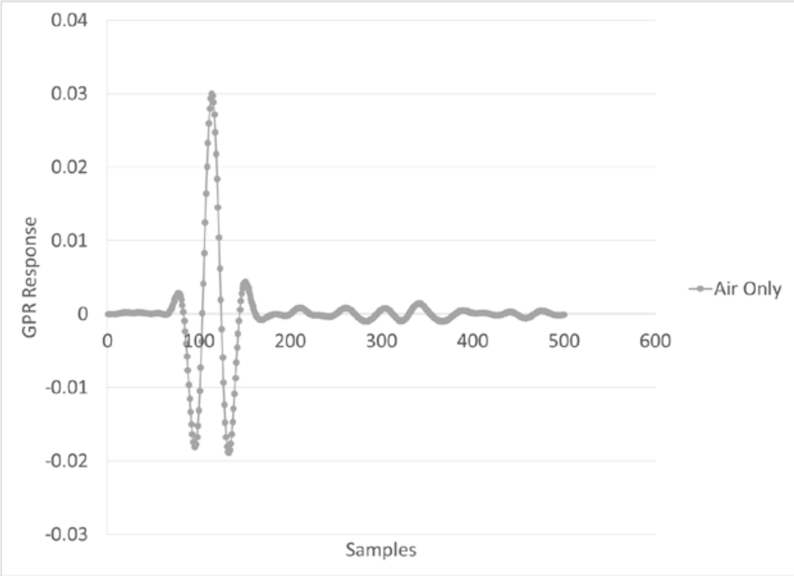


Controlled Laboratory Tests: Air Calibration

Extract "Air Wave"

– Face antenna away from the surface

– Eliminate portion of the signal that is only affected by the antenna

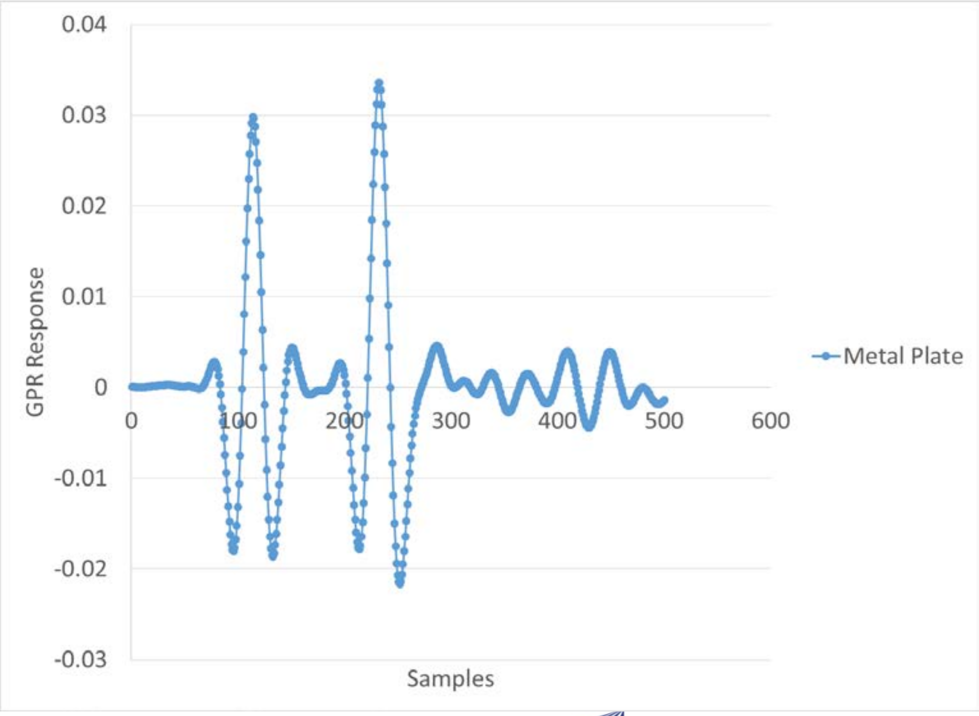


Controlled Laboratory Tests: Metal Calibration

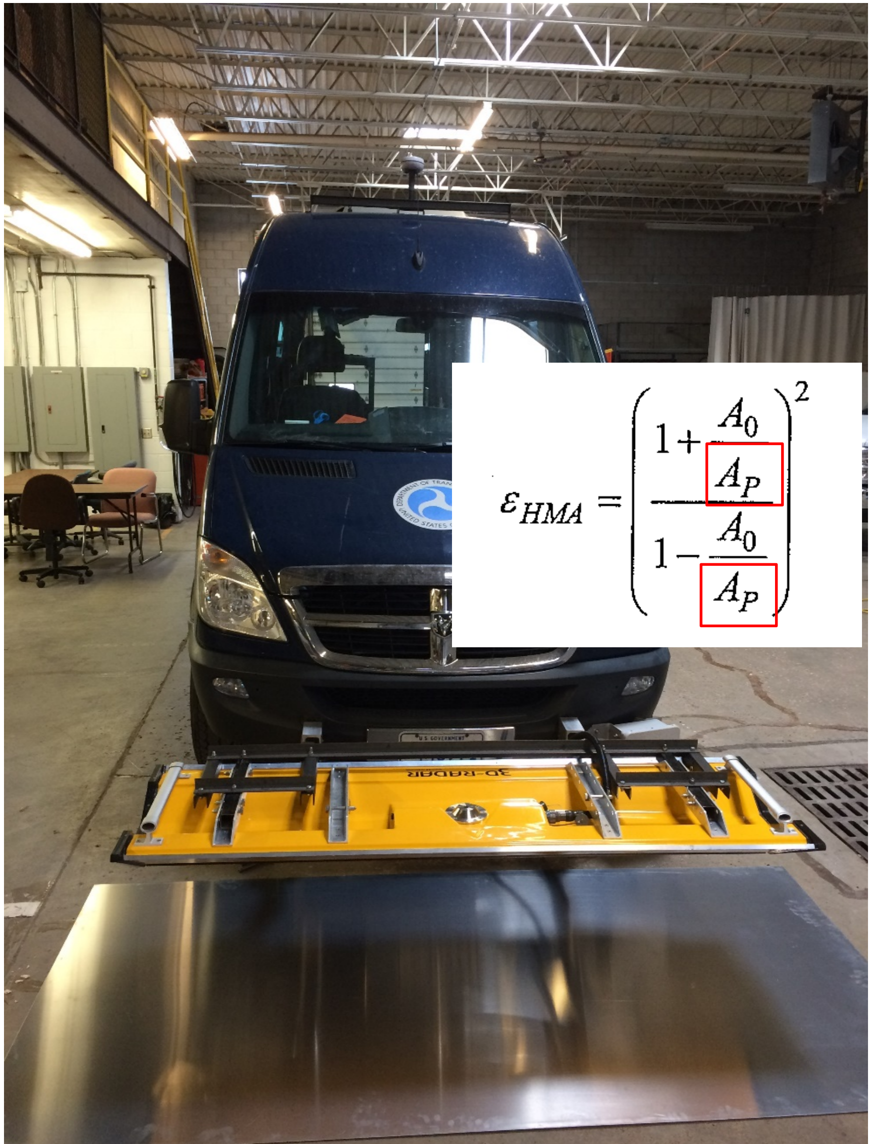
4'x8' Metal Surface Reflection Amplitude

– Placed in the center of the antenna array

– Use the amplitude of the surface reflection to characterize the signal magnitude



Controlled Laboratory Tests: Metal Calibration

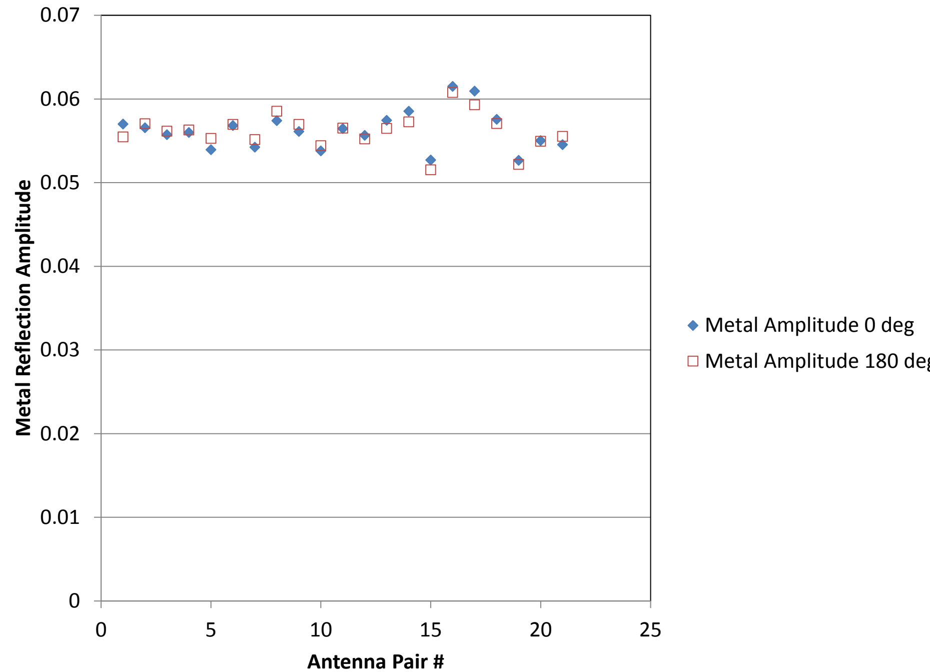


$$\varepsilon_{HMA} = \left(\frac{1 + \frac{A_0}{A_P}}{1 - \frac{A_0}{A_P}} \right)^2$$

4'x8' Metal Surface Reflection Amplitude

– Placed in the center of the antenna array

– Rotated 180 degrees and placed in the center of the antenna array



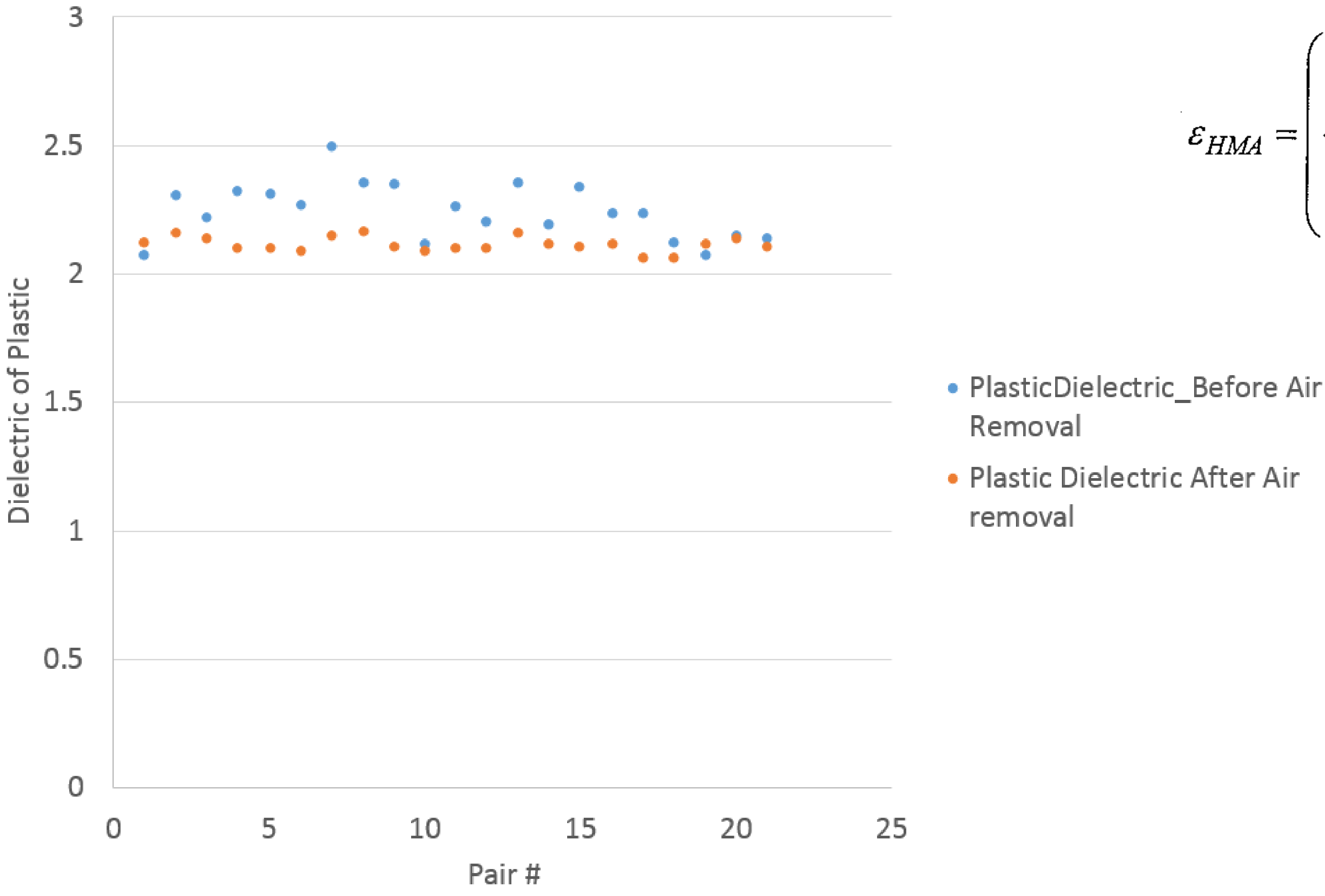
Controlled Laboratory Tests: HDPE Plastic

HDPE Surface Reflection Amplitude

- Plastic Sheet (HDPE) Calibration
- Manufacturer Dielectric Listed: 2.30
- Known Dielectric can be used to evaluate effectiveness of air, metal, and oversampling calibrations

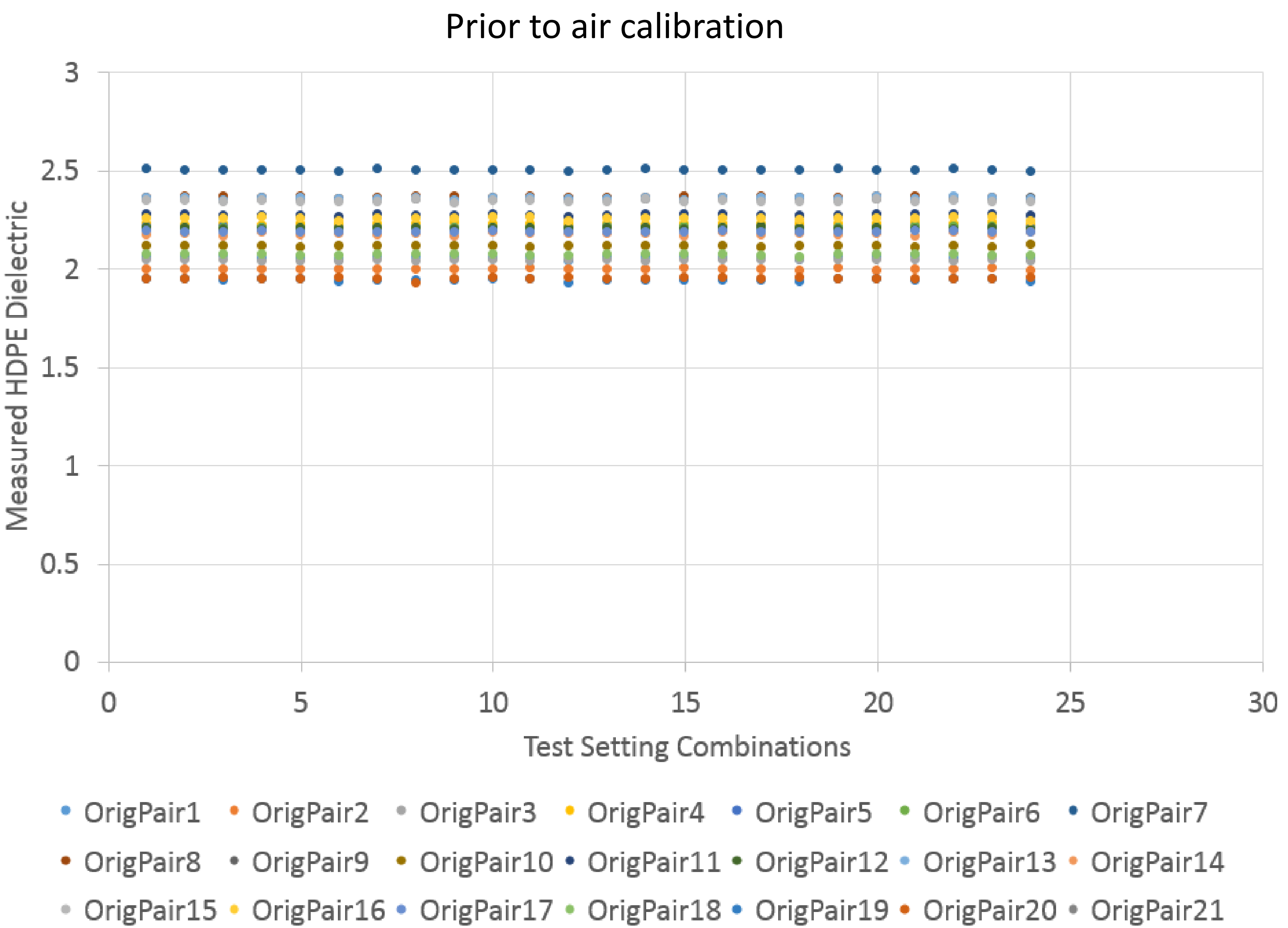
$$\varepsilon_{HMA} = \left(\frac{1 + \frac{A_0}{A_P}}{1 - \frac{A_0}{A_P}} \right)^2$$

Controlled Laboratory Tests: HDPE Plastic Dielectric

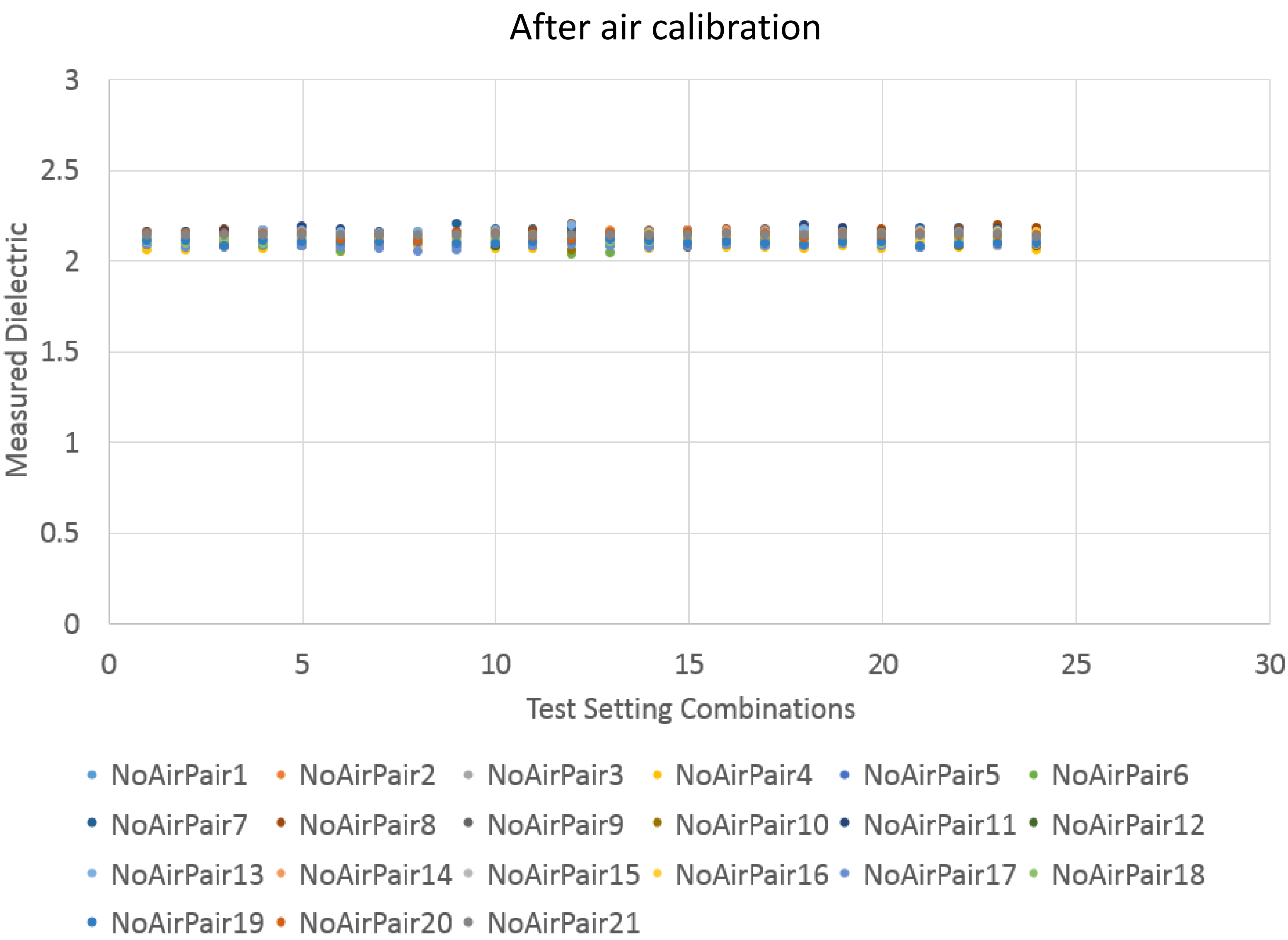


$$\varepsilon_{HMA} = \left(\frac{1 + \frac{A_0}{A_P}}{1 - \frac{A_0}{A_P}} \right)^2$$

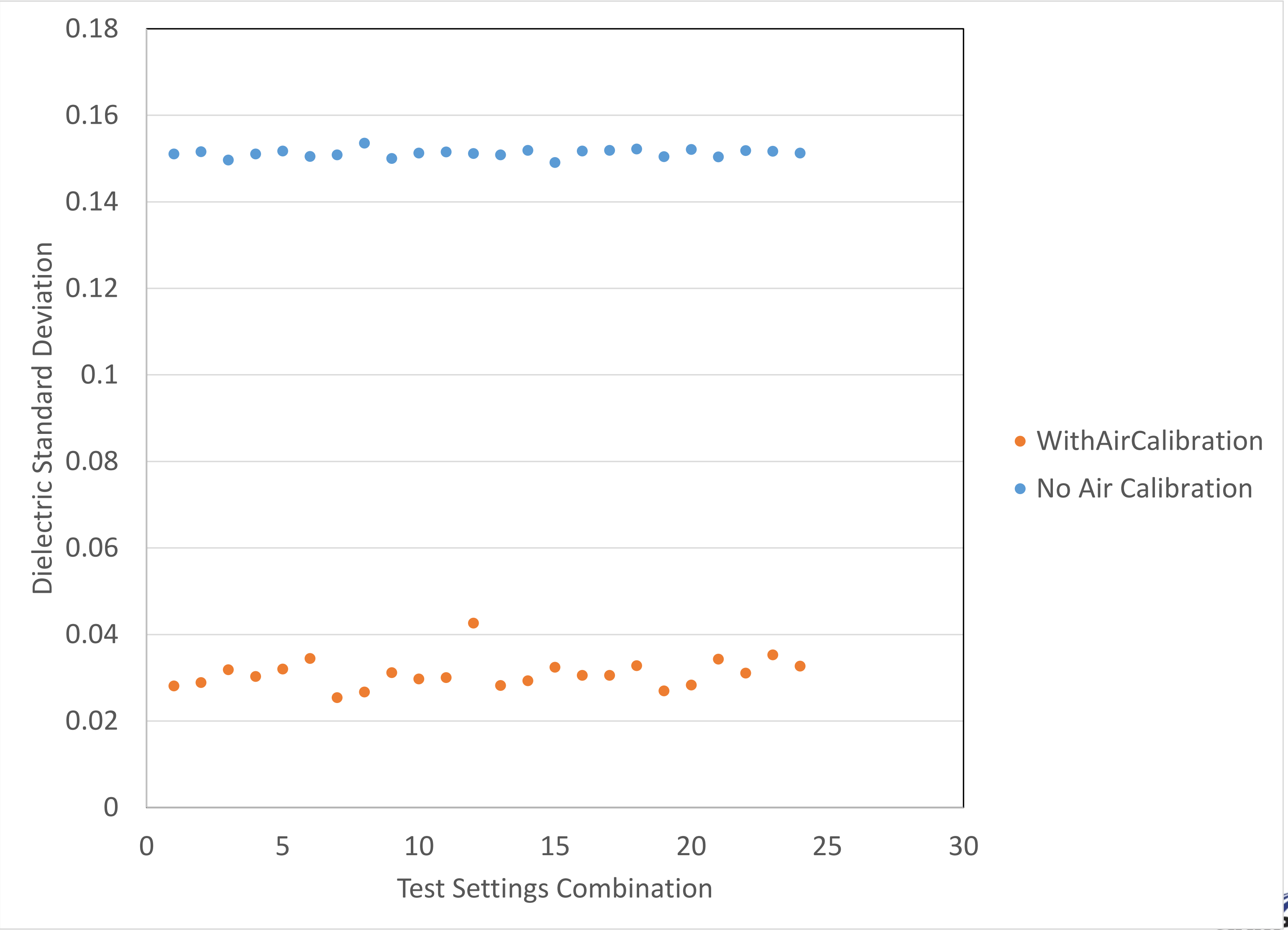
Controlled Laboratory Tests: HDPE Plastic Dielectric Test



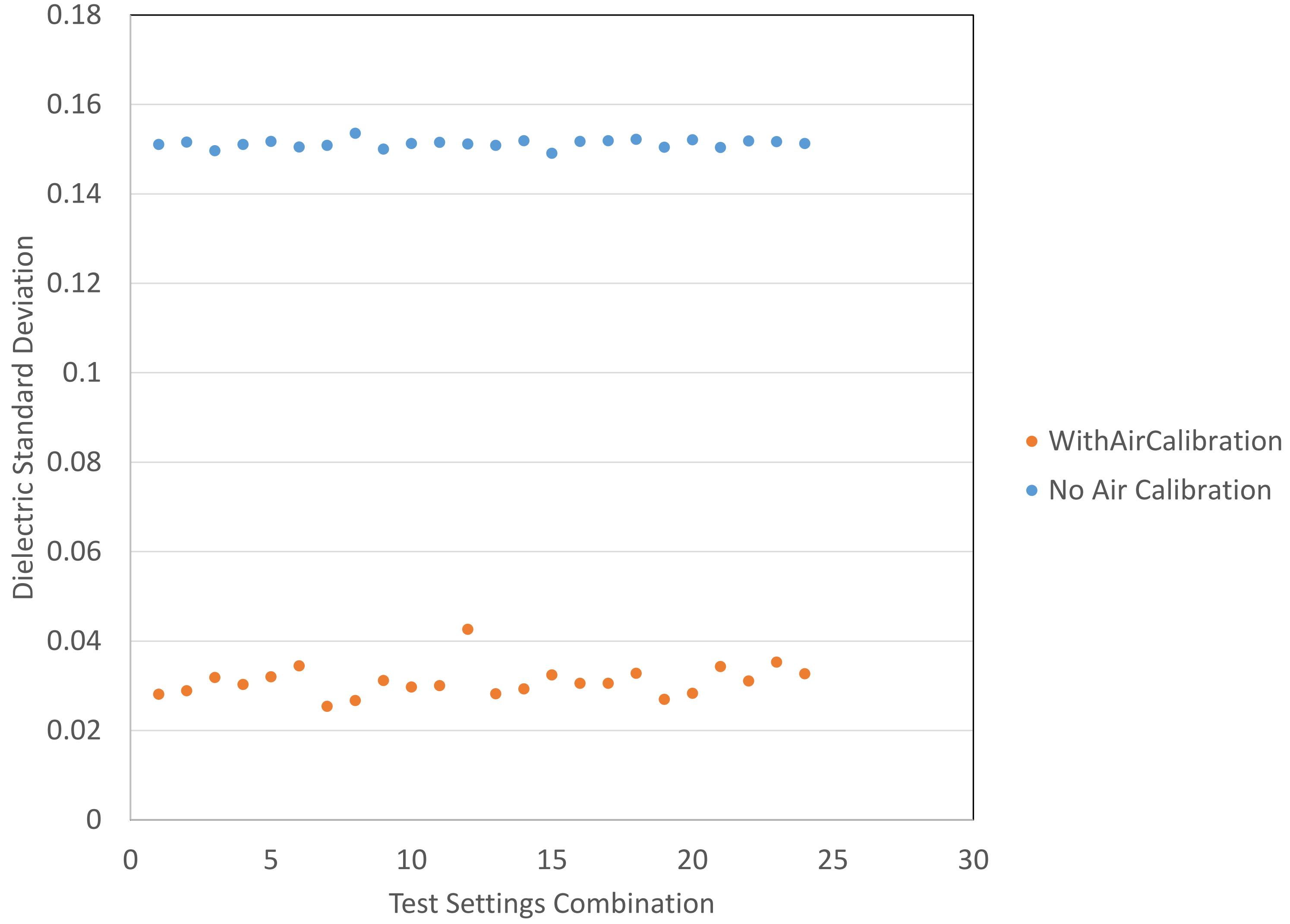
Controlled Laboratory Tests: HDPE Plastic Dielectric Test



Controlled Laboratory Tests: HDPE Plastic Dielectric Test



Controlled Laboratory Tests: HDPE Plastic Dielectric Test



Calibration Result Implications

- 3D Radar equipment can integrate the GPS with the GPR data with high accuracy even at highway speed
  - Useful to integrate an external GPS connected to a virtual reference station or other correction method to get full potential of equipment
  - This allows for selection of validation cores fully based on GPS data
  - Improved accuracy and efficiency of selecting core validation locations
- Incorporation of oversampling, metal, and air calibration into analysis can improve 3D radar signal
  - 3D Radar is working on incorporating some of these calibration options, but none are currently available in examiner and require outside analysis.
  - Oversampling can improve digital representation of the true analogue signal which is important for amplitude calculations and filtering technique applications
  - Metal and air calibrations are critical to addressing antenna to antenna variation and reducing signal noise

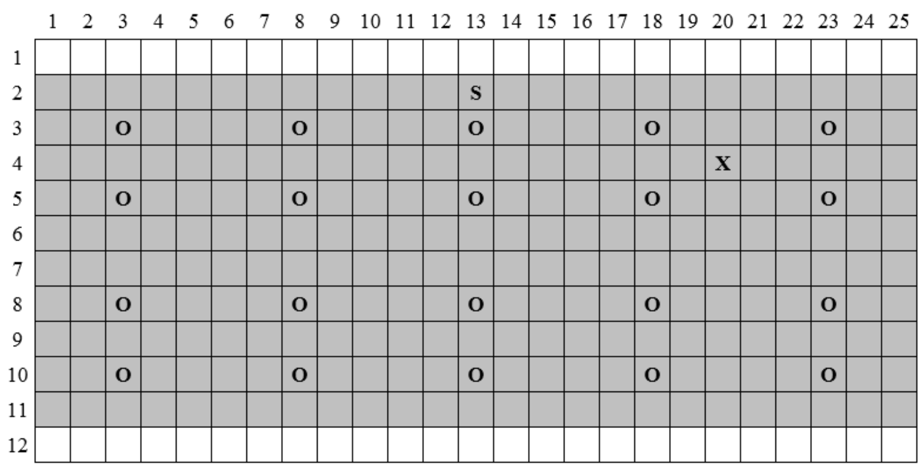
Evaluation of Stripping using 3D Radar Data

1. Review SHRP2 Research Data from NCAT
2. Activity Analysis Algorithm for Automated Detection
3. Application to MnROAD Data
4. Application to TH 7 data

3D Equipment at NCAT – March 2010

NCAT Test Track

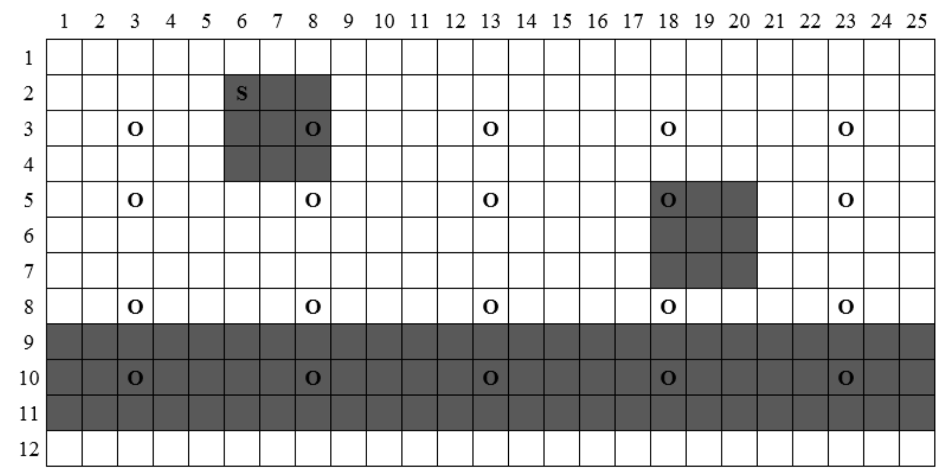
Debonding at 2” depth



Gray = bag house dust; delamination depth = ~ 2 in.; O = locations where point-load methods were conducted; X = verification core; S = standpipe.

FIGURE 15 Section 5: HMA Pavement, Full Width Delamination (STA 1+15 to 1+40).

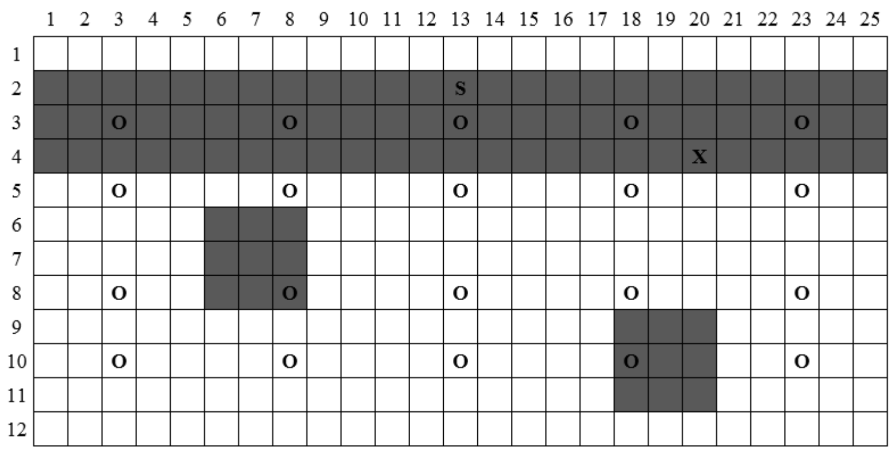
Stripping at 2” depth



Dark gray = RAP; bottom of delamination = ~ 2 in.; RAP thickness = ~ 0.75 in.; O = locations where point-load methods were conducted; S = standpipe.

FIGURE 16 Section 6: HMA Pavement, Partial Stripping (STA 1+40 to 1+65).

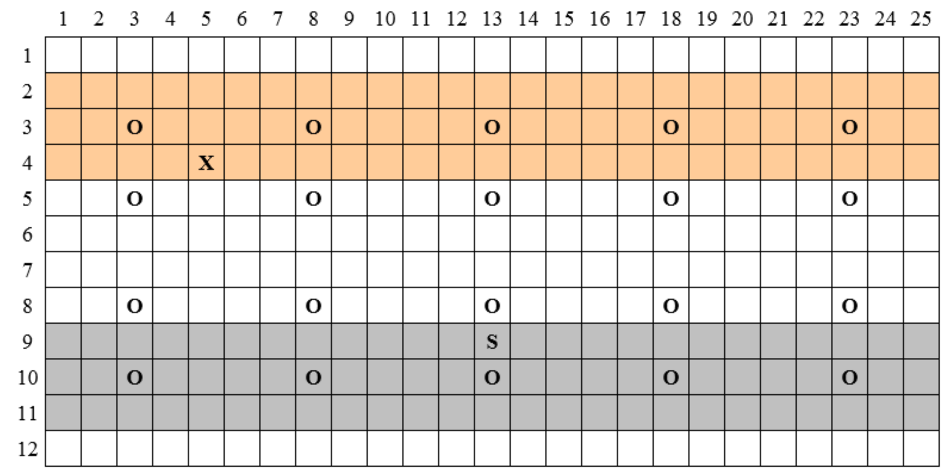
Stripping at 5" depth



Dark gray = RAP; bottom of delamination = ~ 5 in.; RAP thickness = ~ 0.75 inches; O = locations where point-load methods were conducted; X = verification core; S = standpipe.

FIGURE 18 Section 8: HMA Pavement, Partial Stripping (STA 1+90 to 2+15).

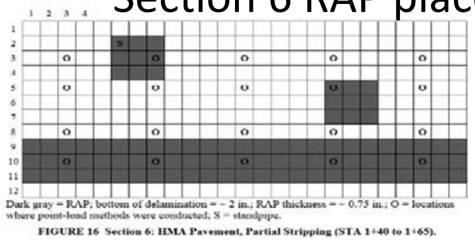
Debonding at 5" depth



Gray = bag house dust; tan = paper; delamination depth = ~ 5 in.; O = locations where point-load methods were conducted; X = verification core; S = standpipe.

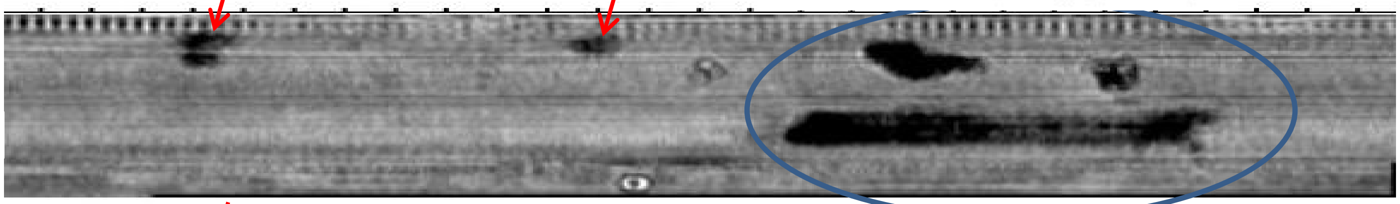
FIGURE 19 Section 9: HMA Pavement, Wheel Path Delamination (STA 2+15 to 2+40).

Section 6 RAP placed at 2" depth



Section 5 – Debond placed at 2" depth

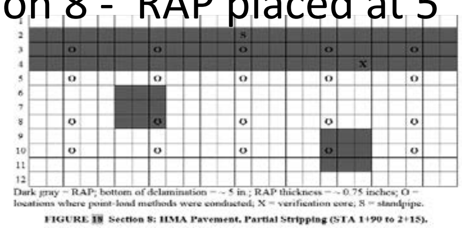
3D Depth Slice at 2"



= water introduced

"Stripped" areas

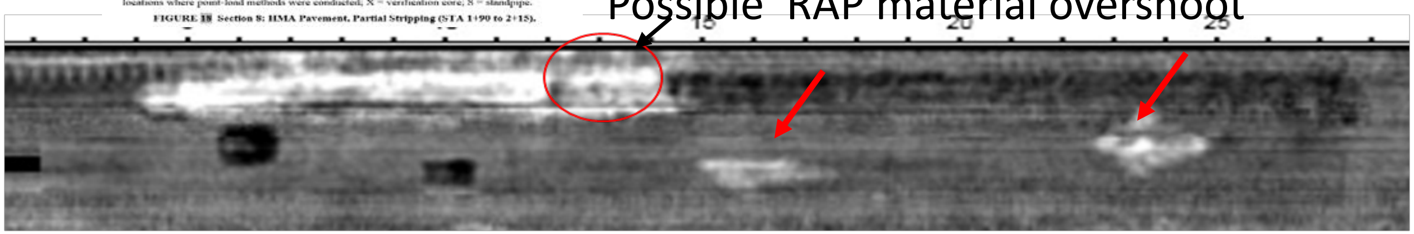
Section 8 - RAP placed at 5" depth



Section 9 – Debond at 5" depth

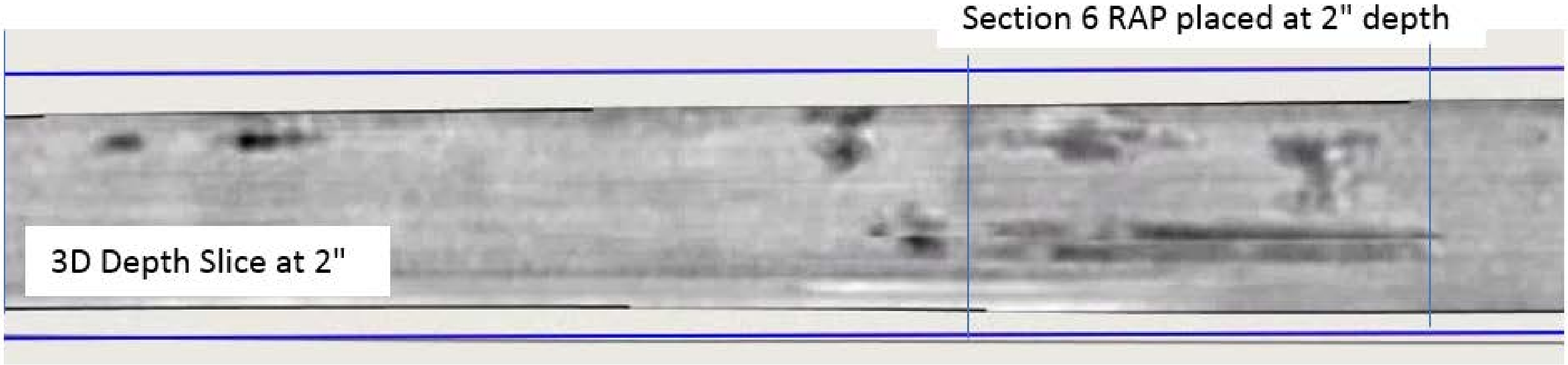
Possible RAP material overshoot

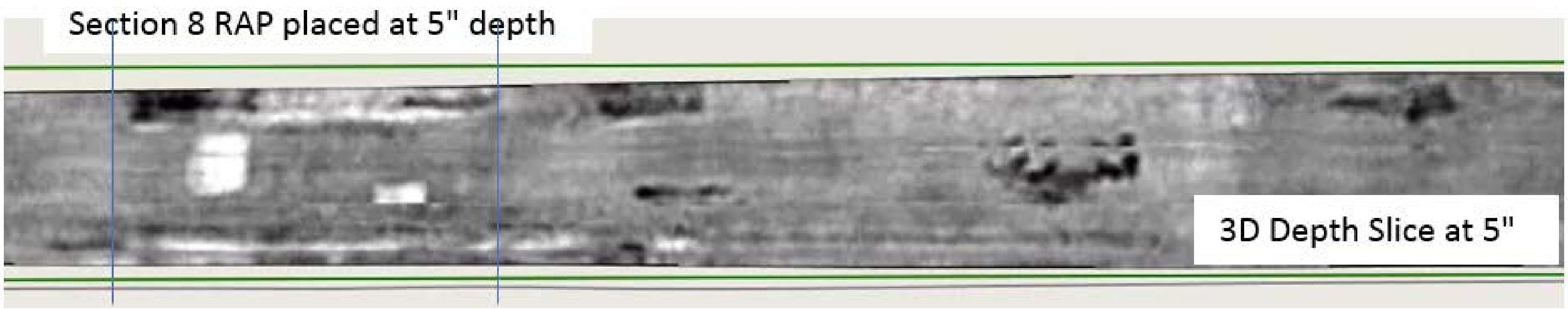
3D Depth Slice at 5"



3D Radar System at NCAT in October 2016

2016 NCAT Data

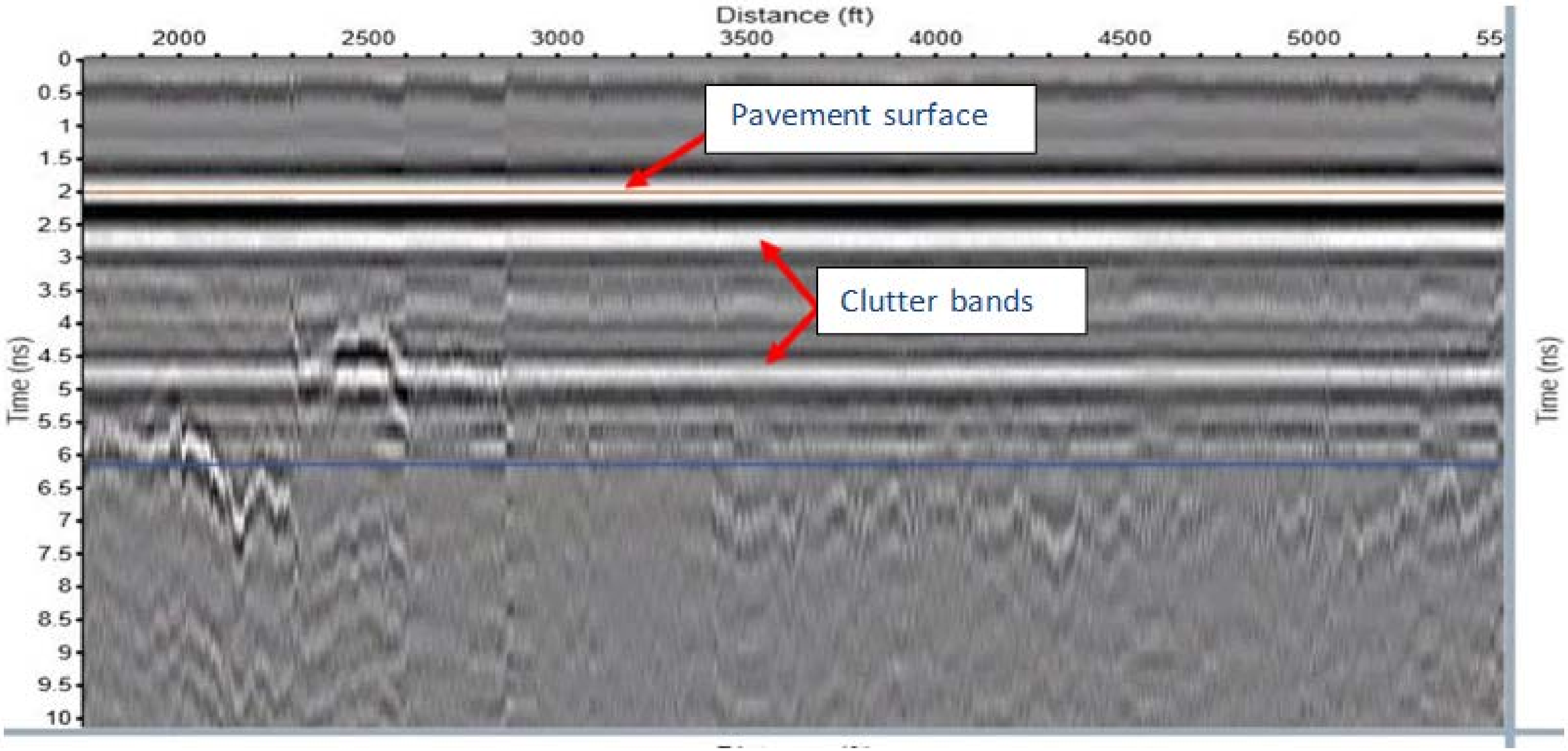




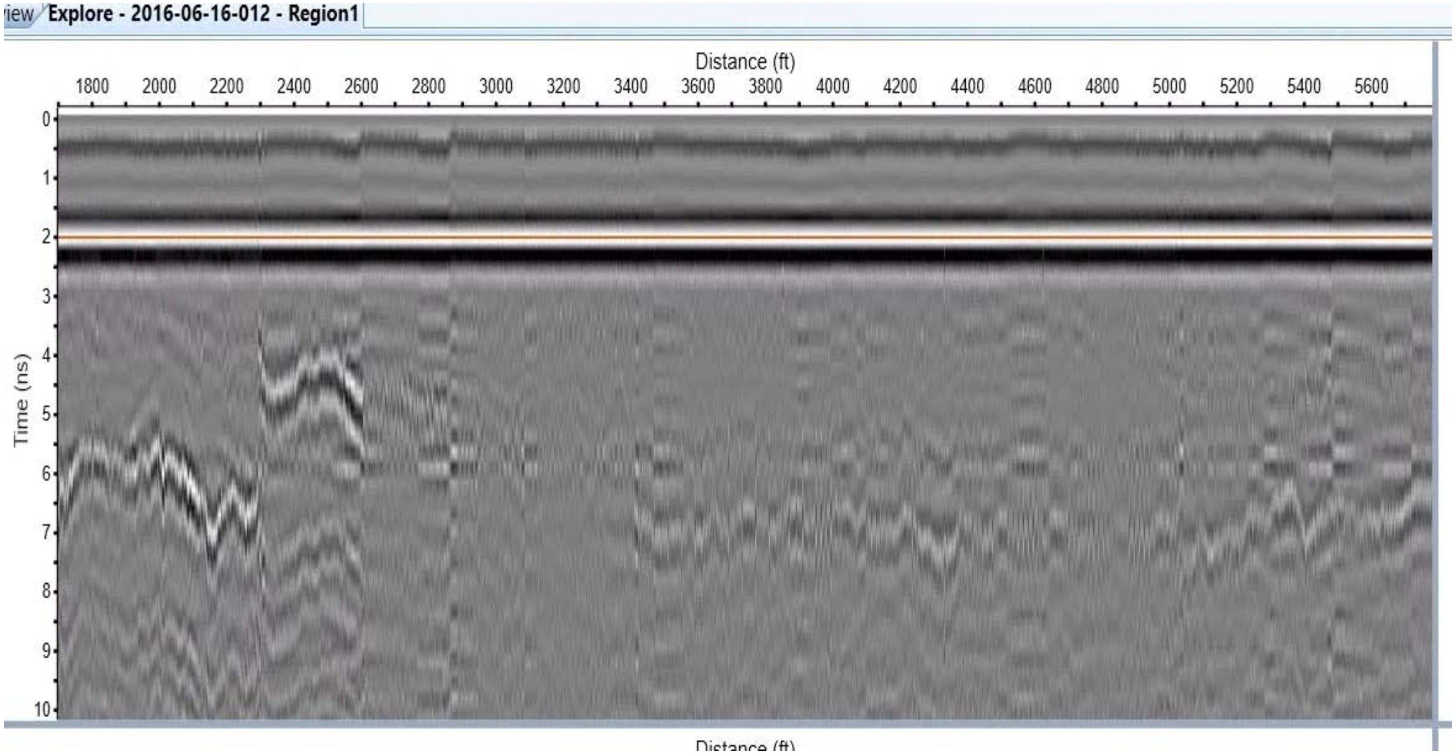
Vehicle Mounted Equipent For Highway Application

MnROAD Data – Vehicle Interference

File 6-16-16-012



Same Data with background removal below surface



Analysis Methods

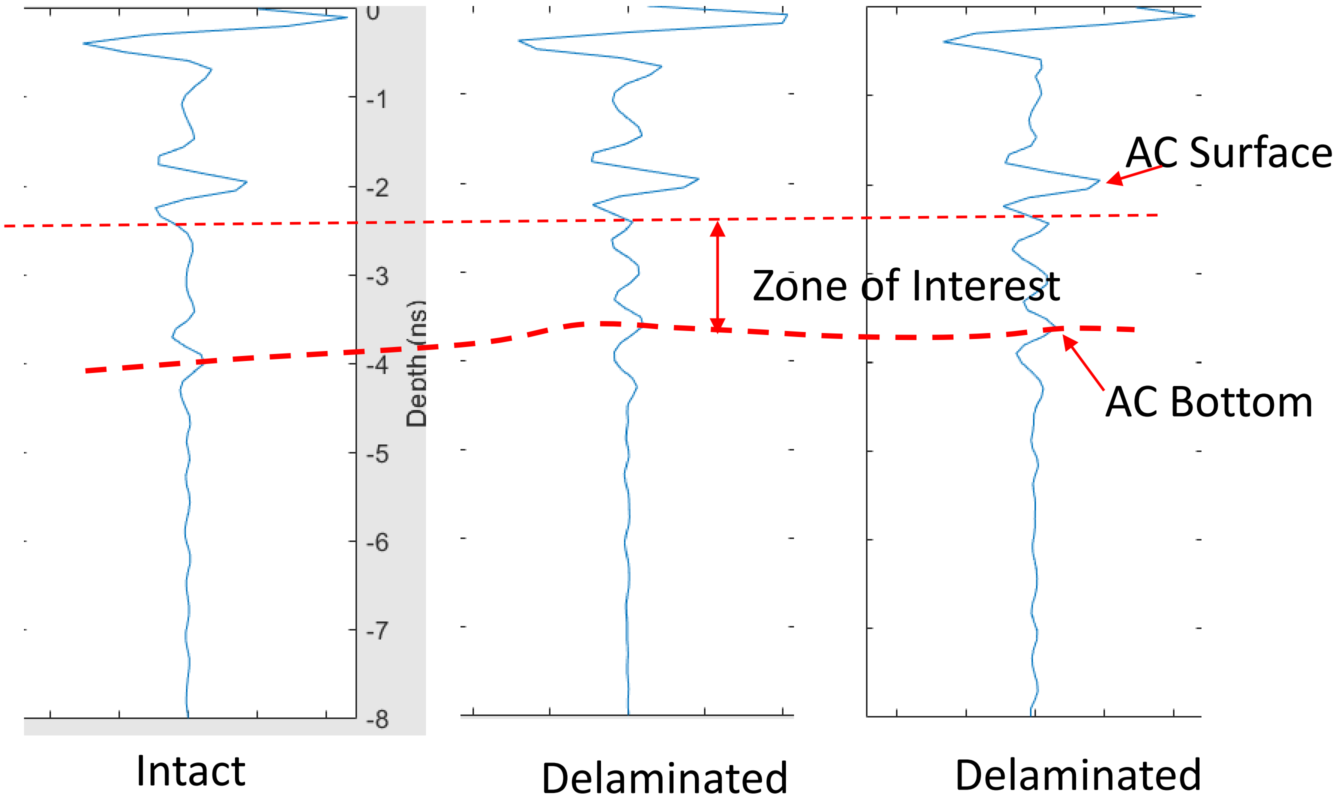
- 3D Radar "Examiner"

  - Processes and displays raw GPR data to facilitate interpretation

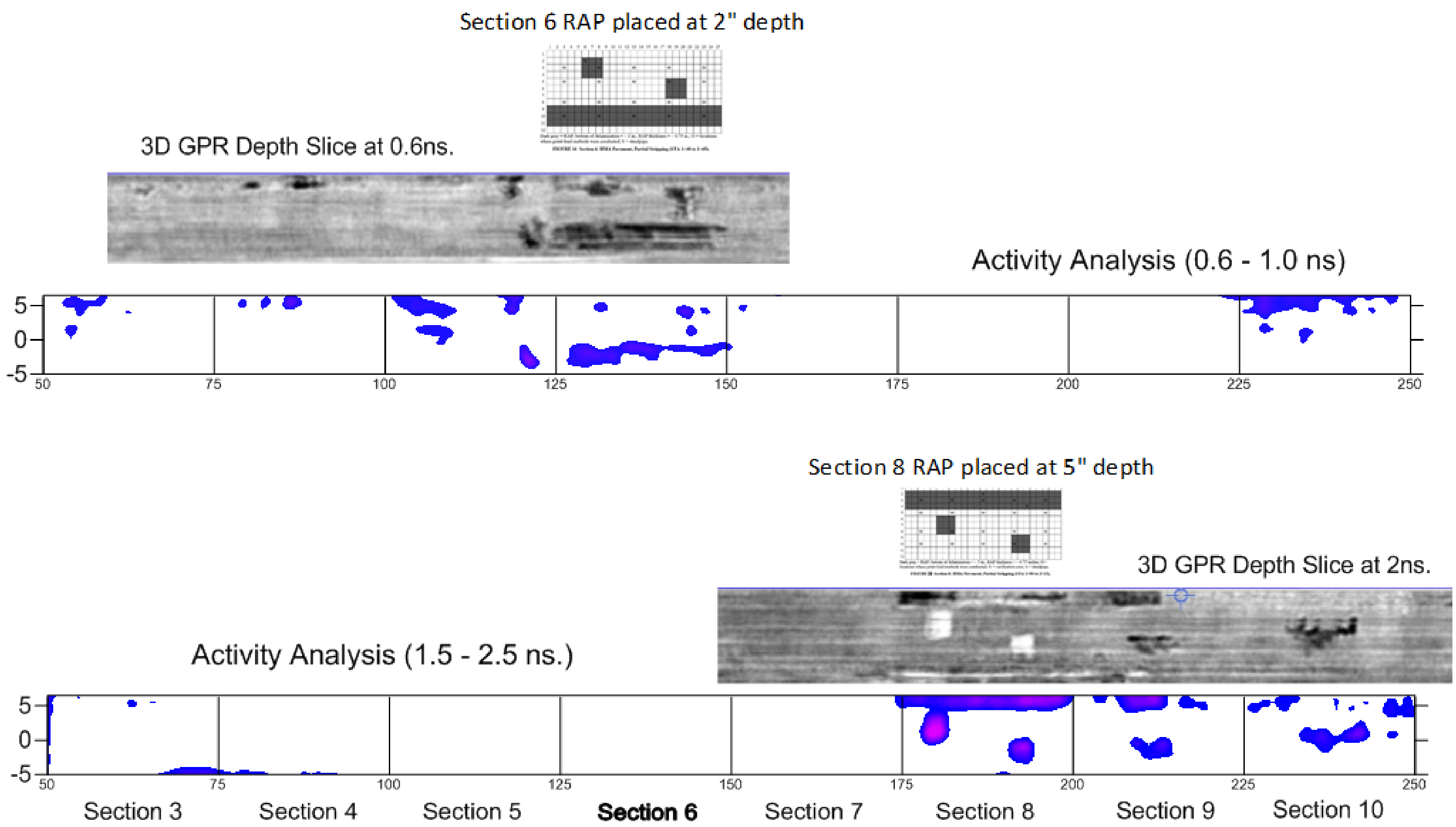
- ExploreGPR

  - Conducts quantitative analyses using data generated by "Examiner"

Activity Algorithm



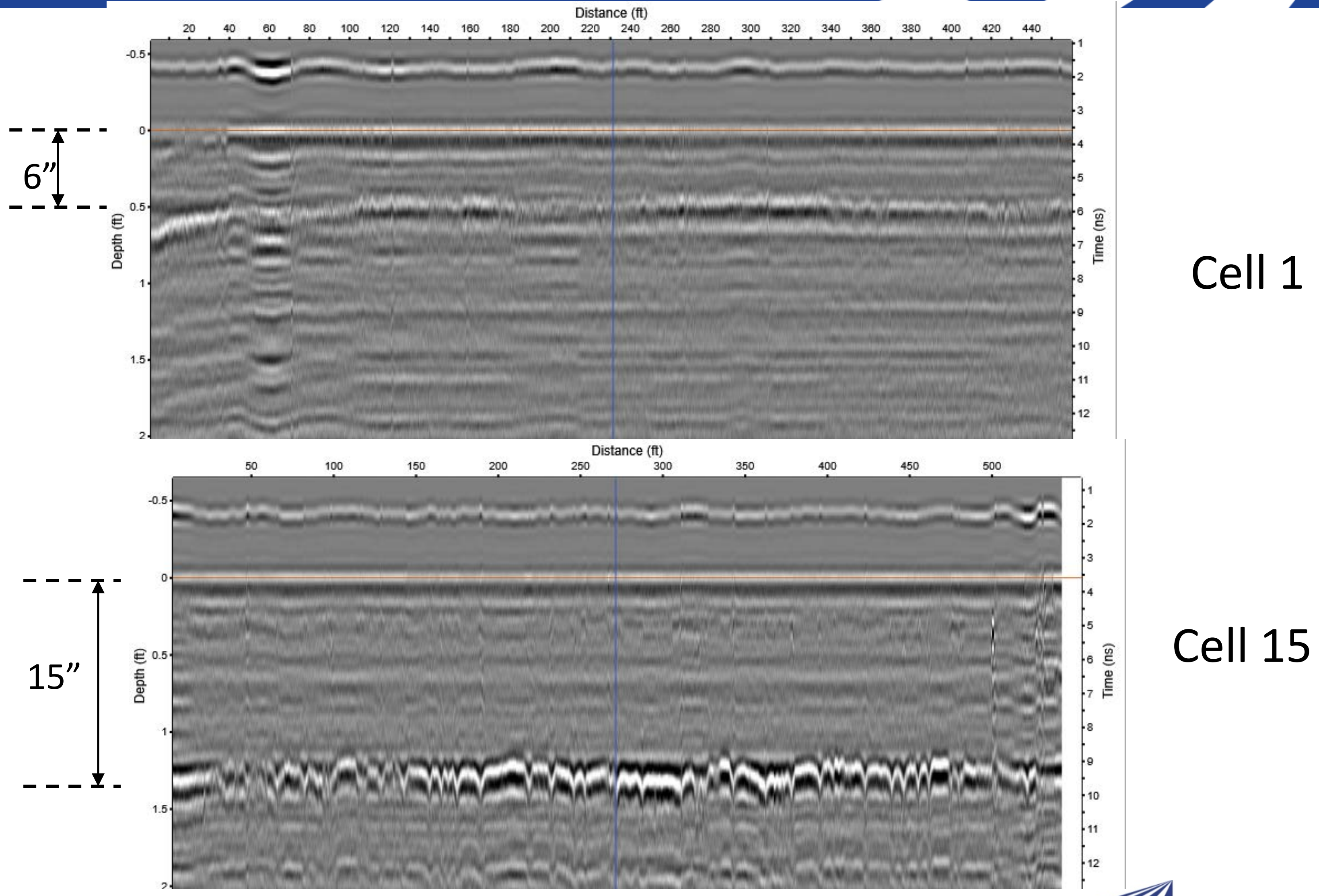
Activity Analysis on NCAT Test Sections



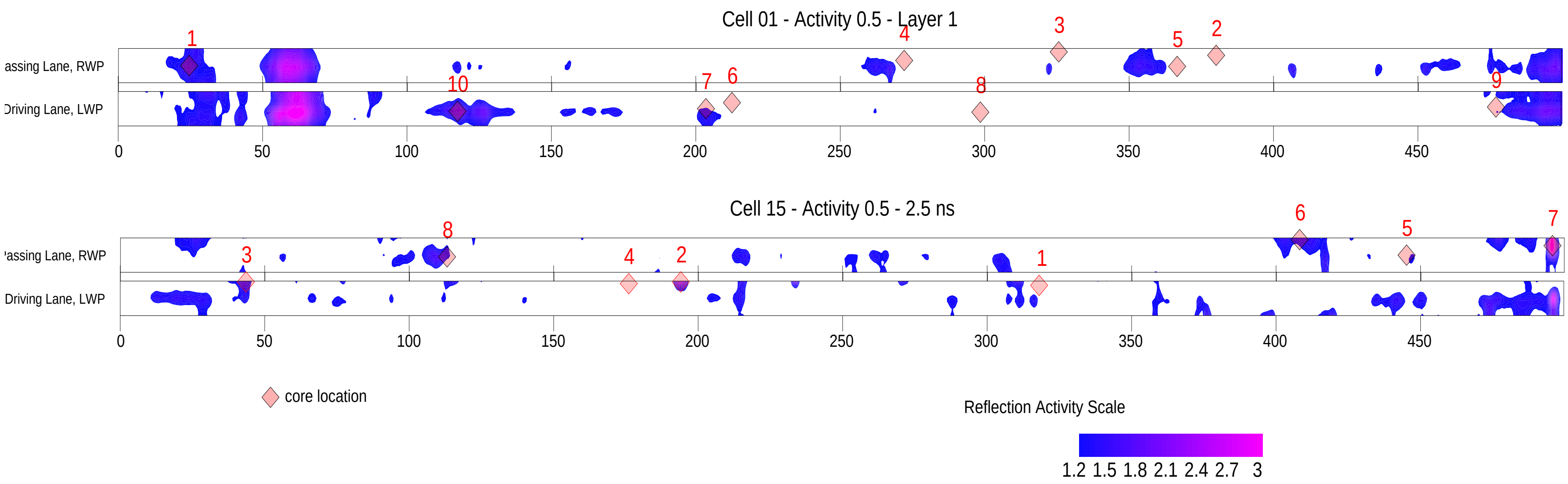
Correlation with Stripping on Well Documented In-Service Roads:

- MnROAD Test Sections
- TH 7 in Clara City, ,MN

MnROAD Analysis: Cells 1 and 15 – GPR Data



MnROAD Analysis



MnROAD Analysis

Cell 1		
Core ID	**Core Condition**	**Confirm?**
1	shallow slight deter/strip	yes
2	insignficant	yes
3	none/sound condition	yes
4	lg crack/deterioration	close
5	deterioration (coring caused?)	close
6	slight shallow/bottom deterioration	no
7	shallow slight deter/delam	yes
8	minimal middepth stripping	no
9	slight deterioration/strip	yes
10	shallow slight deter/delam	yes

Cell 15		
Core ID	**Core Condition**	**Confirm?**
1	mid-depth strip/delam	close
2	clear stripping	yes
3	crumbled stripping	yes
4	slight strip/deterioration	no
5	no significant distress	close
6	clear stripping	yes
7	clear stripping	yes
8	slight deterioration	yes

Correlation Result:

11 confirm

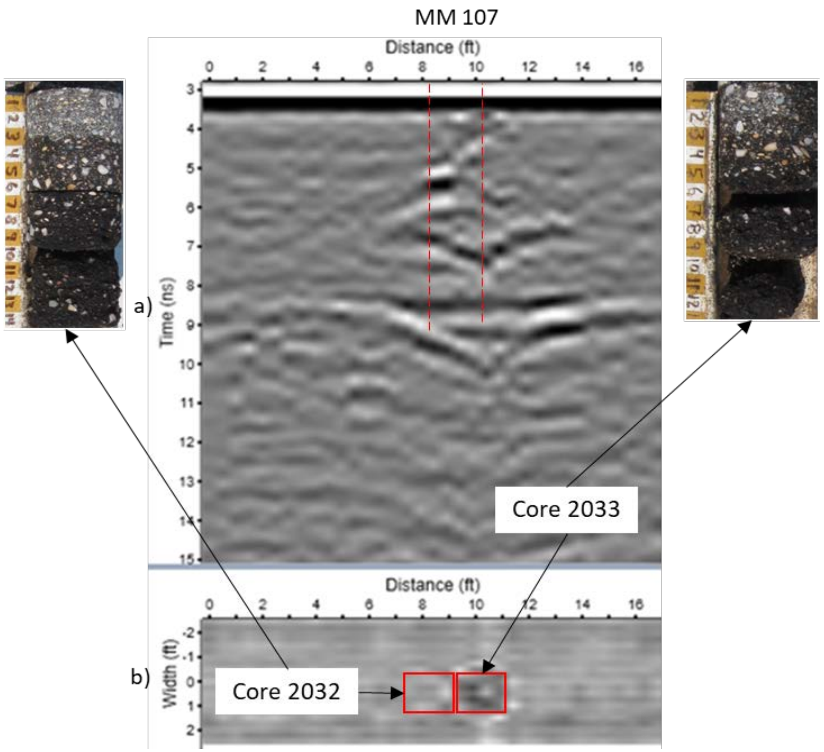
4 close

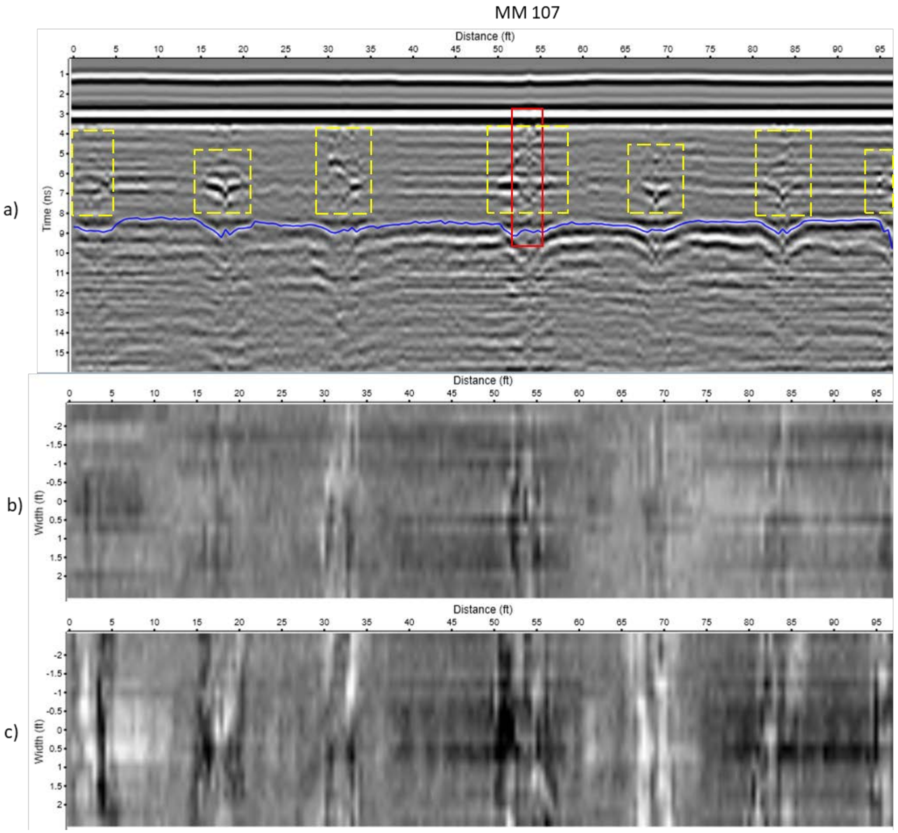
3 not confirmed

TH 7 in Clara City, Mn

- 16 mile section, 1 lane in each direction
- Pavement thickness ~ 10 inches
- Pavement has regular transverse cracking, spaced 10 – 30 feet
- 2 Cores were taken near each MP, one over a crack and one 2 feet away
- Many cores showed evidence of stripping
- 3D Radar data was collected – Dec. 2016 and May 2017
  - Dec 2016 – many short files directly over the cores
  - May 2017 – long files covering multiple core areas

TH-7 GPR Data at Core Locations



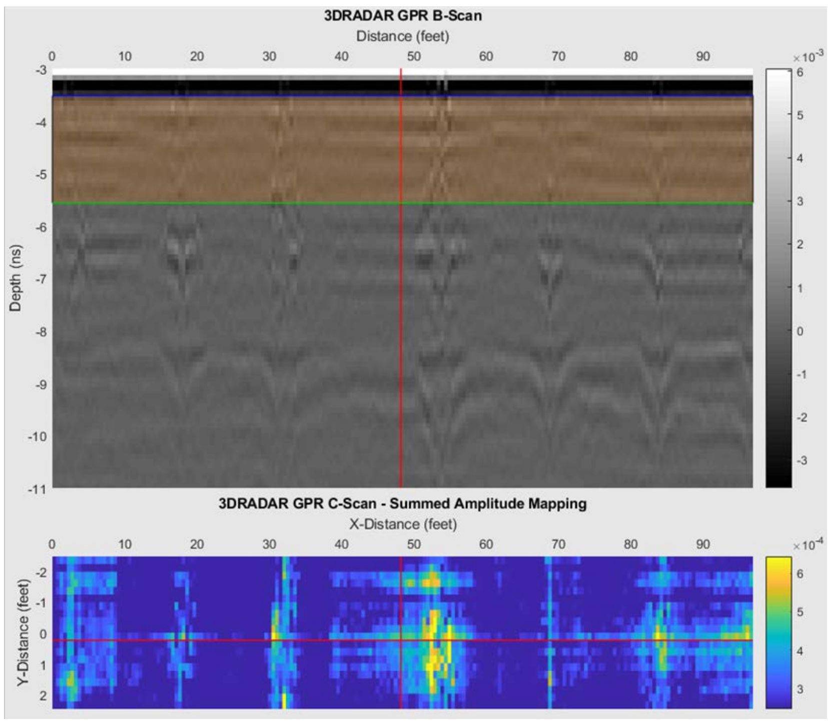


Activity Analysis at 2 Levels using ExploreGPR

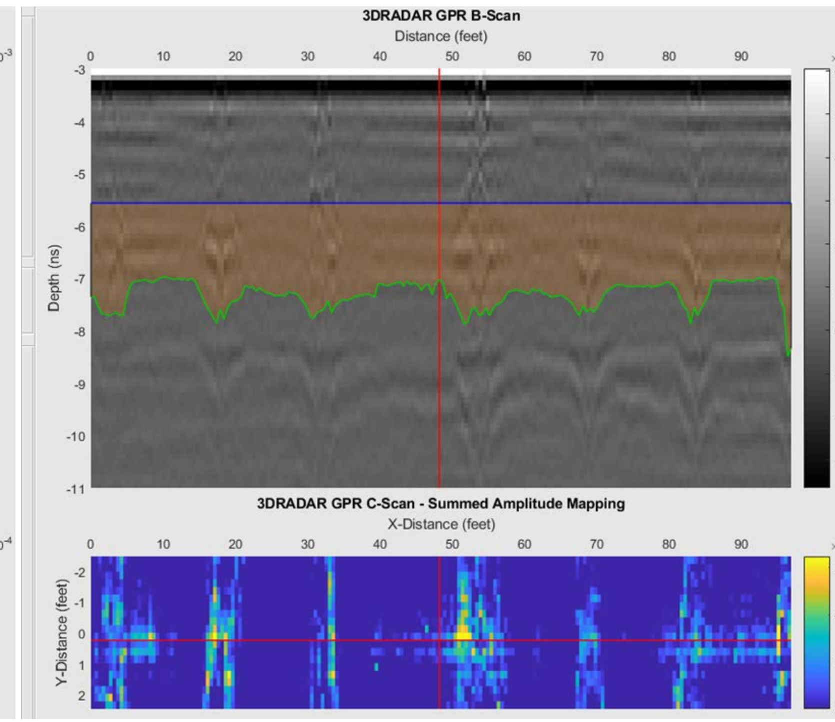
Upper Level Activity

a)

b)

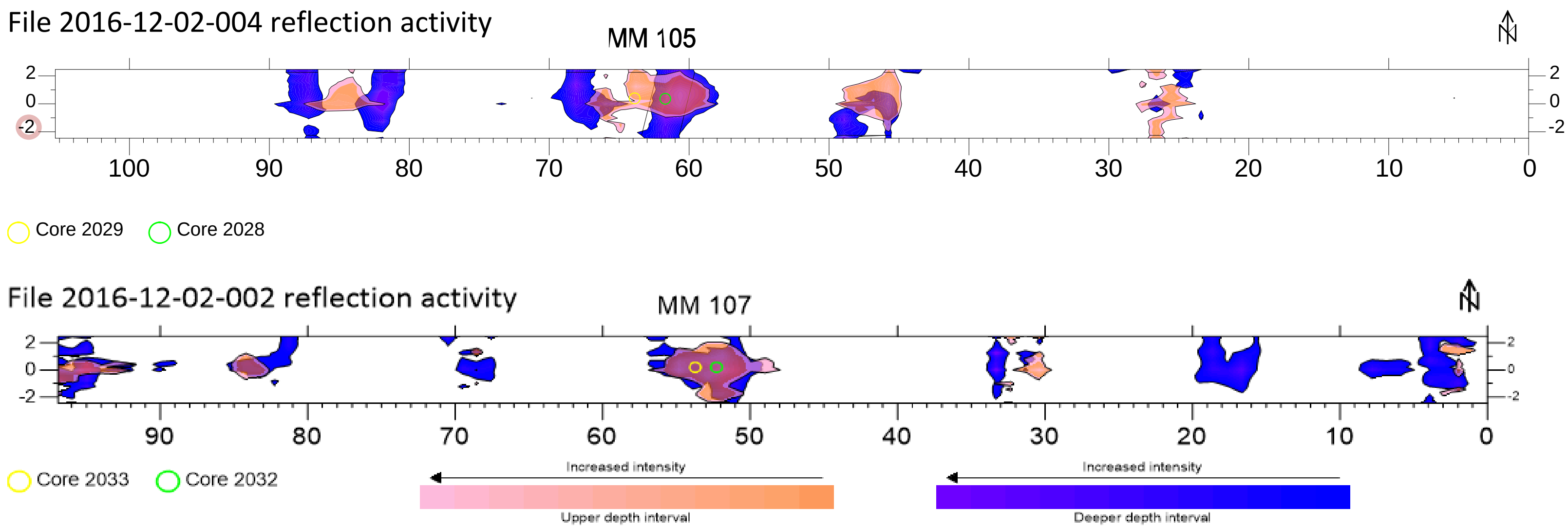


Lower Level Activity



Analysis Results

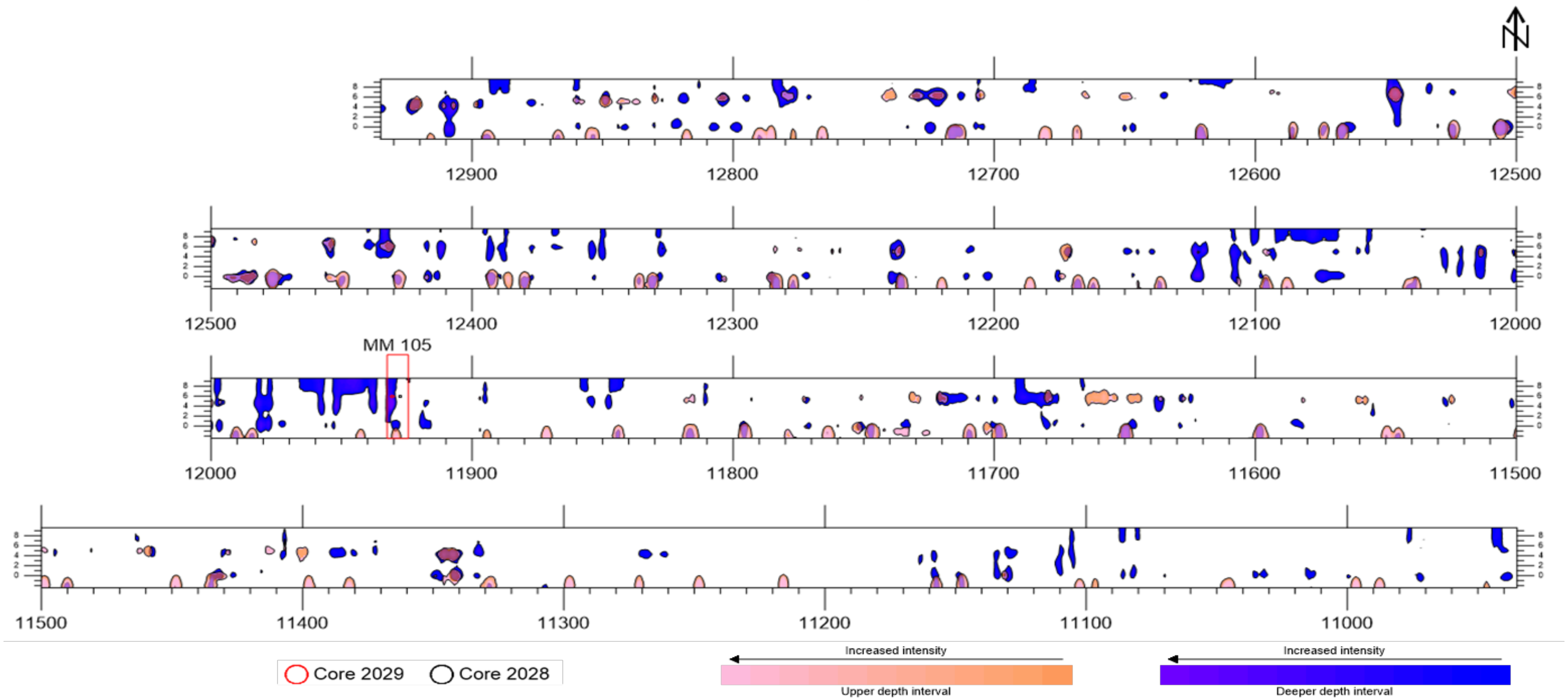
Local Analysis



Threshold = 1.5 x mean

Analysis Results

Larger Scale Analysis



Analysis Summary – 75% correct

MM | Core number	Core Condition	activity> threshold	Assessment	MM | Core number	Core Condition	activity> threshold	Assessment
91 | 2000	stripped	yes	correct	99 | 2017	stripped	no	false negative
91 | 2001	stripped	yes	correct	100 | 2018	intact	yes	false positive
92 | 2002	intact	no	correct	100 | 2019	stripped	yes	Correct
92 | 2003	stripped	yes	correct	101 | 2020	stripped	yes	Correct
93 | 2004	stripped	no	false negative	101 | 2021	stripped	yes	Correct
93 | 2005	stripped	no	false negative	102 | 2022	stripped	yes	Correct
94 | 2006	intact	no	correct	103 | 2024	stripped	no	false negative
94 | 2007	stripped	no	false negative	103 | 2025	stripped	yes	Correct
95 | 2008	stripped	yes	correct	104 | 2026	intact	no	Correct
95 | 2009	stripped	yes	correct	104 | 2027	stripped	no	false negative
96 | 2010	intact	yes	false positive	105 | 2028	stripped	yes	Correct
96 | 2011	stripped	yes	correct	105 | 2029	stripped	yes	Correct
97 | 2012	stripped	yes	correct	106 | 2030	intact	no	Correct
97 | 2013	stripped	yes	correct	106 | 2031	stripped	yes	Correct
98 | 2014	intact	no	correct	107 | 2032	stripped	yes	Correct
98 | 2015	stripped	yes	correct	107 | 2033	stripped	yes	Correct
99 | 2016	intact	no	correct				

Conclusions

- Activity analysis reasonably quantifies locations of moisture damage and stripping
- Can be applied to long segments of pavement
- Threshold is arbitrary – core correlation is needed to set the threshold
- Core condition has been visual and qualitative – could benefit from quantitative testing such as indirect tensile testing..

Stripping Detection through Signal Analysis of 3D GPR Waveform

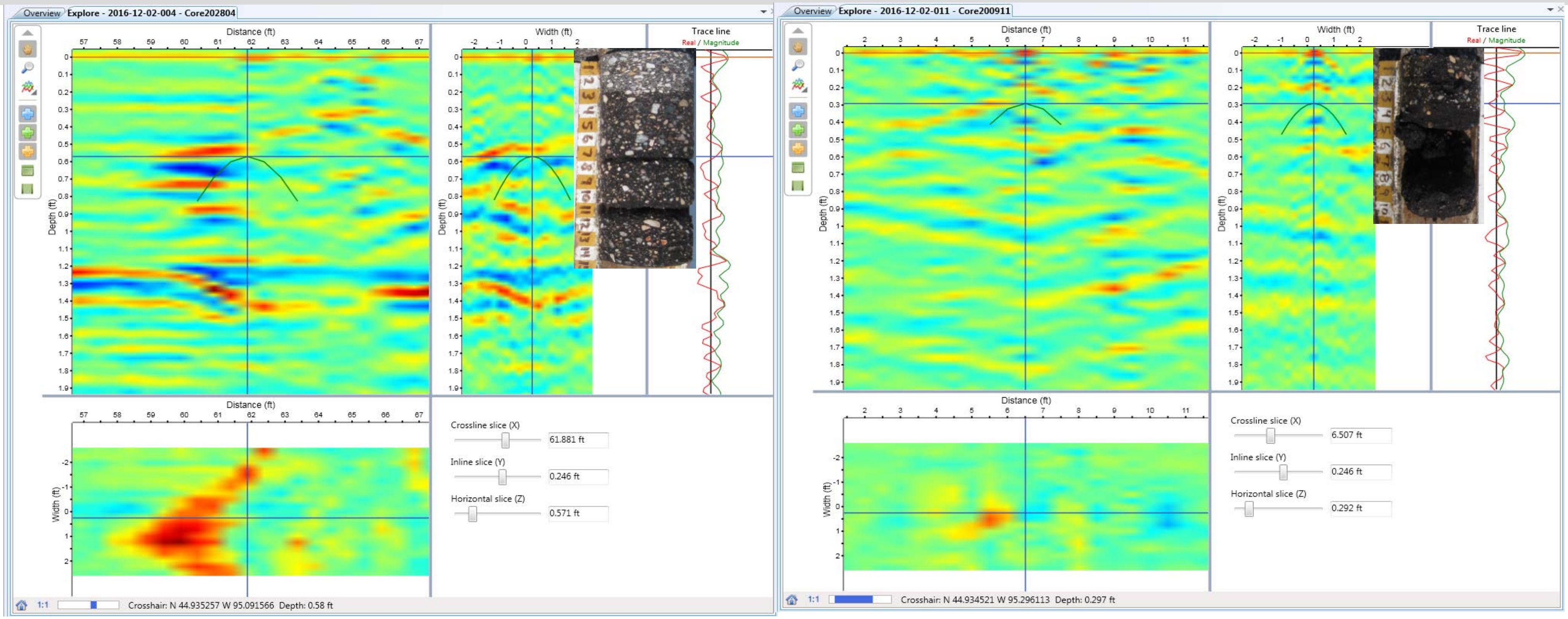
Acknowledgement

Acknowledgement

FHWA/SHRP2 (3D GPR equipment and funding)
3D Radar
NCAT
MnDOT District Offices

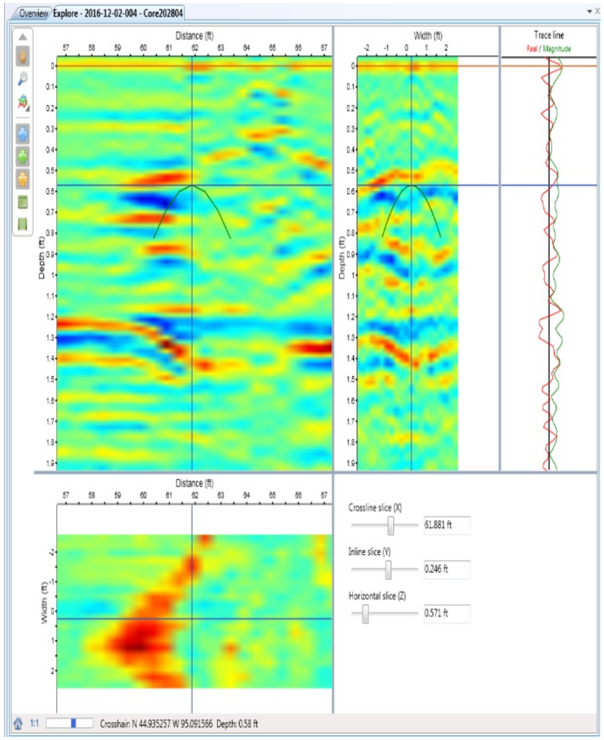
Using GPR to Detect Potential Stripping

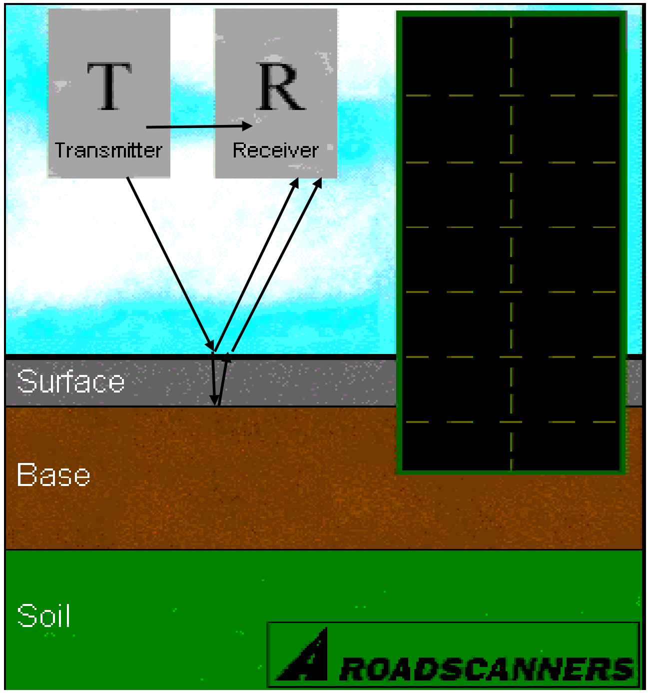
- Looking at GPR images
  - Very subjective to the person analyzing the image
  - Time-consuming and labor intensive
- GPR can not definitively identify stripping

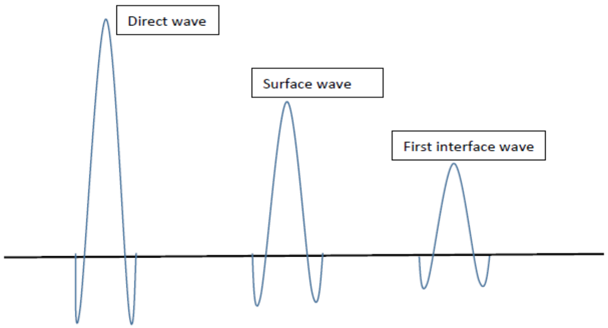


Concept of Signal Analysis

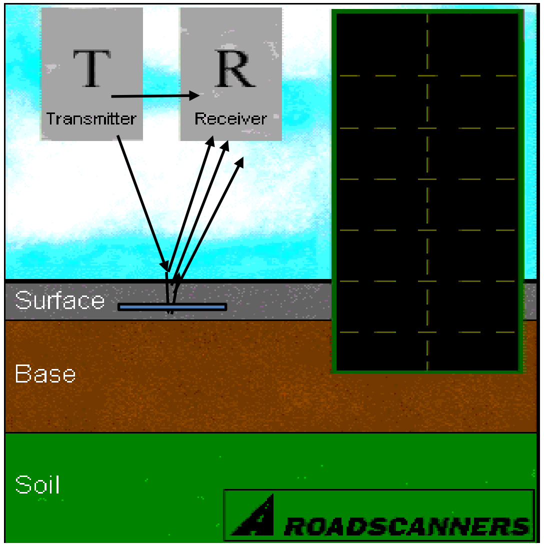
- GPR image consists of a lot of time-history waveforms
- Each waveform contains some information about the pavement
- A Perfect (homogenous and uniform) Layered System

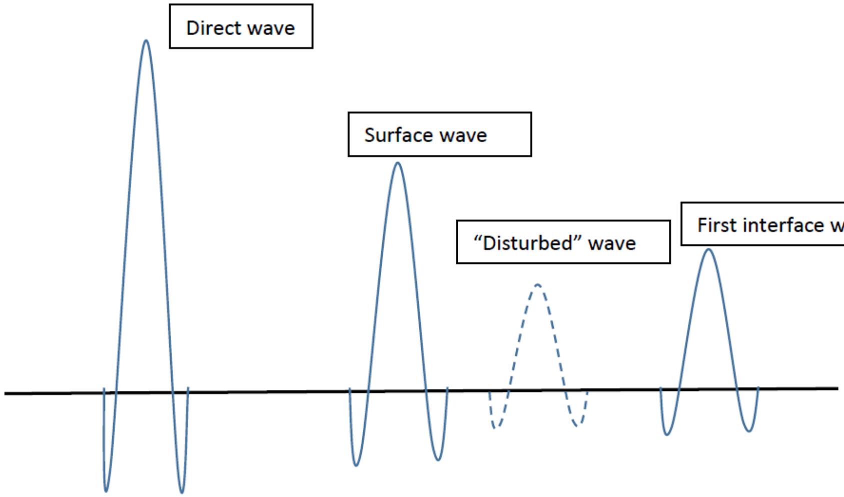




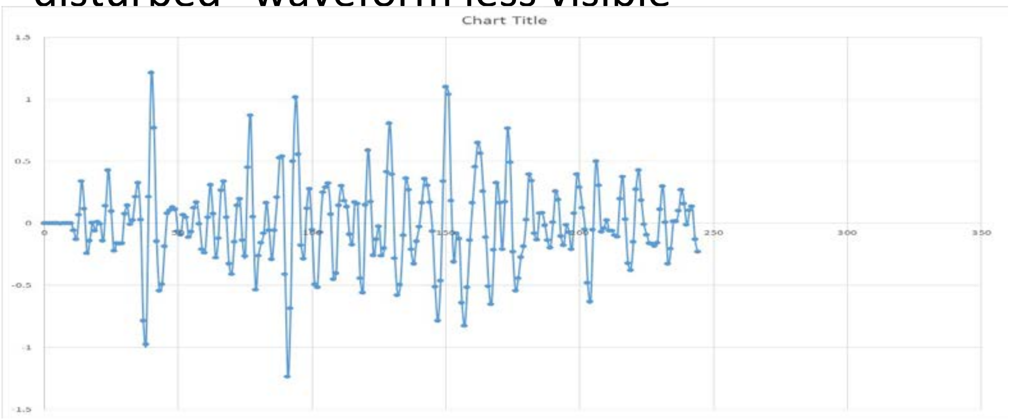


A Layered System with Defect (Stripping)





- **Real Signal Contains Noise**
  - Noise makes "disturbed" waveform less visible



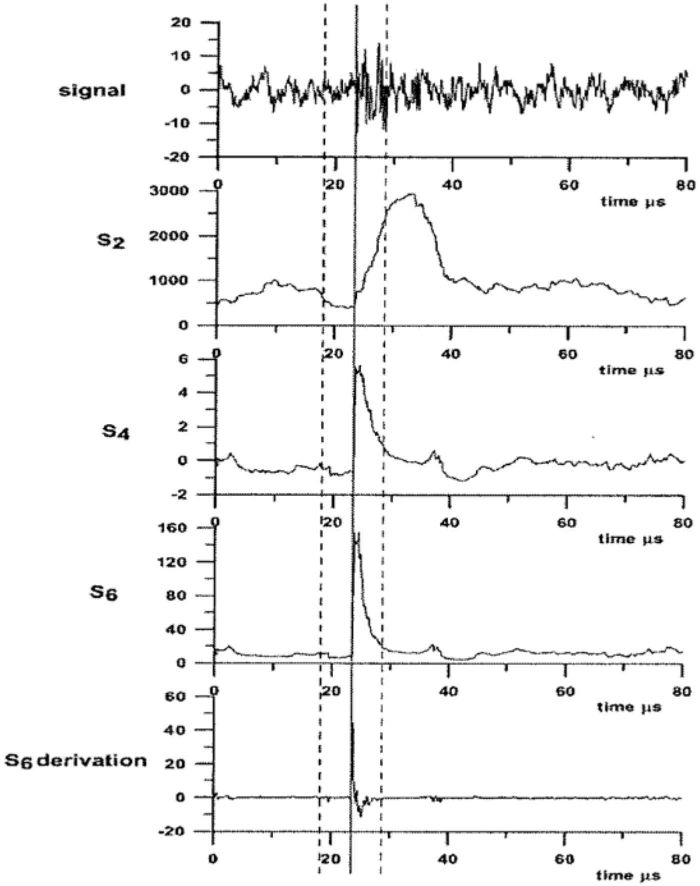
Purpose:

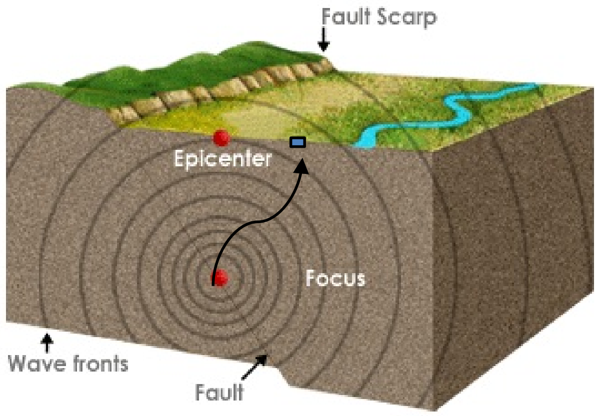
Evaluate different signal analysis methods to minimize noise and enhance “disturbed” signal by defect.

Eventually use computer to automatically pick the potential defects.

Signal Analysis Methods from Acoustic Emission (AE)

- **AE is used for detecting earthquake**
- **First arrival of P wave used to estimate hypocenter location**





$$S_2 = \sigma^2 = \frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}{N-1}.$$

$$S_4 = \text{kurtosis} = \frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^4}{(N-1)\sigma^4} - 3.$$

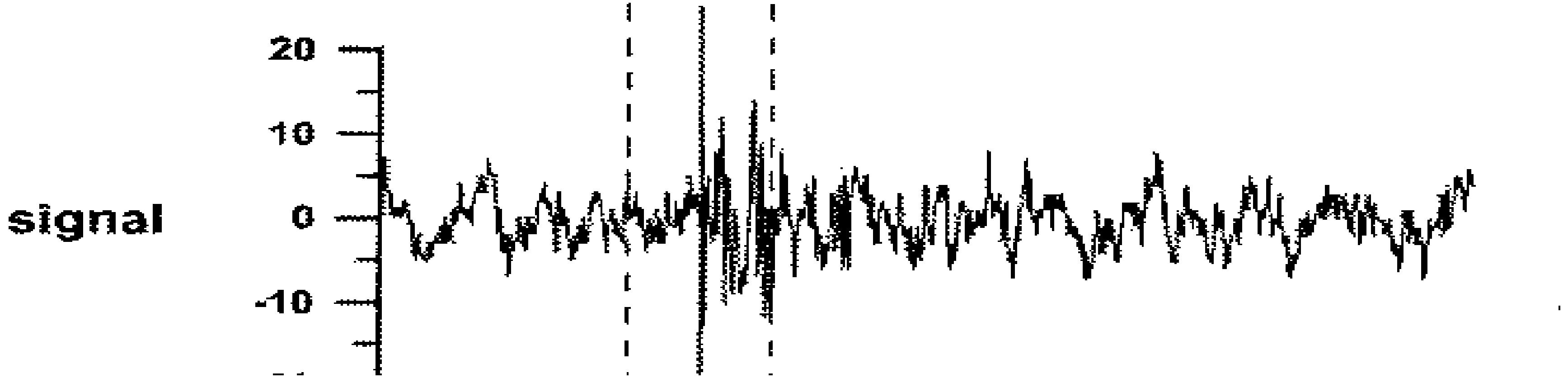
$$S_6 = \frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^6}{(N-1)\sigma^6} - 15.$$

A first arrival identification system of AE Signals
T. Lokajicek and K Klima, Meas.Sci. Technol,2006

Maximum Energy Ratio

- Energy before and after the first arrival in a small time window has a large difference

$$R_p = \frac{\sum_{i=p+1}^{p+M} Y_i^2}{\sum_{i=p-M}^{p-1} Y_i^2}$$

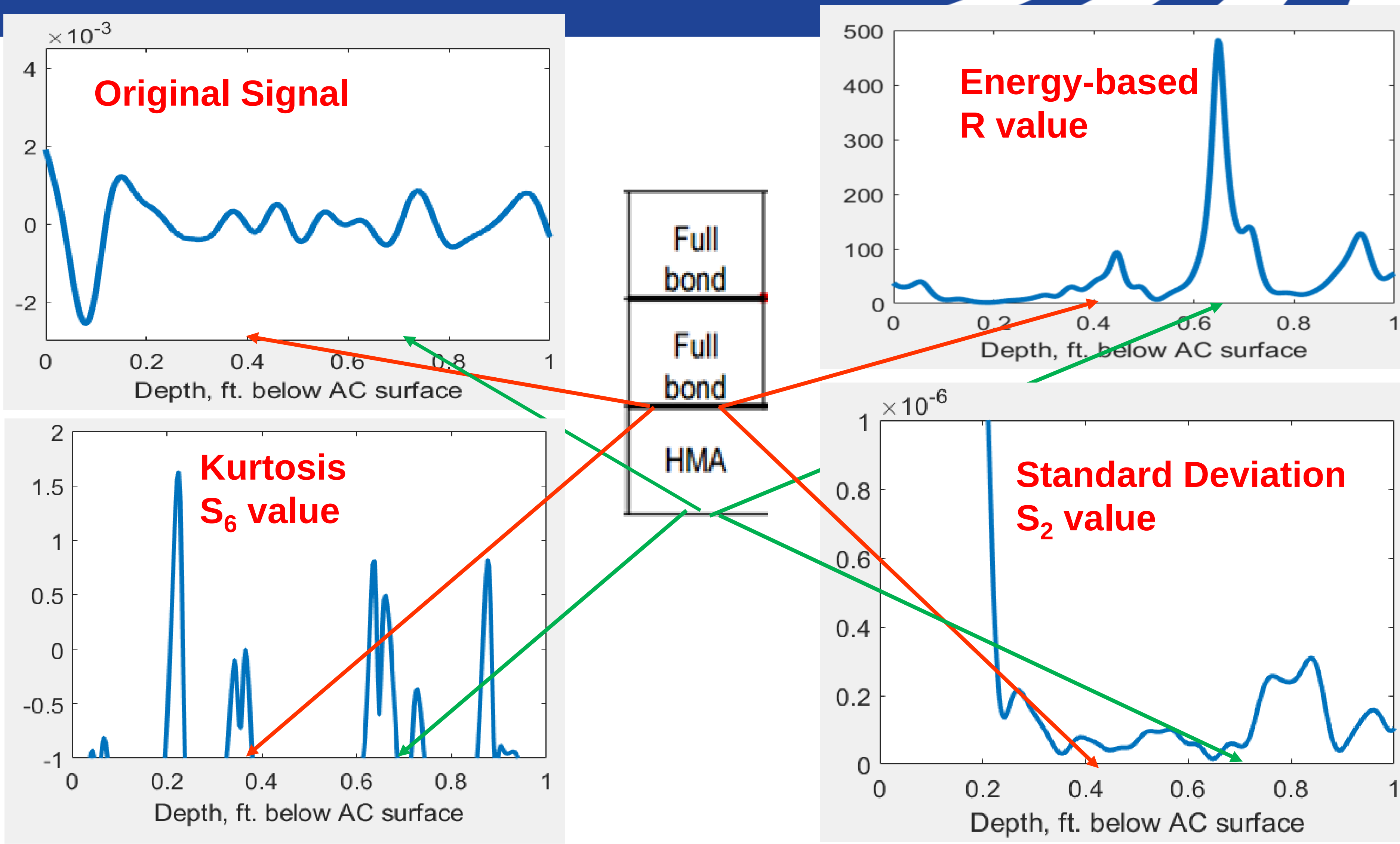


(Shah and Labuz, 1995)

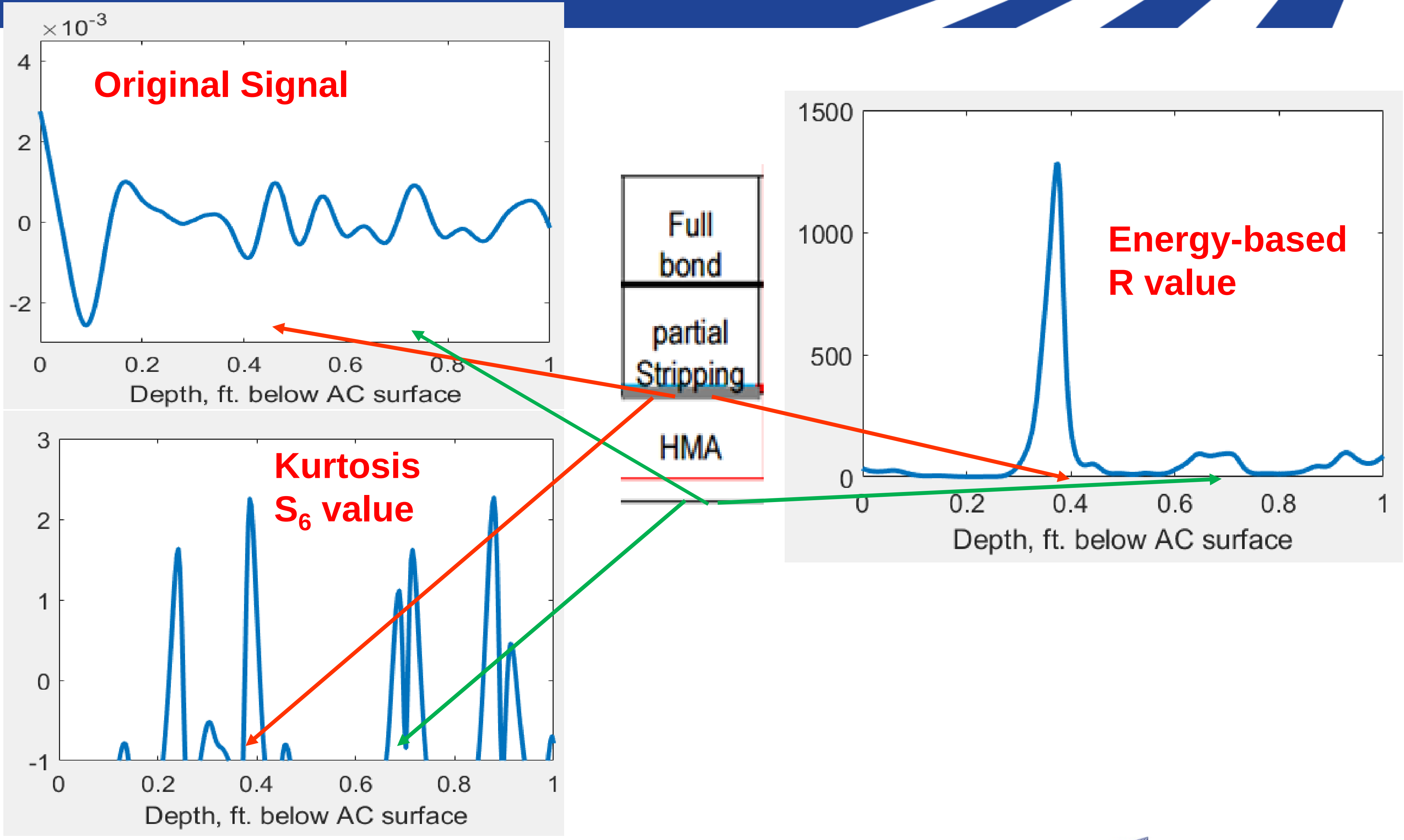
NCAT Test Sections

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9	Section 10
Top 2-inch lift	Full bond	Full bond	Full bond	Partial No bond	No bond	partial stripping	Full bond	Full bond	Full bond	Full bond
Bottom 3-inch lift	no bond	Full bond	Full bond	Full bond	Full bond	Full bond	Full bond	partial Stripping	partial No bond	No bond
Existing surface	PCC	PCC	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA

Non-stripped Location



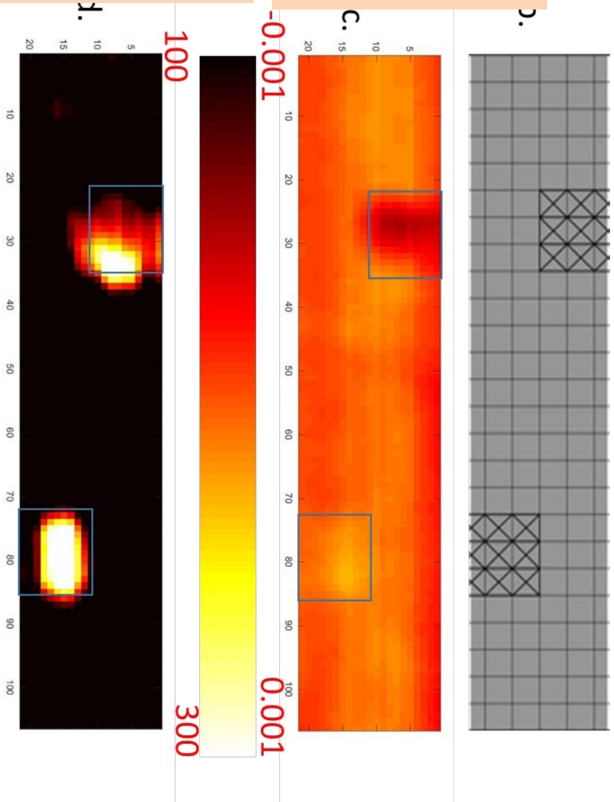
Stripped Location



Raw signal c-scan compared to the filtered data c-scan

C-scan of Energy-filtered Data

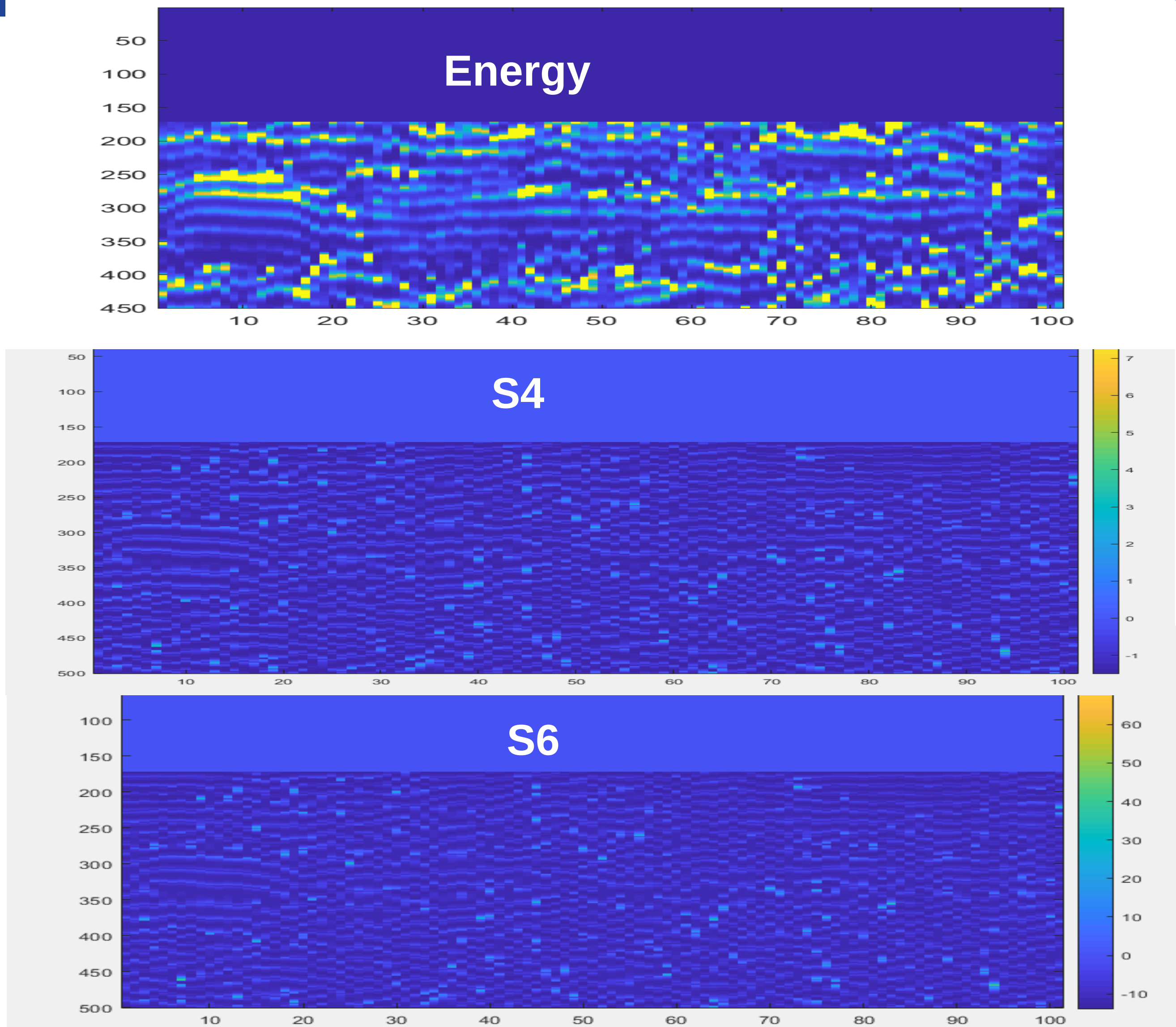
C-scan of Raw Data



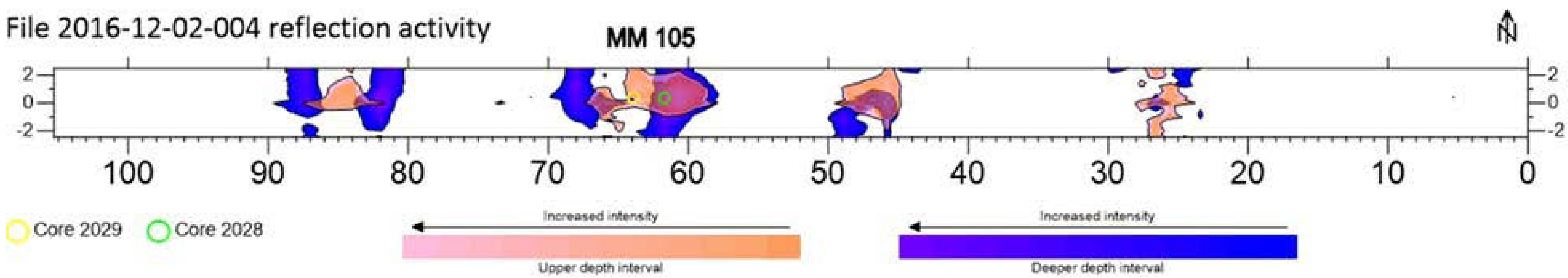
C-scan at design depth (~0.4 ft)

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9	Section 10
Top 2-inch lift	Full bond	Full bond	Full bond	Partial No bond	No bond	partial stripping	Full bond	Full bond	Full bond	Full bond
Bottom 3-inch lift	no bond	Full bond	Full bond	Full bond	Full bond	Full bond	Full bond	partial Stripping	partial No bond	No bond
Existing surface	PCC	PCC	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA

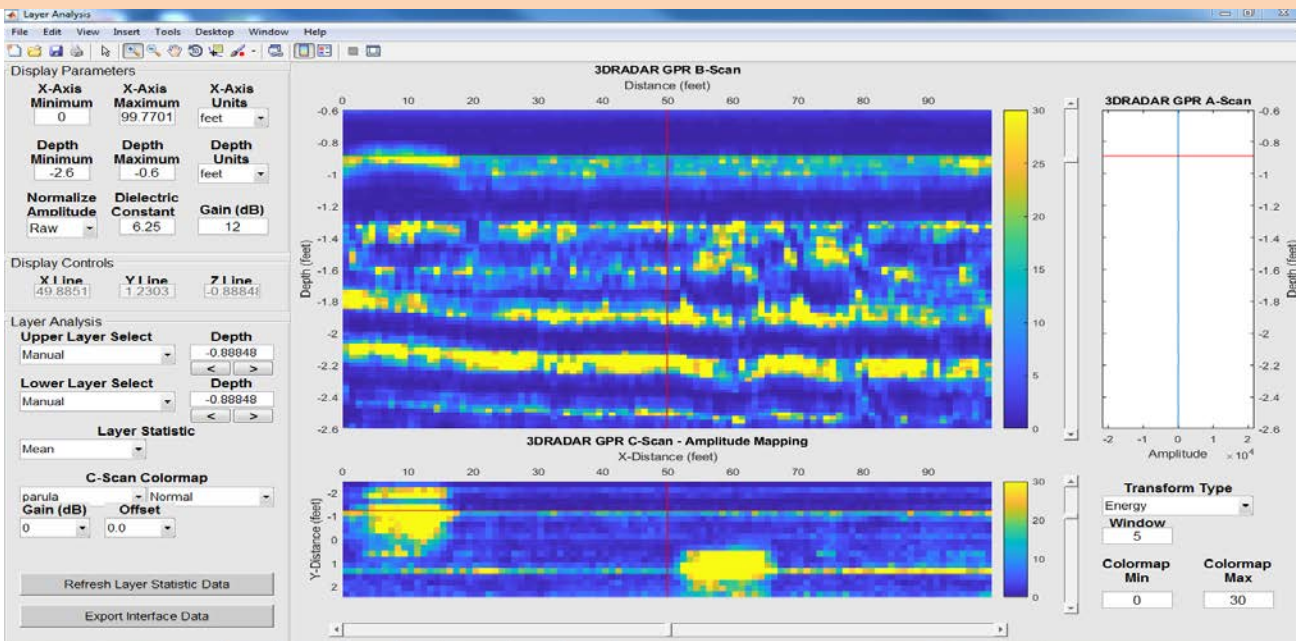
Analysis Results



ExploreGPR: Activity Method (Dr. Ken Maser)



- Energy method in ExploreGPR



Summary

- On-going effort
- Energy, S4 and S6 analysis approaches successful in identifying stripping at a controlled section at NCAT
- Need to be evaluated on multiple field projects where the stripping is more variable
- Goal: Use different methods to analyze signal. If all or most methods indicate a common area with “unusual” activity, the area is worth to be investigated further, could be “stripping”.