Data Automation for Pavement Distress Survey in the 3D World

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Two Parts

- Current 3D System
  - Highway
  - Airfield
- New Developments/Challenges
  - Inertial Sensor for IRI (WIS)
  - Deep-Learning Plan

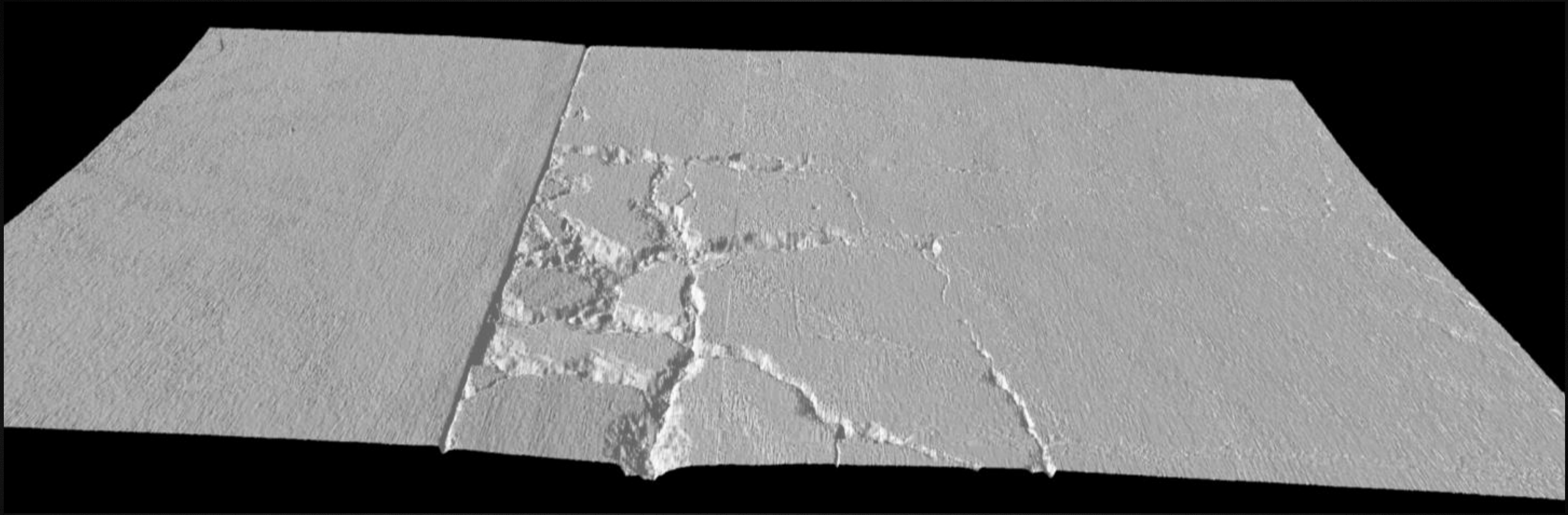
Part One

Current 3D System

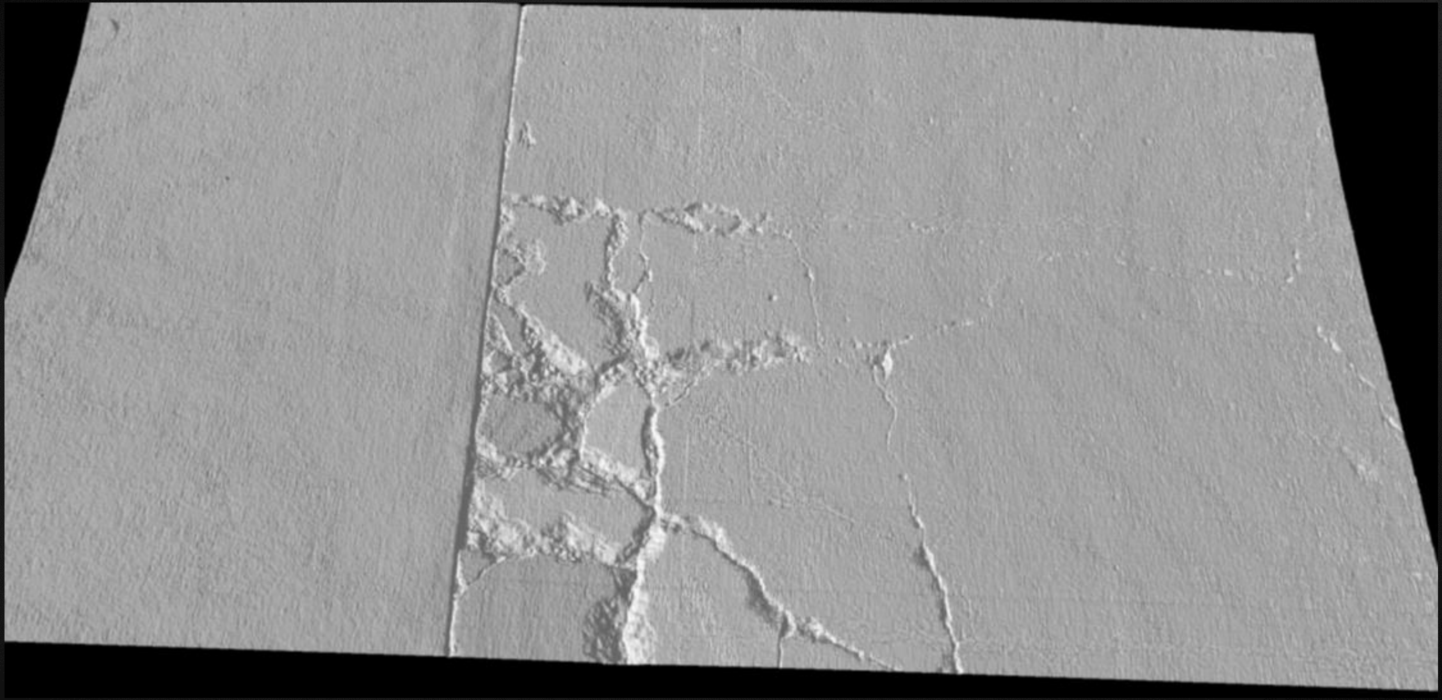
PaveVision3D Ultra （3D Ultra）

3D Ultra Vehicular Platform

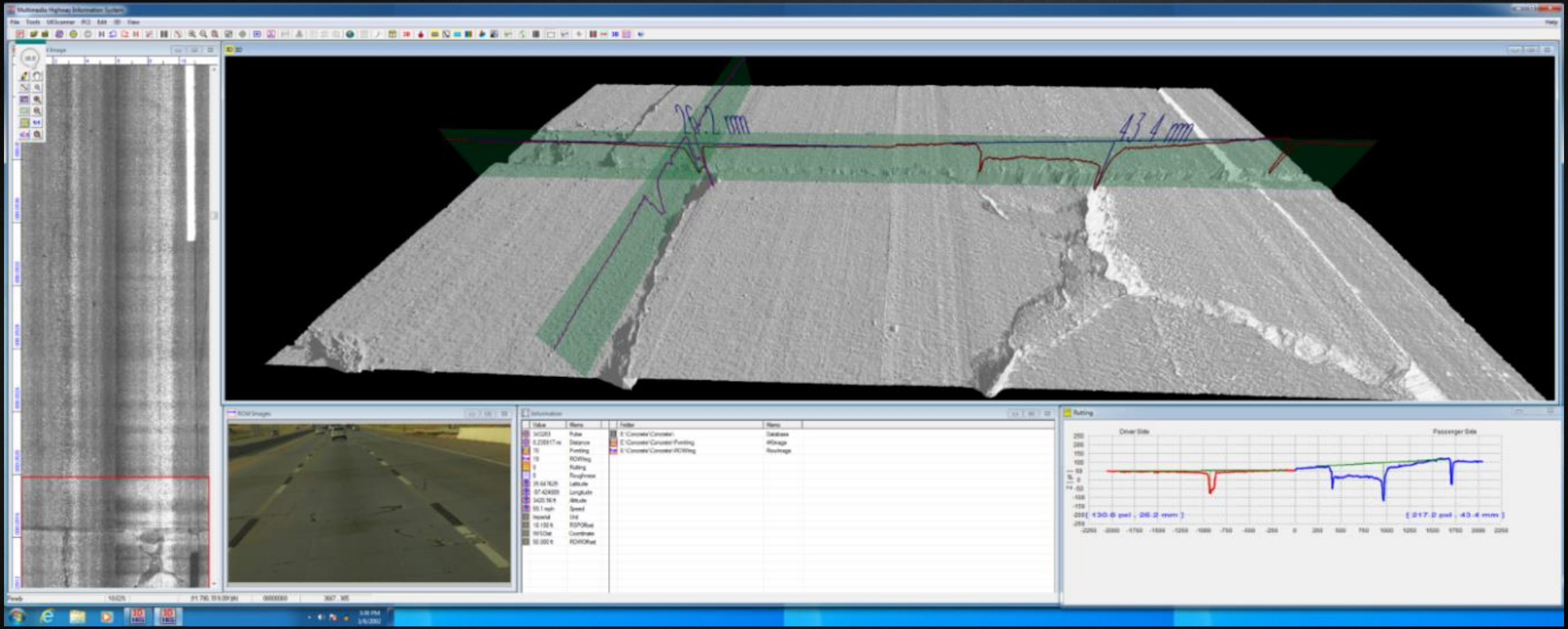
1mm Resolution 3D Pavement Surface



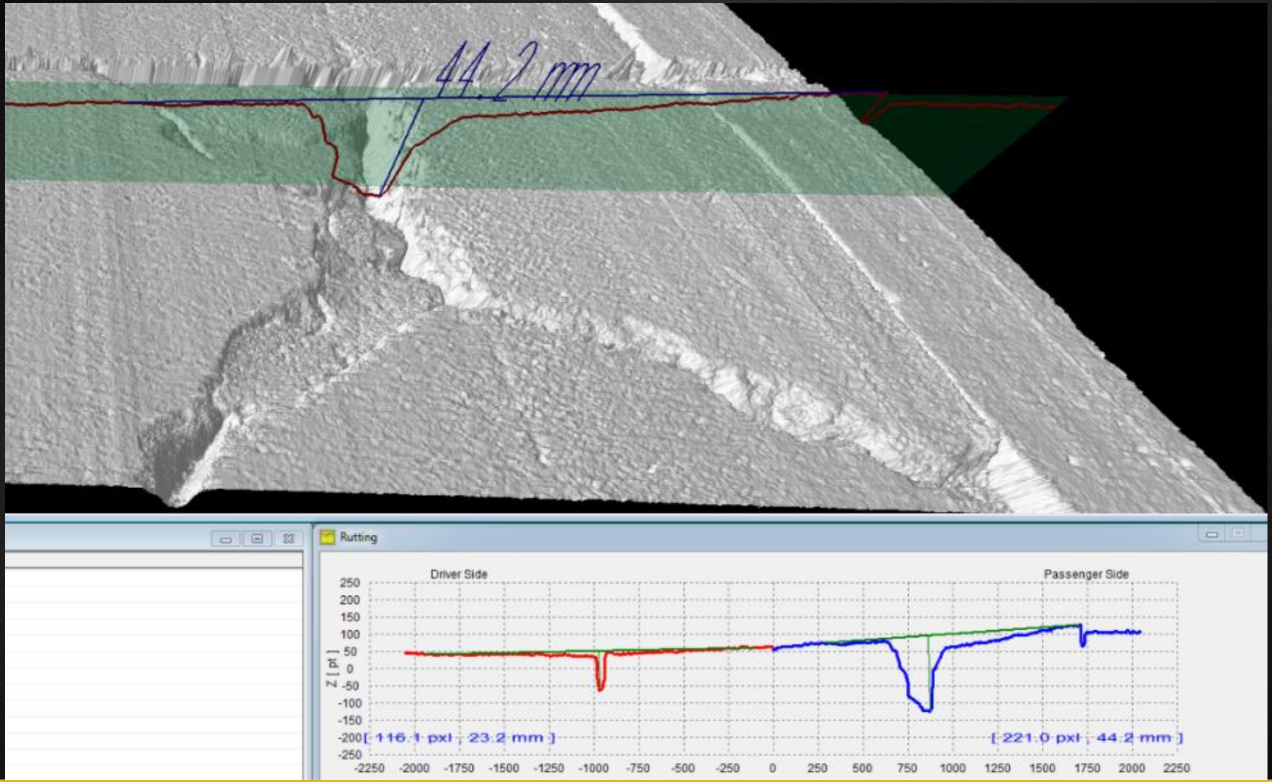
1mm Resolution 3D Pavement Surface



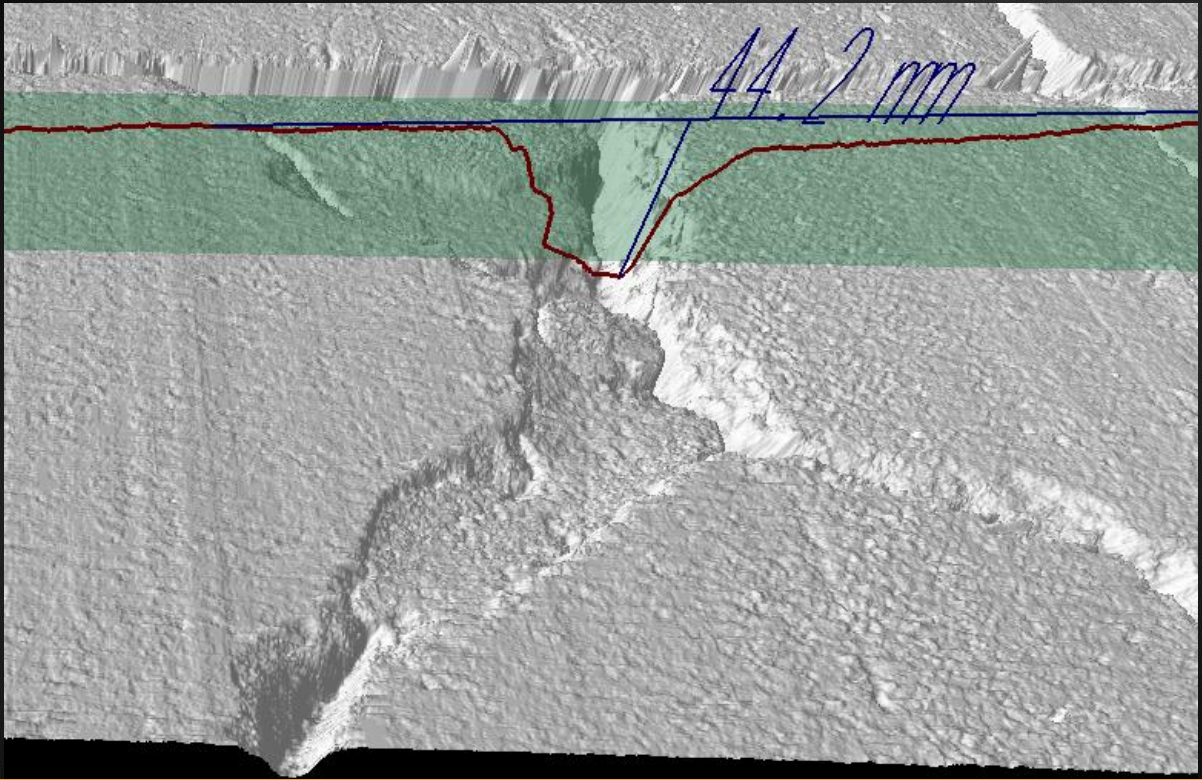
3D Data Collected at 100KPH



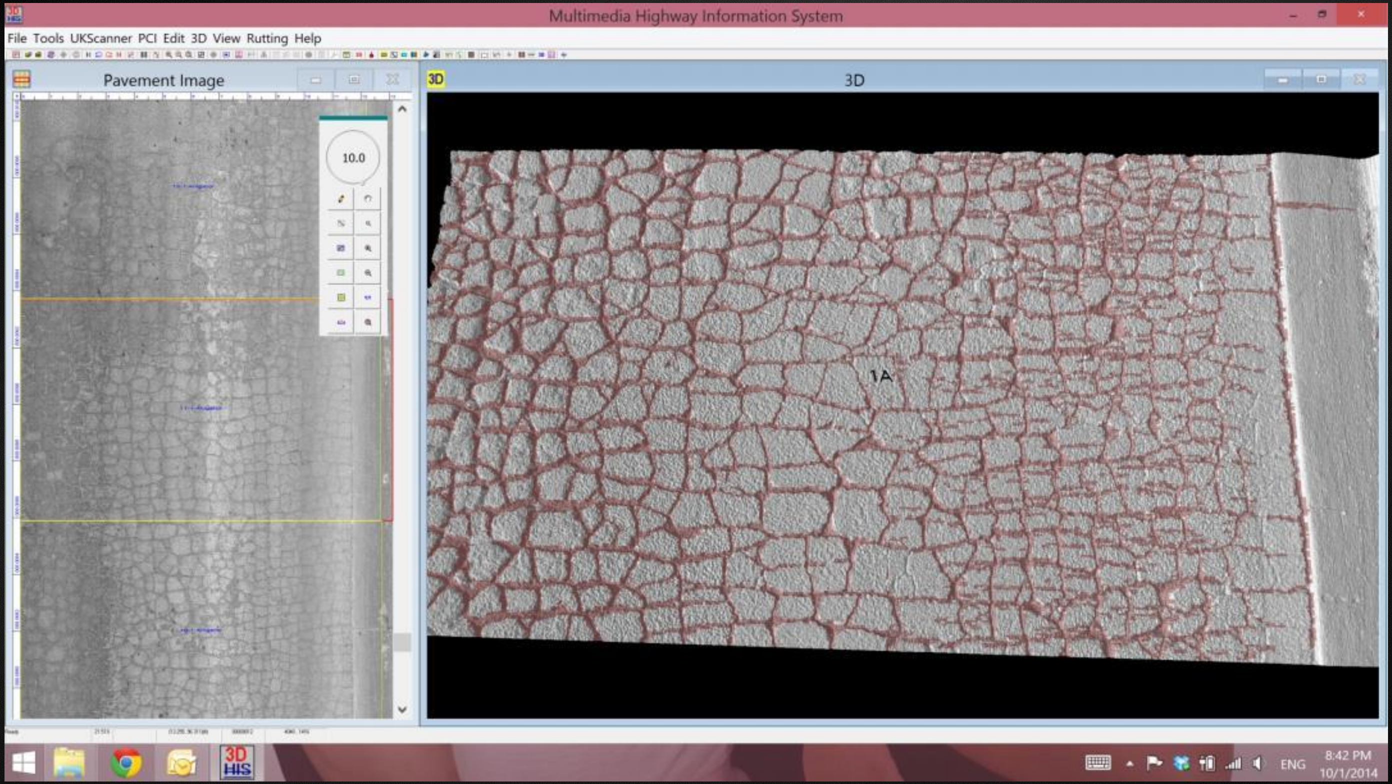
3D Data Collected at 100KPH



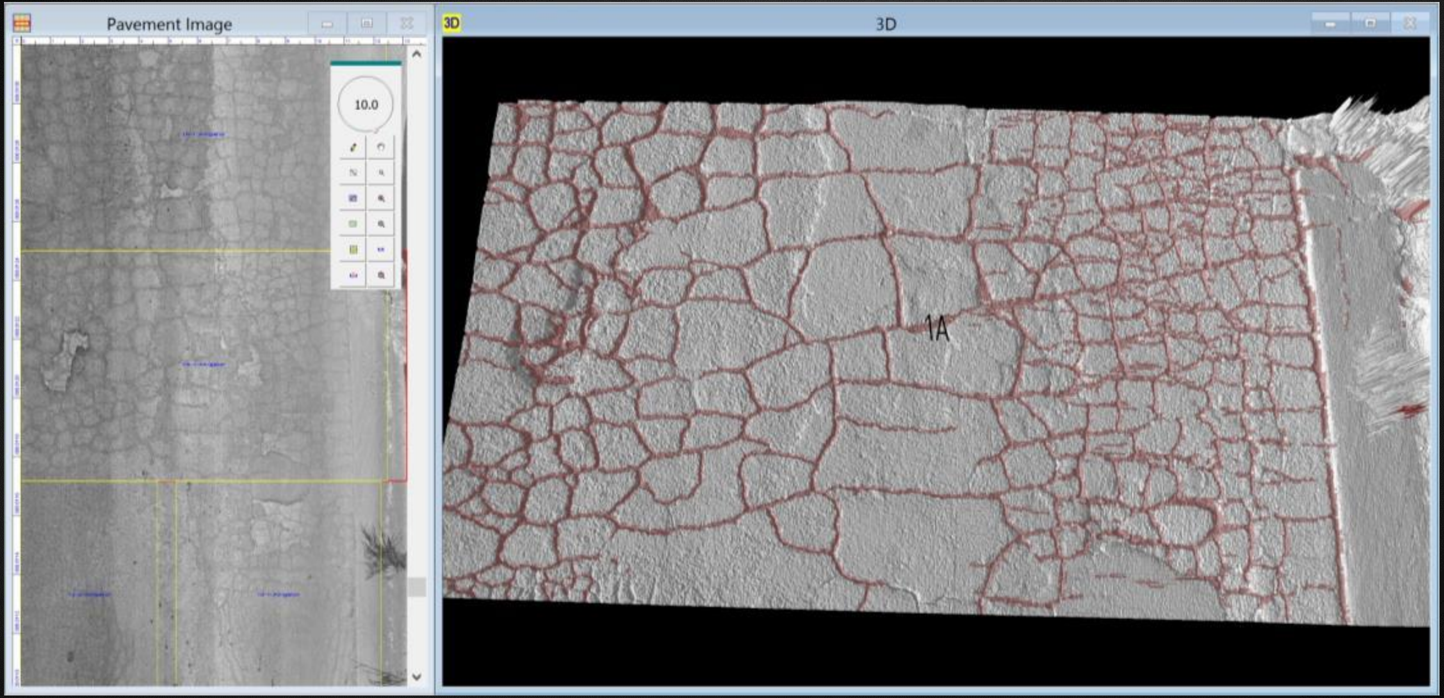
3D Data Collected at 100KPH



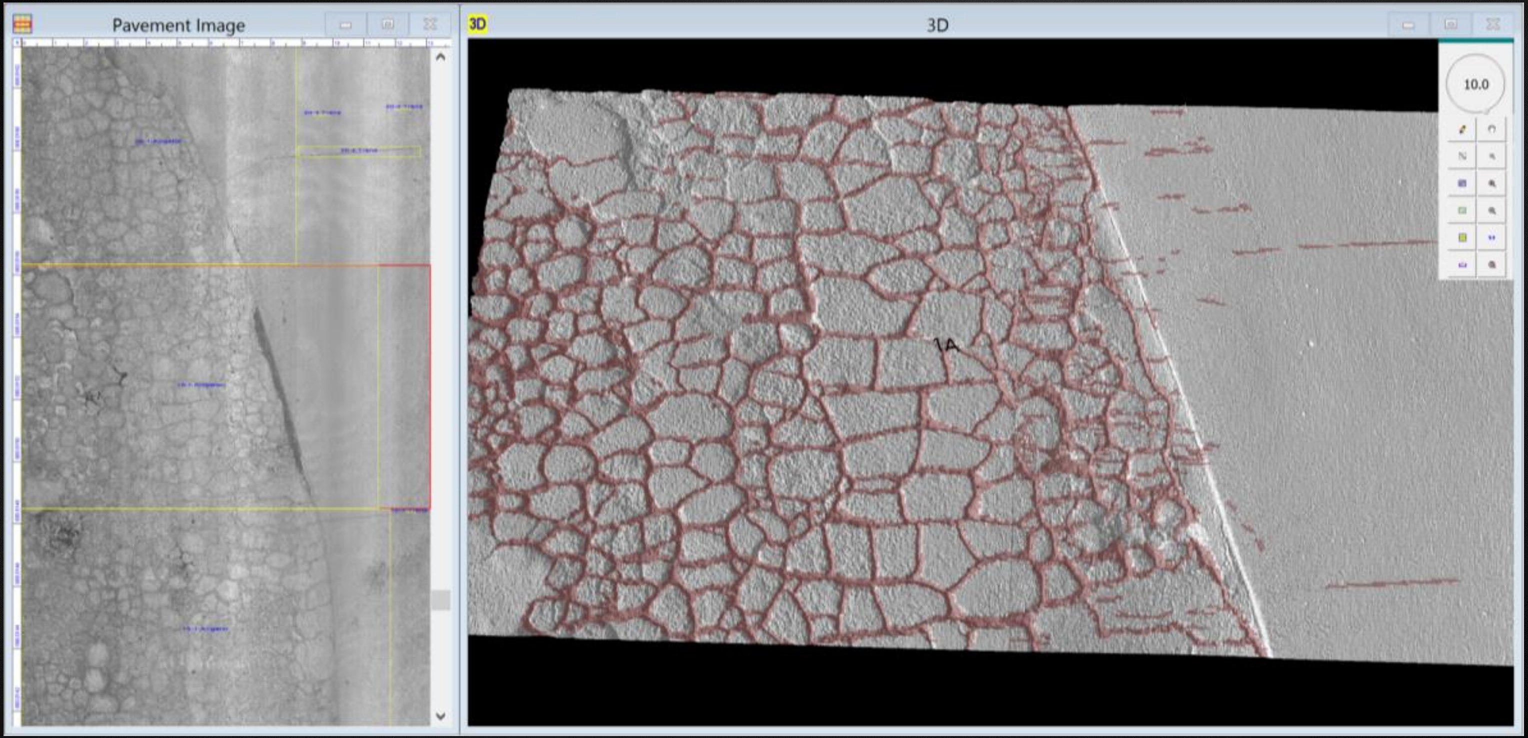
Automated Processing



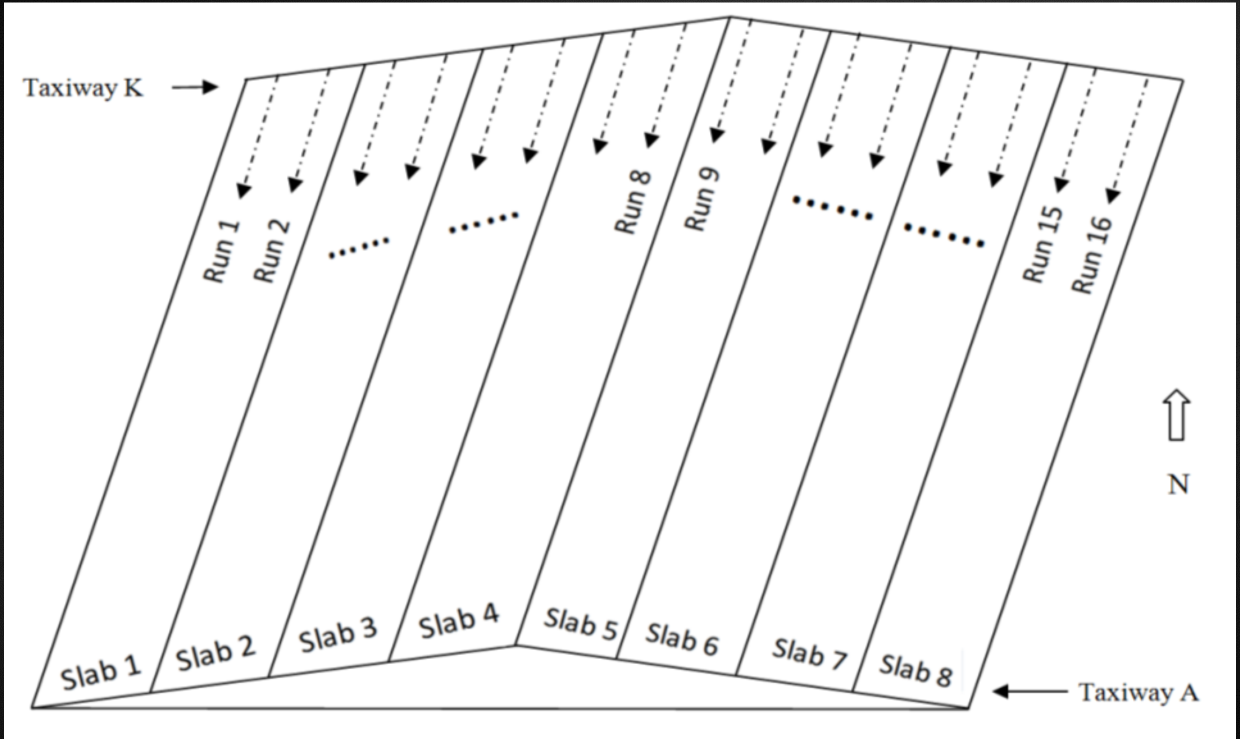
Automated Processing



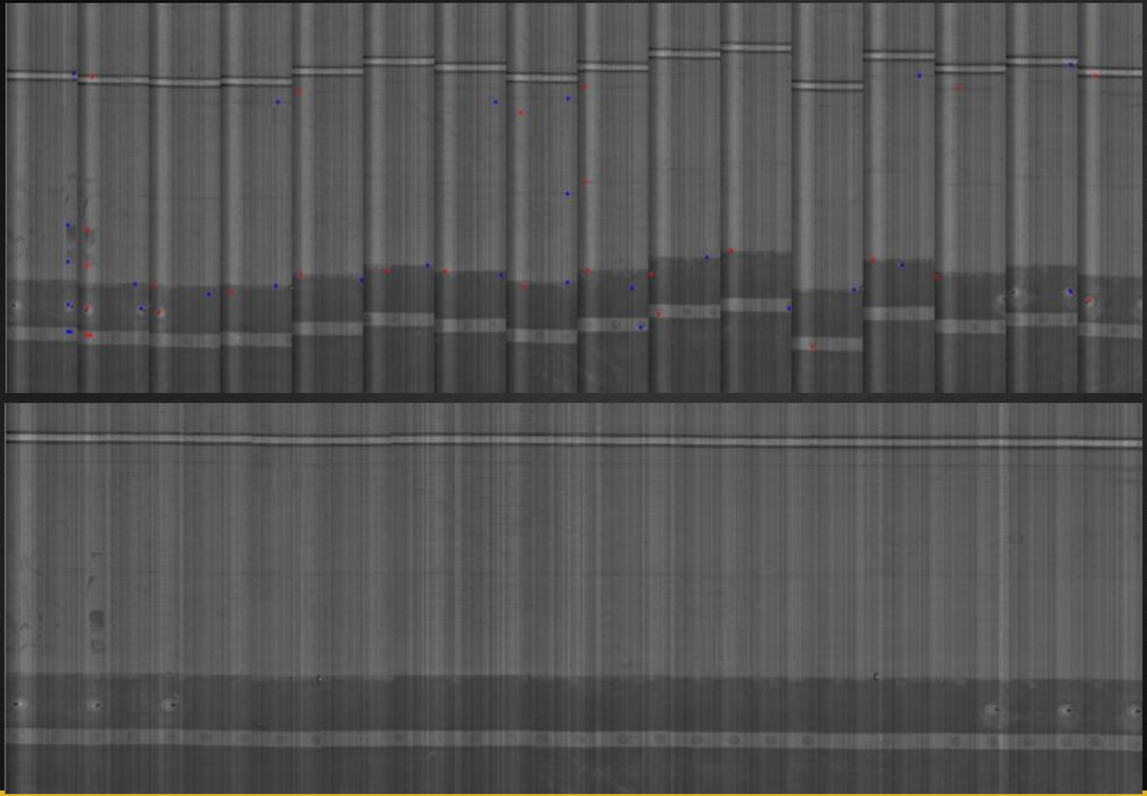
Automated Processing



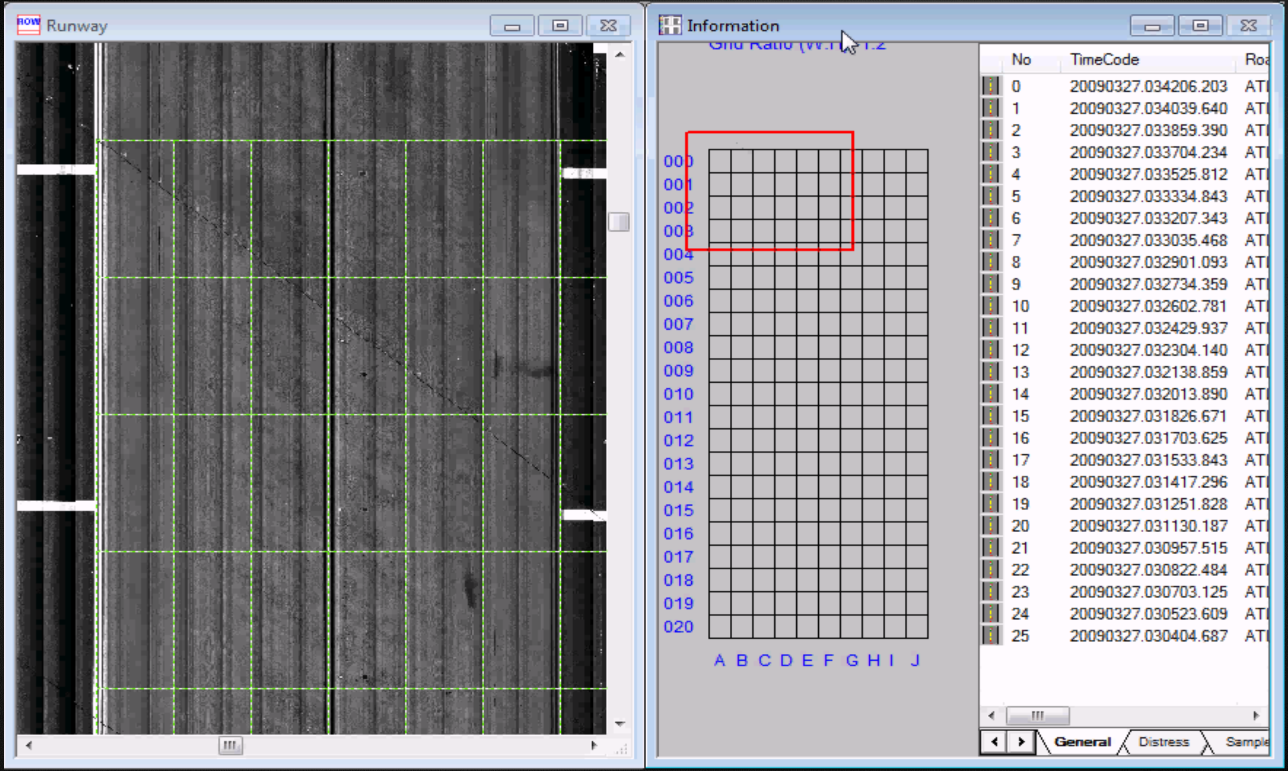
Inspection of Airport Runway



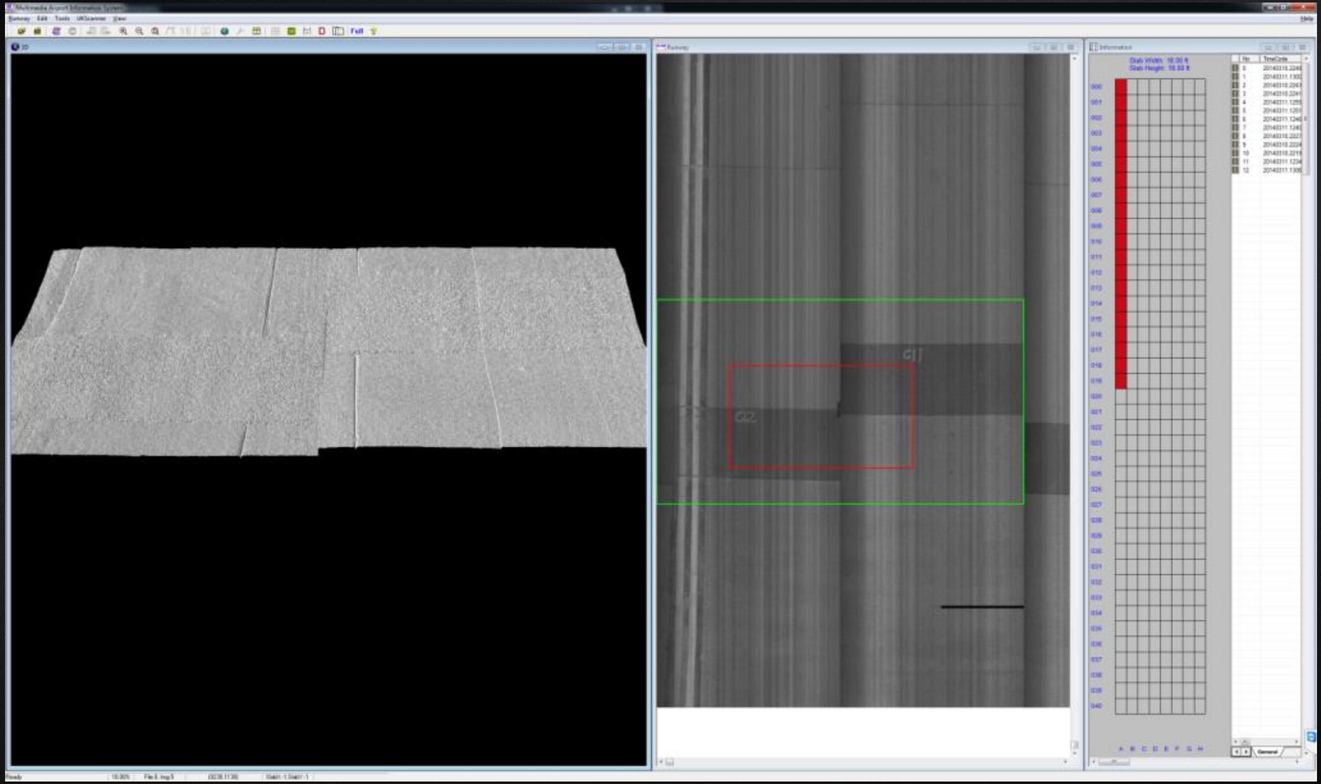
Airport Runway Data



Runway PCI Analysis



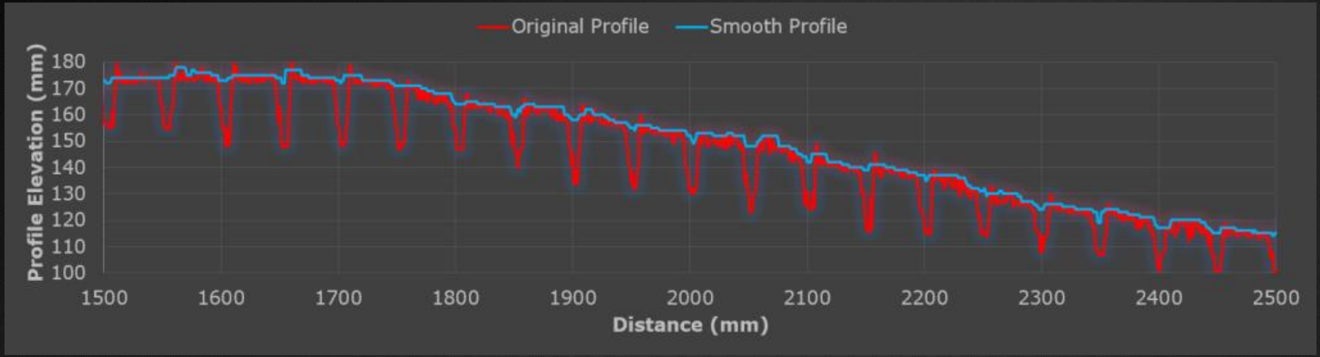
Runway PCI Analysis



Objectives: Groove Evaluation

- To develop algorithms to automatically estimate the runway groove dimension
  - Groove Depth
  - Groove Width, and
  - Groove Spacing
- To evaluate runway groove performance based on AC 150/5320-12C

Profile Data Filtering

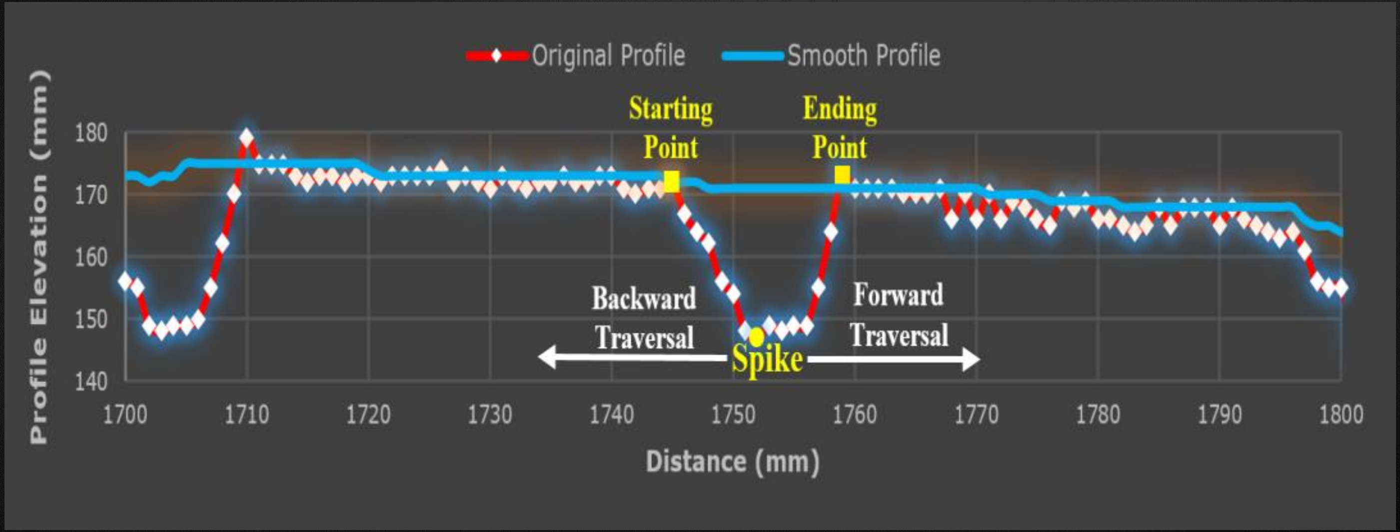


Geometry Contour Algorithm

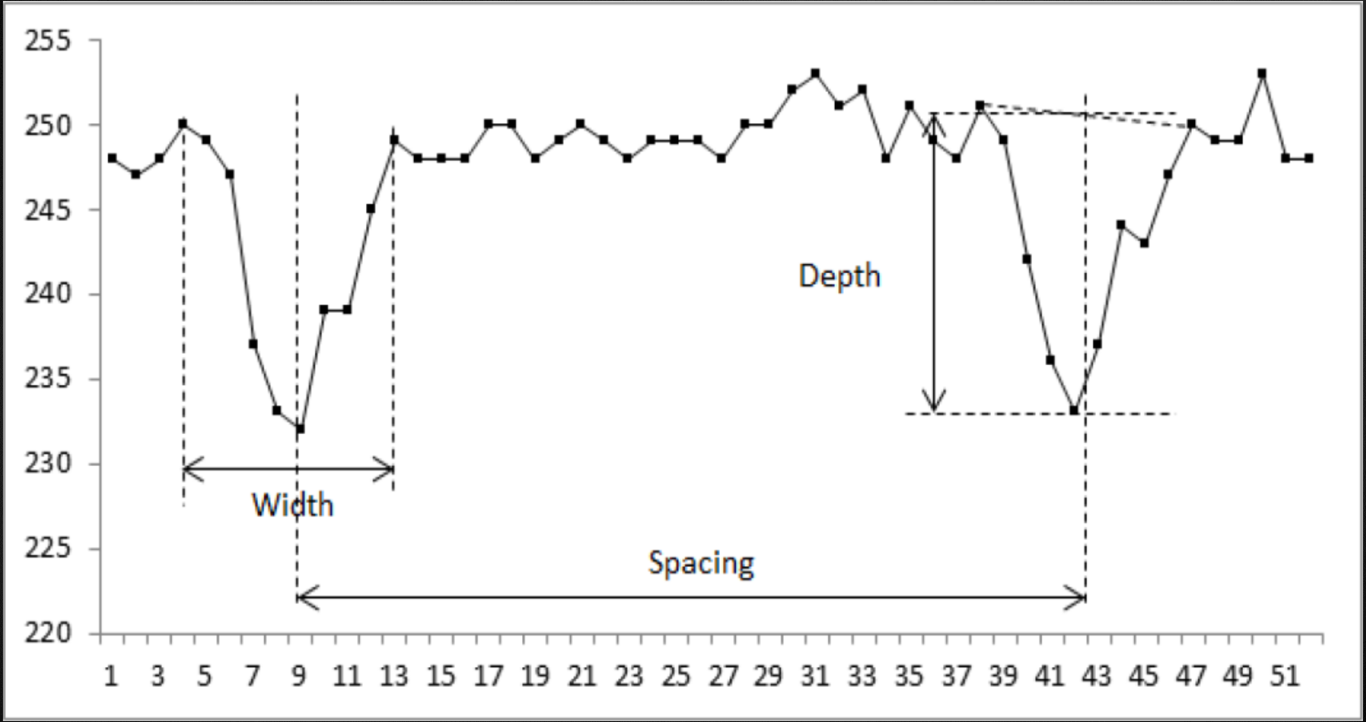
- Red Box – Moving Window
- Blue Circle – Deepest Point in the Moving Window

Backward & Forward Traversal

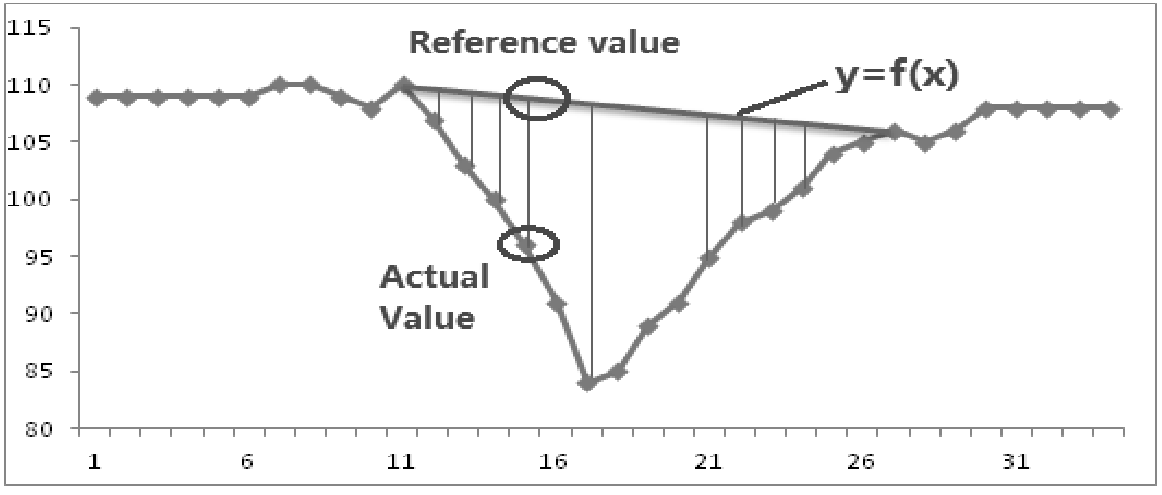
- Determine the starting & ending points of grooves based on changes of gradient /slope
- Use to measure groove dimensions



Groove Dimension Estimation

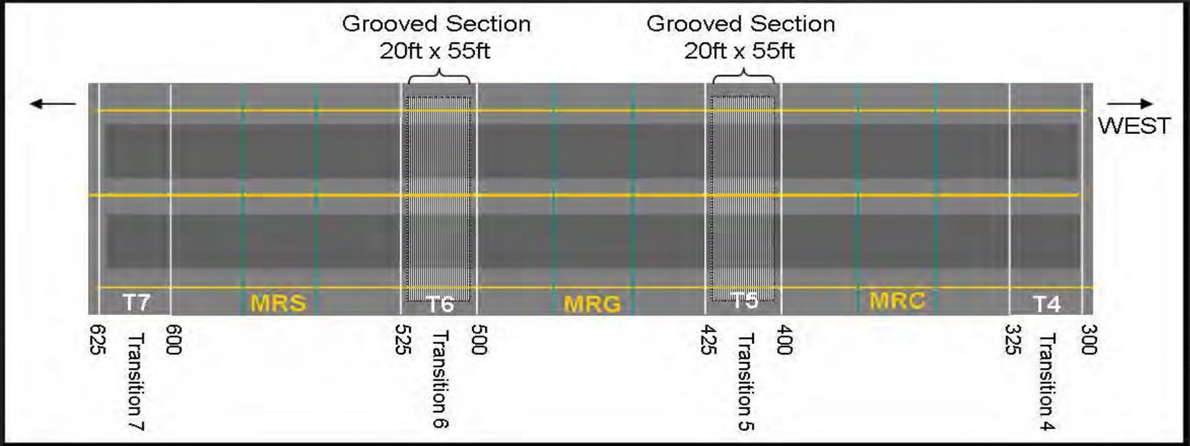


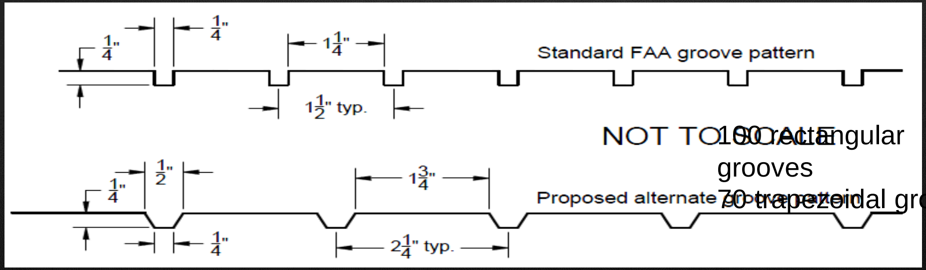
Groove Volume Estimation



$$V = \sum_{i=1}^{n} (f(xi) - y_i) * \Delta x * \Delta z$$

Algorithm Validation

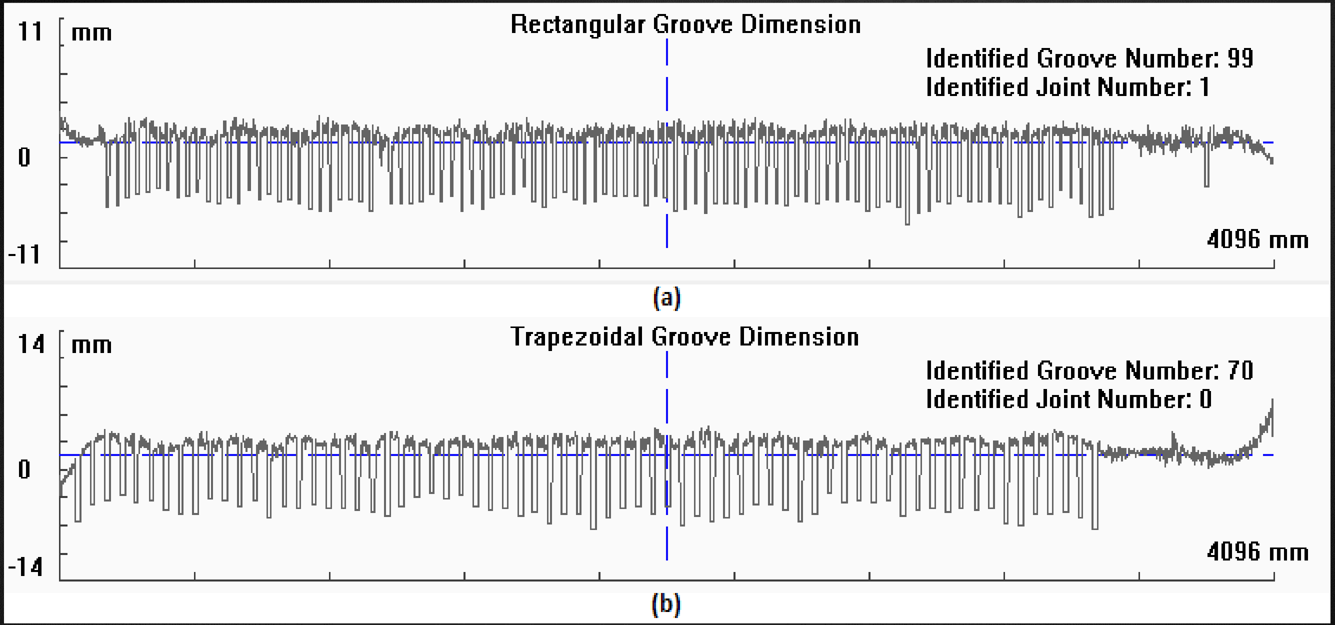




100 rectangular grooves

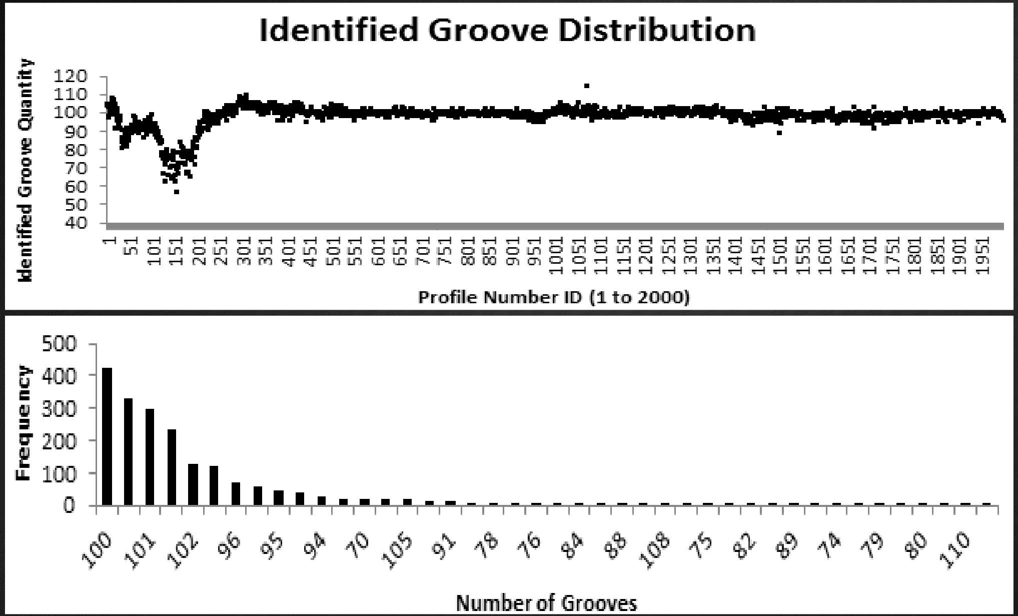
70 trapezoidal groove

Algorithm Validation



Grooves Identification Based On One Single Profile

Algorithm Validation



Grooves Identification Based On All Profiles

Groove Evaluation

Groove Depth or Width Distribution Range (mm)	Full Lane based Scenario			
	Width		Depth	
	Frequency	Percentage %	Frequency	Percentage %
$< \frac{3}{16}$ in. ($<$ 4.76 mm)	1366	0.7 %	34011	17.32 %
$\geq \frac{3}{16}$ in. ($\geq$ 4.76 mm)	16837	99.30 %	102448	82.68 %
$\geq \frac{1}{4}$ in. ($\geq$ 6.35 mm)	17952	90.73 %	56394	30.51 %
$\geq \frac{5}{16}$ in. ($\geq$ 7.94 mm)	160213	81.59 %	3515	1.79 %

Part Two

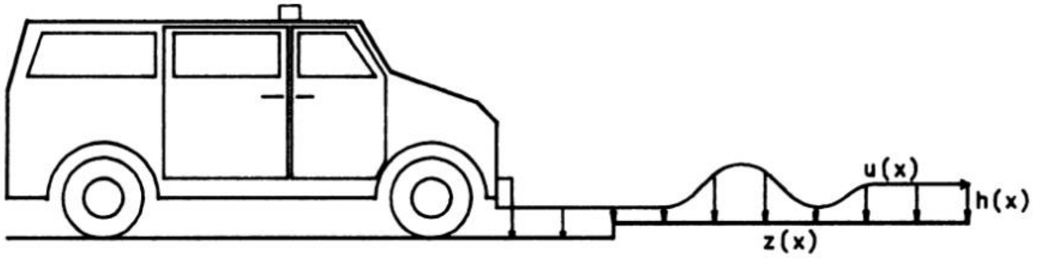
New Developments/Challenges

WIS Inertial Module for Longitudinal Profiling

WIS Inertial Module

- A self-contained, fist-size inertial sensor designed & developed by Dr. Wang's team
  - Integrated into PaveVision3D sensor case
  - Built-in: hardware filtering & power

Profile Measurement Principle



h(x) – Vehicle Height Above Pavement

u(x) – Vehicle Position

z(x) – Vertical Road Profile

Profile = z(x) = u(x) – h(x)

Image Reference: ***Description and Evaluation of the South Dakota Road Profiler***

Validation Tests: 3 Pavement Sections

Testing Site I W Lakeview Rd. and Driving Speed 30 mph

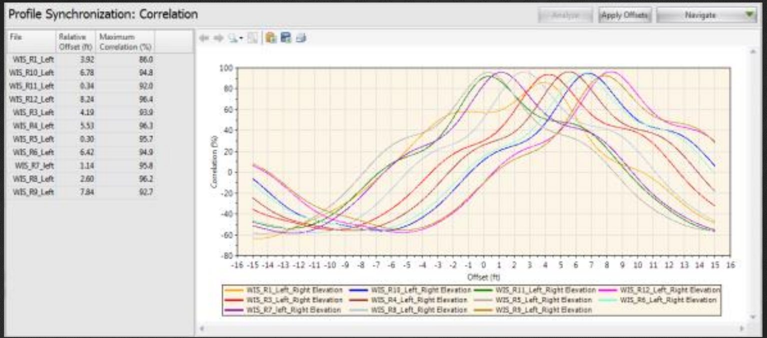
Testing Site II Country Club Rd and Driving Speed 40 mph

Testing Site III W 6th Ave and Driving Speed 60 mph

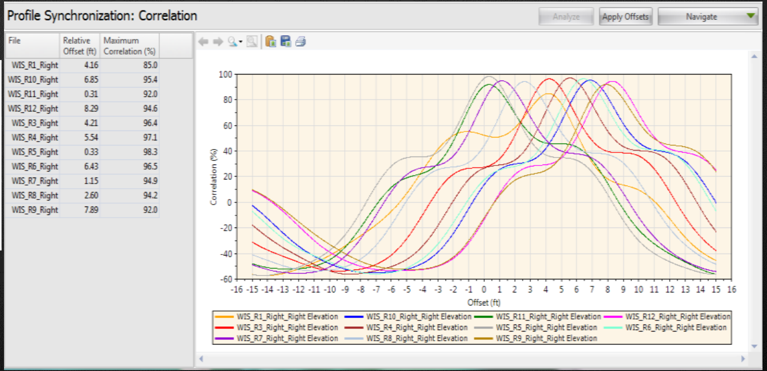
Test Site I: W Lakeview Rd 12 Passes

- Repeatability of 3D Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
94.06	96.4	86.0



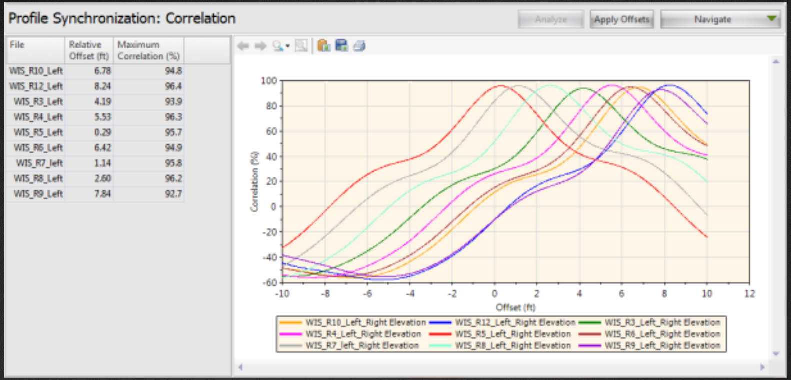
Right Side		
Avg %	Max %	Min%
94.20	98.3	85.0



Test Site I: W Lakeview Rd **10 Best Passes**

- Repeatability of 3D Data From Left and Right Side (WIS)

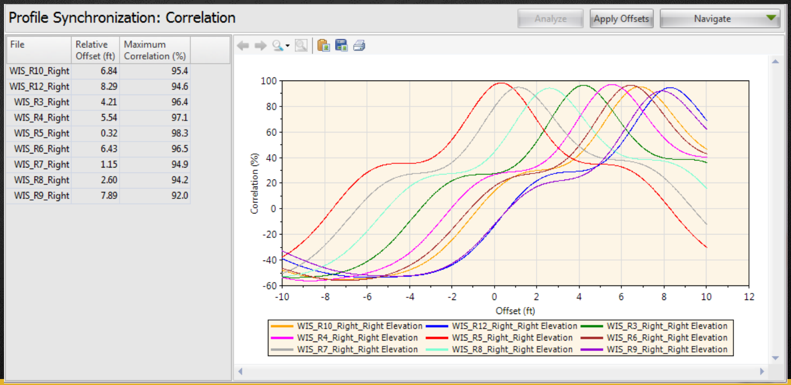
Left Side		
Avg %	Max %	Min%
95.1	96.4	92.7



Profile Synchronization: Correlation

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10_Left	6.78	94.8
WIS_R12_Left	8.24	96.4
WIS_R3_Left	4.19	93.9
WIS_R4_Left	5.53	96.3
WIS_R5_Left	0.29	95.7
WIS_R6_Left	6.42	94.9
WIS_R7_left	1.14	95.8
WIS_R8_Left	2.60	96.2
WIS_R9_Left	7.84	92.7

Right Side		
Avg %	Max %	Min%
95.48	98.3	92.0



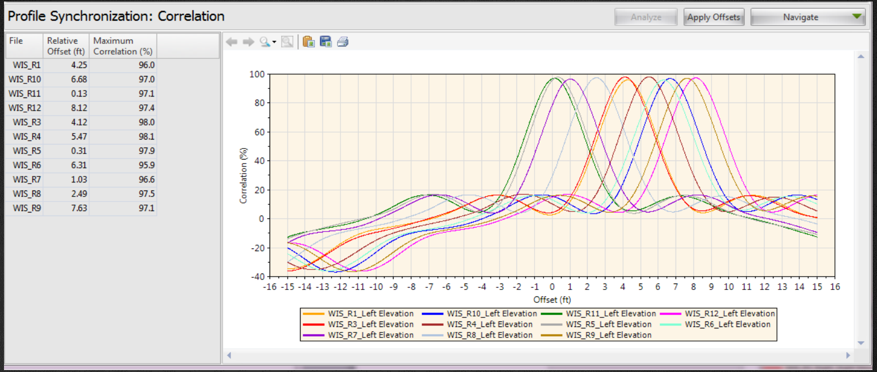
Profile Synchronization: Correlation

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10_Right	6.84	95.4
WIS_R12_Right	8.29	94.6
WIS_R3_Right	4.21	96.4
WIS_R4_Right	5.54	97.1
WIS_R5_Right	0.32	98.3
WIS_R6_Right	6.43	96.5
WIS_R7_Right	1.15	94.9
WIS_R8_Right	2.60	94.2
WIS_R9_Right	7.89	92.0

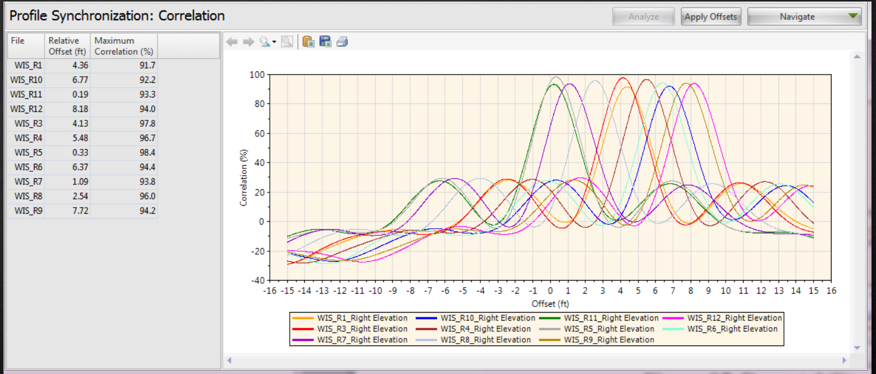
Test Site I: W Lakeview Rd 12 Passes

- Repeatability of Profile Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
97.15	98.1	95.9



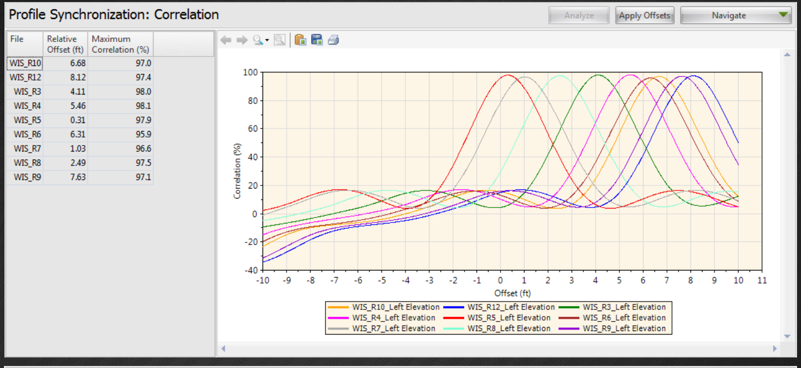
Right Side		
Avg %	Max %	Min%
94.77	98.4	91.7



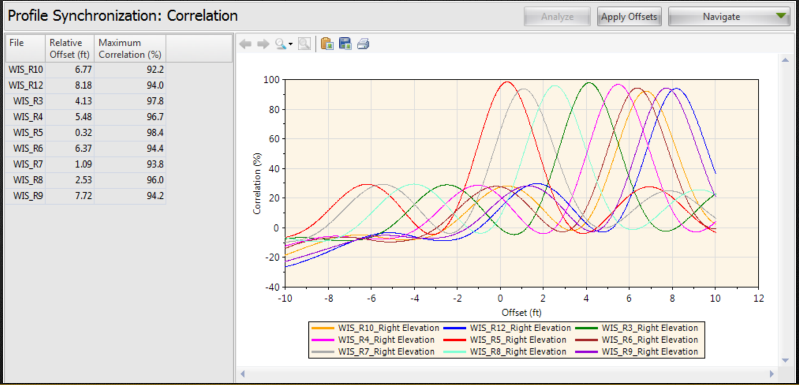
Test Site I: W Lakeview Rd **10 Best Passes**

- Repeatability of Profile Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
97.28	98.1	95.9



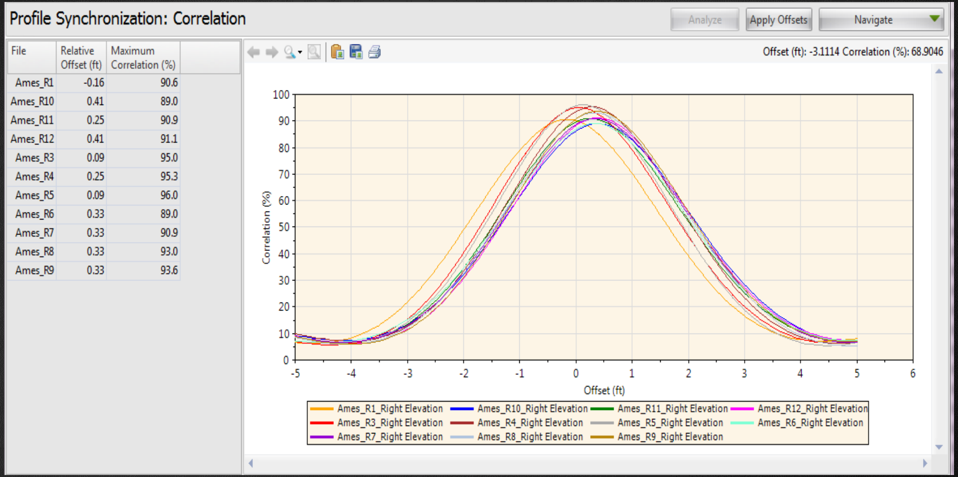
Right Side		
Avg %	Max %	Min%
95.28	98.4	92.2



Test Site I: W Lakeview Rd 12 Passes

- Repeatability of Profile Data From Left Side (Ames)

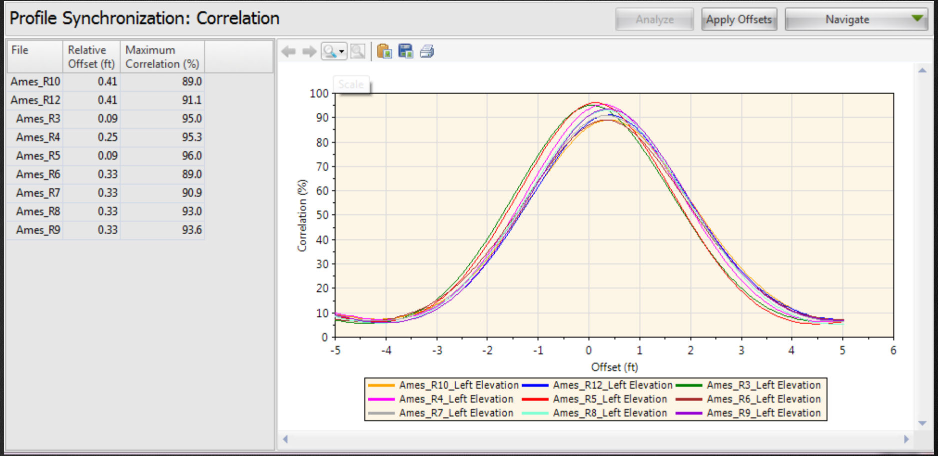
Left Side		
Avg %	Max %	Min%
92.22	96.0	89.0



Test Site I: W Lakeview Rd **10 Best Passes**

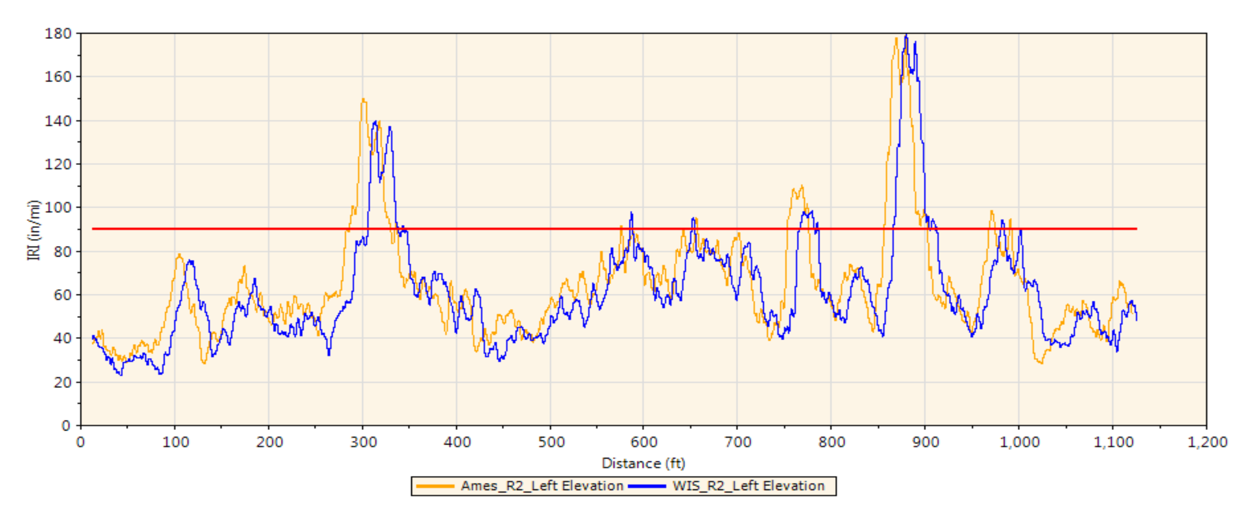
- Repeatability of Profile Data From Left Side (Ames)

Left Side		
Avg %	Max %	Min%
92.54	96.0	89.0



Test Site I: W Lakeview Rd 12 Passes

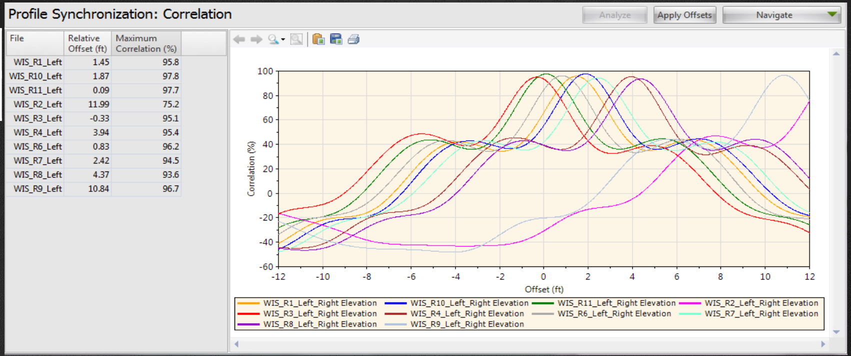
- Continuous IRI Results
  - Calculate an IRI Result in Every Small Distance, e.g. 25 ft., from the First Point to the Last Point of the Profile.
  - Plot the Calculated IRI Results into a Continuous Curve.
  - Displayed WIS data and Ames data From the Second Pass.



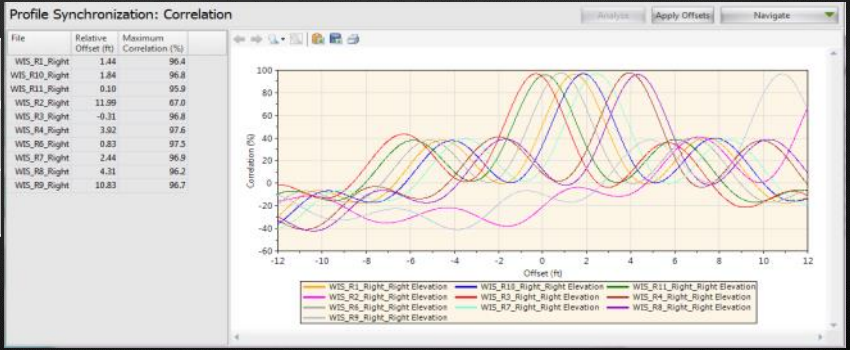
Test Site II: Country Club Rd 11 Passes

- Repeatability of 3D Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
93.81	97.8	75.2



Right Side		
Avg %	Max %	Min%
93.78	97.6	67.0



Test Site II: Country Club Rd **10 Best Passes**

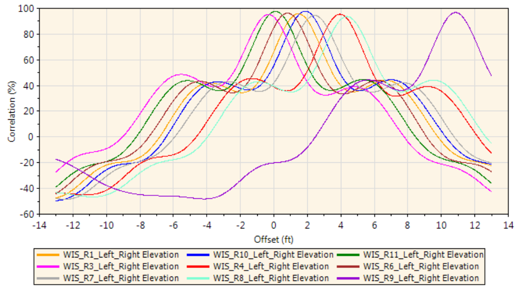
- Repeatability of 3D Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
95.87	97.8	93.6

Profile Synchronization: Correlation

Analyze | Apply Offsets | Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R1_Left	1.45	95.8
WIS_R10_Left	1.87	97.8
WIS_R11_Left	0.09	97.7
WIS_R3_Left	-0.33	95.1
WIS_R4_Left	3.94	95.4
WIS_R6_Left	0.82	96.2
WIS_R7_Left	2.42	94.5
WIS_R8_Left	4.37	93.6
WIS_R9_Left	10.84	96.7

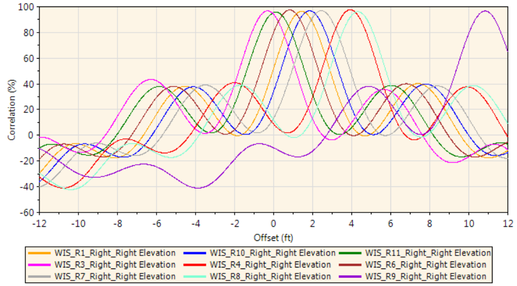


Right Side		
Avg %	Max %	Min%
96.75	97.6	95.9

Profile Synchronization: Correlation

Analyze | Apply Offsets | Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R1_Right	1.44	96.4
WIS_R10_Right	1.84	96.8
WIS_R11_Right	0.10	95.9
WIS_R3_Right	-0.31	96.8
WIS_R4_Right	3.92	97.6
WIS_R6_Right	0.83	97.5
WIS_R7_Right	2.44	96.9
WIS_R8_Right	4.31	96.2
WIS_R9_Right	10.83	96.7



Test Site II: Country Club Rd 11 Passes

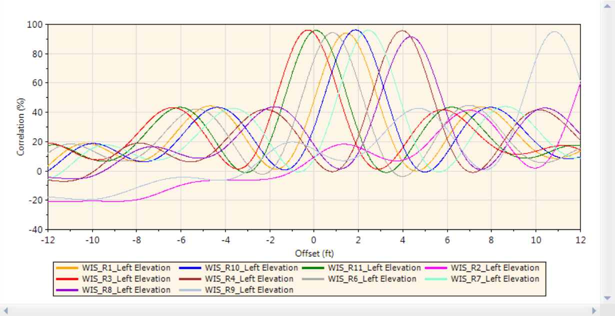
- Repeatability of Profile Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
91.46	96.3	59.5

Profile Synchronization: Correlation

Analyze Apply Offsets Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R1	1.44	94.1
WIS_R10	1.85	96.3
WIS_R11	0.09	95.9
WIS_R2	11.99	59.5
WIS_R3	-0.28	96.1
WIS_R4	3.97	95.7
WIS_R6	0.81	94.4
WIS_R7	2.44	96.0
WIS_R8	4.35	91.5
WIS_R9	10.83	95.1

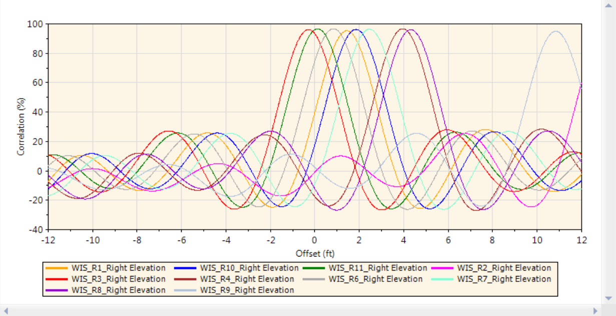


Right Side		
Avg %	Max %	Min%
92.48	96.7	59.7

Profile Synchronization: Correlation

Analyze Apply Offsets Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R1	1.44	95.4
WIS_R10	1.84	96.2
WIS_R11	0.12	96.6
WIS_R2	11.99	59.7
WIS_R3	-0.29	96.1
WIS_R4	3.95	96.7
WIS_R6	0.83	96.7
WIS_R7	2.45	96.4
WIS_R8	4.31	96.0
WIS_R9	10.84	95.0



Test Site II: Country Club Rd **10 Best Passes**

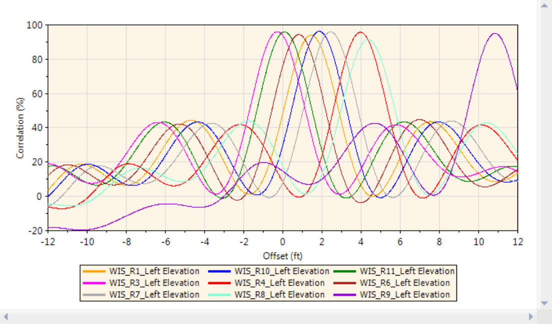
- Repeatability of Profile Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
95.00	96.3	91.5

Profile Synchronization: Correlation

Analyze | Apply Offsets | Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R1	1.44	94.1
WIS_R10	1.85	96.3
WIS_R11	0.09	95.9
WIS_R3	-0.28	96.1
WIS_R4	3.97	95.7
WIS_R6	0.81	94.4
WIS_R7	2.44	96.0
WIS_R8	4.35	91.5
WIS_R9	10.83	95.1

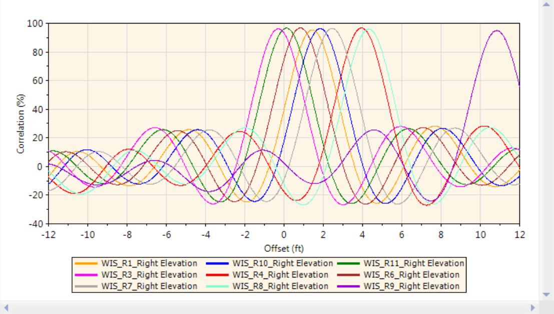


Right Side		
Avg %	Max %	Min%
96.13	96.7	95.0

Profile Synchronization: Correlation

Analyze | Apply Offsets | Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R1	1.44	95.4
WIS_R10	1.84	96.2
WIS_R11	0.12	96.6
WIS_R3	-0.29	96.1
WIS_R4	3.95	96.7
WIS_R6	0.83	96.7
WIS_R7	2.45	96.4
WIS_R8	4.31	96.0
WIS_R9	10.84	95.0



Test Site II: Country Club Rd 11 Passes

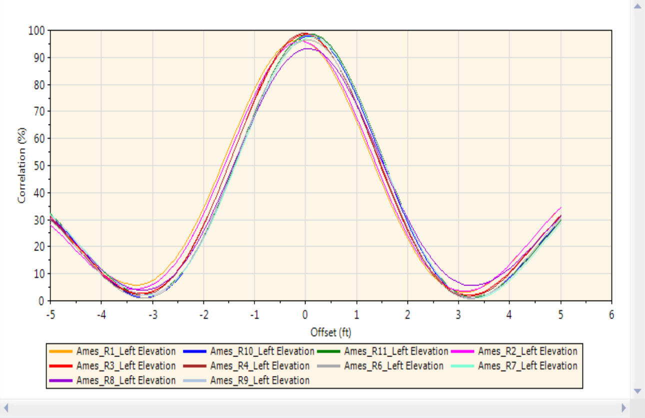
- Repeatability of Profile Data From Left Side (Ames)

Left Side		
Avg %	Max %	Min%
97.19	98.9	93.3

Profile Synchronization: Correlation

Analyze Apply Offsets Navigate

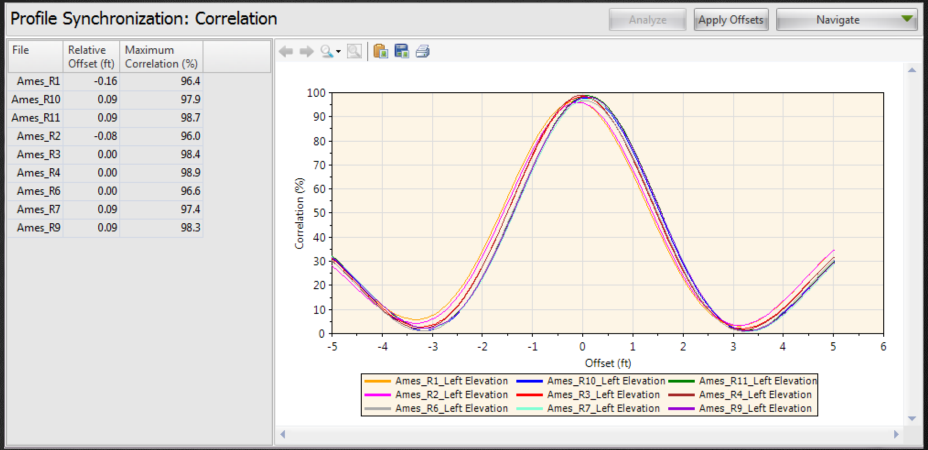
File	Relative Offset (ft)	Maximum Correlation (%)
Ames_R1	-0.16	96.4
Ames_R10	0.09	97.9
Ames_R11	0.09	98.7
Ames_R2	-0.08	96.0
Ames_R3	0.00	98.4
Ames_R4	0.00	98.9
Ames_R6	0.00	96.6
Ames_R7	0.09	97.4
Ames_R8	0.09	93.3
Ames_R9	0.09	98.3



Test Site II: Country Club Rd **10 Best Passes**

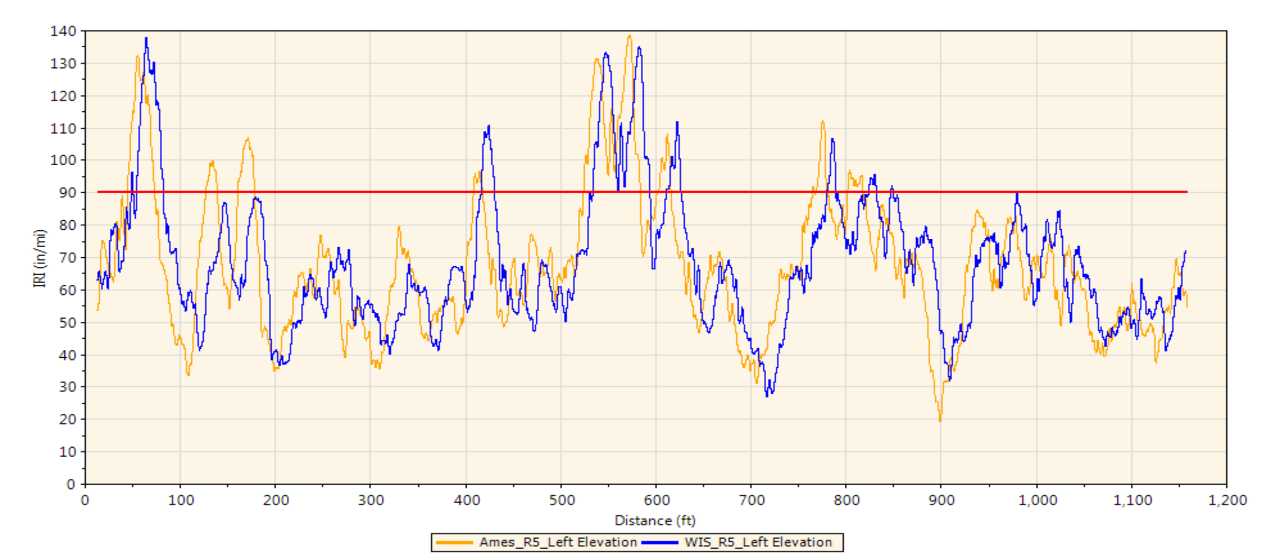
- Repeatability of Profile Data From Left Side (Ames)

Left Side		
Avg %	Max %	Min%
97.61	98.9	96.0



Test Site II: Country Club Rd 11 Passes

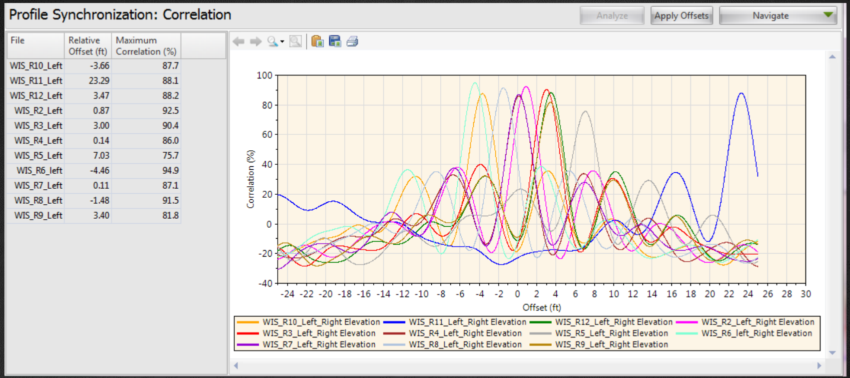
- Continuous IRI Results
  - Calculate an IRI Result in Every Small Distance, e.g. 25 ft., from the First Point to the Last Point of the Profile.
  - Plot the Calculated IRI Results into a Continuous Curve.
  - Displayed WIS data and Ames data From the Fifth Pass.



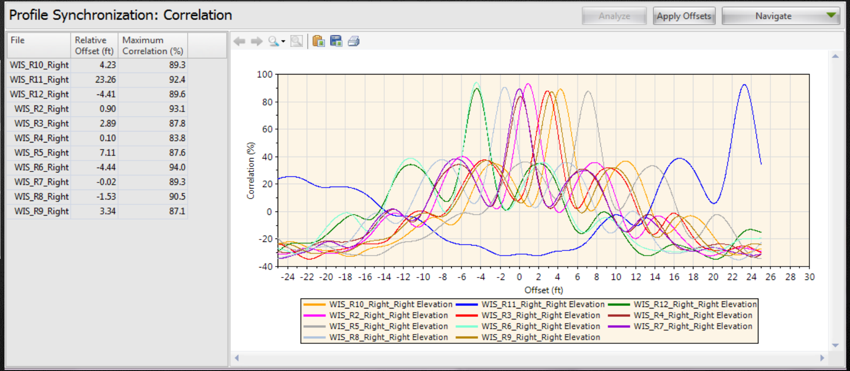
Test Site III: W 6th Ave 12 Passes

- Repeatability of 3D Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
87.63	94.9	75.7



Right Side		
Avg %	Max %	Min%
89.5	94.0	83.8



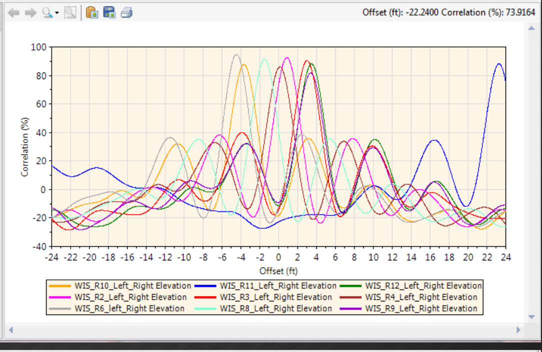
Test Site III: W 6th Ave **10 Best Passes**

- Repeatability of 3D Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
89.00	94.9	81.8

Profile Synchronization: Correlation

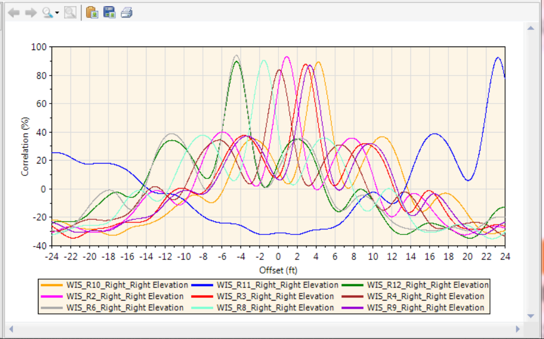
File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10_Left	-3.67	87.7
WIS_R11_Left	23.28	88.1
WIS_R12_Left	3.46	88.2
WIS_R2_Left	0.85	92.5
WIS_R3_Left	2.99	90.4
WIS_R4_Left	0.13	86.0
WIS_R6_left	-4.47	94.9
WIS_R8_Left	-1.49	91.5
WIS_R9_Left	3.38	81.8



Right Side		
Avg %	Max %	Min%
89.74	94.0	83.8

Profile Synchronization: Correlation

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10_Right	4.21	89.3
WIS_R11_Right	23.25	92.4
WIS_R12_Right	-4.42	89.6
WIS_R2_Right	0.88	93.1
WIS_R3_Right	2.88	87.8
WIS_R4_Right	0.09	83.8
WIS_R6_Right	-4.46	94.0
WIS_R8_Right	-1.54	90.5
WIS_R9_Right	3.32	87.1



Test Site III: W 6th Ave 12 Passes

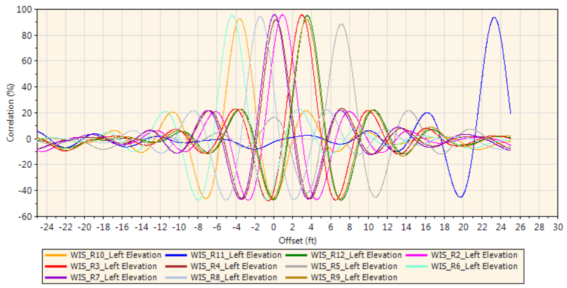
- Repeatability of Profile Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
93.76	95.8	88.8

Profile Synchronization: Correlation

Analyze Apply Offsets Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10	-3.60	92.7
WIS_R11	23.28	93.8
WIS_R12	3.53	95.1
WIS_R2	0.93	95.8
WIS_R3	2.97	95.7
WIS_R4	0.22	91.8
WIS_R5	7.14	88.8
WIS_R6	-4.41	95.3
WIS_R7	0.07	95.9
WIS_R8	-1.44	94.5
WIS_R9	3.44	92.0

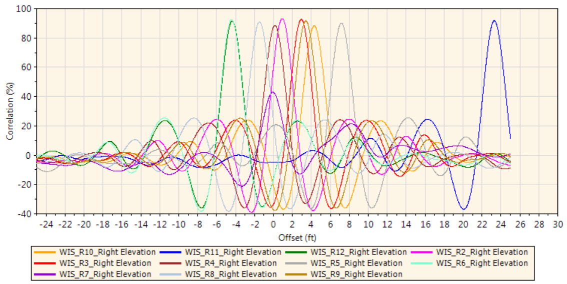


Right Side		
Avg %	Max %	Min%
86.78	93.2	43.0

Profile Synchronization: Correlation

Analyze Apply Offsets Navigate

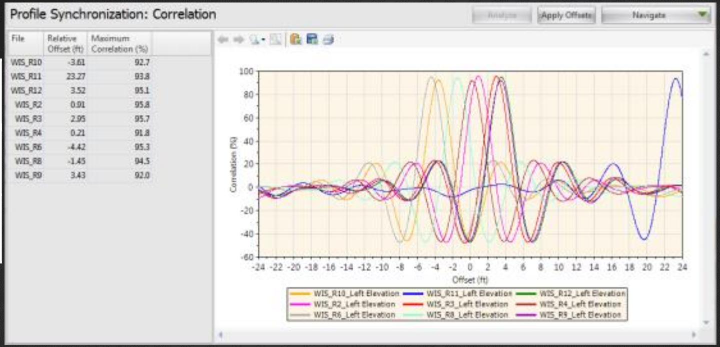
File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10	4.29	88.3
WIS_R11	23.29	91.8
WIS_R12	-4.37	91.5
WIS_R2	0.93	93.2
WIS_R3	2.92	92.7
WIS_R4	0.16	88.5
WIS_R5	7.17	90.1
WIS_R6	-4.43	92.6
WIS_R7	-0.07	43.0
WIS_R8	-1.48	91.0
WIS_R9	3.41	91.7



Test Site III: W 6th Ave **10 Best Passes**

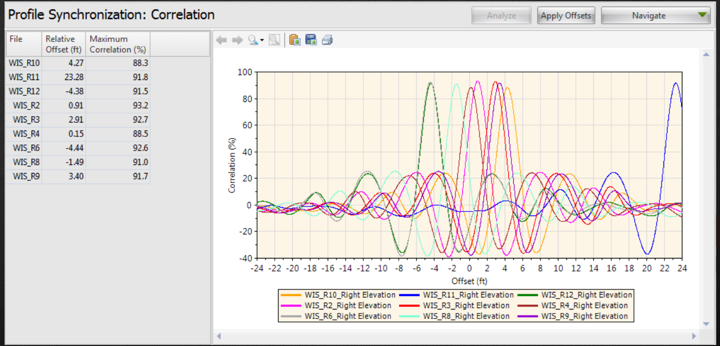
- Repeatability of Profile Data From Left and Right Side (WIS)

Left Side		
Avg %	Max %	Min%
94.08	95.8	91.8



File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10	-3.61	92.7
WIS_R11	23.27	93.8
WIS_R12	3.52	95.1
WIS_R2	0.91	95.8
WIS_R3	2.95	95.7
WIS_R4	0.21	91.8
WIS_R6	-4.42	95.3
WIS_R8	-1.45	94.5
WIS_R9	3.43	92.0

Right Side		
Avg %	Max %	Min%
91.24	93.2	88.3



File	Relative Offset (ft)	Maximum Correlation (%)
WIS_R10	4.27	88.3
WIS_R11	23.28	91.8
WIS_R12	-4.38	91.5
WIS_R2	0.91	93.2
WIS_R3	2.91	92.7
WIS_R4	0.15	88.5
WIS_R6	-4.44	92.6
WIS_R8	-1.49	91.0
WIS_R9	3.40	91.7

Test Site III: W 6th Ave 12 Passes

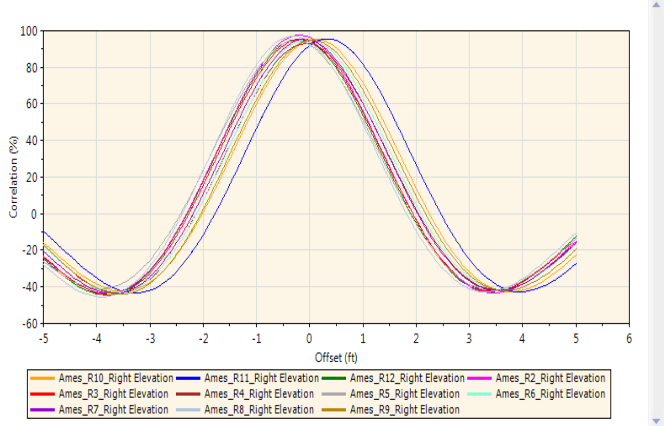
- Repeatability of Profile Data From Left Side (Ames)

Left Side		
Avg %	Max %	Min%
95.43	97.6	93.0

Profile Synchronization: Correlation

Analyze | Apply Offsets | Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
Ames_R10	0.09	95.3
Ames_R11	0.33	95.7
Ames_R12	-0.24	95.5
Ames_R2	-0.16	97.6
Ames_R3	-0.16	95.4
Ames_R4	-0.08	93.0
Ames_R5	-0.24	94.6
Ames_R6	0.00	95.3
Ames_R7	-0.08	95.4
Ames_R8	-0.32	97.1
Ames_R9	0.00	94.8



Test Site III: W 6th Ave **10 Best Passes**

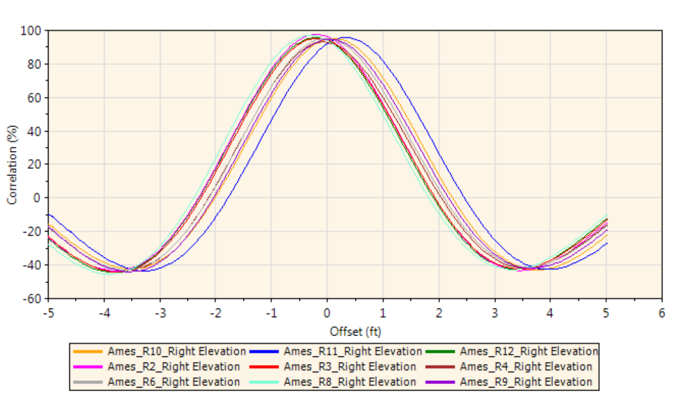
- Repeatability of Profile Data From Left Side (Ames)

Left Side		
Avg %	Max %	Min%
95.52	97.6	93.0

Profile Synchronization: Correlation

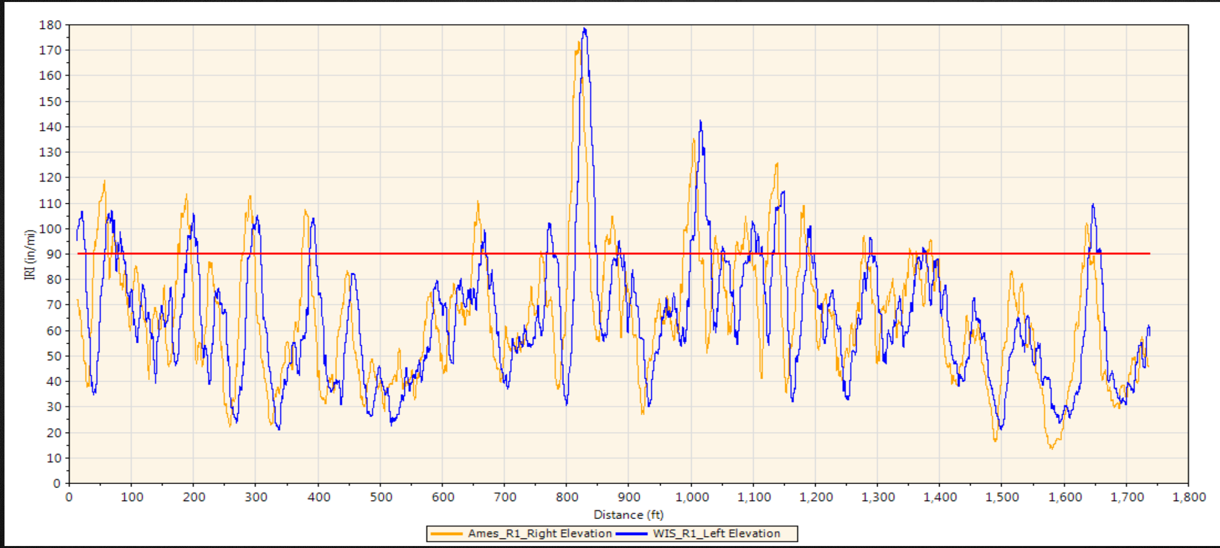
Analyze | Apply Offsets | Navigate

File	Relative Offset (ft)	Maximum Correlation (%)
Ames_R10	0.09	95.3
Ames_R11	0.33	95.7
Ames_R12	-0.24	95.5
Ames_R2	-0.16	97.6
Ames_R3	-0.16	95.4
Ames_R4	-0.08	93.0
Ames_R6	0.00	95.3
Ames_R8	-0.32	97.1
Ames_R9	0.00	94.8



Test Site III: W 6th Ave 12 Passes

- Continuous IRI Results
  - Calculate an IRI Result in Every Small Distance, e.g. 25 ft., from the First Point to the Last Point of the Profile.
  - Plot the Calculated IRI Results into a Continuous Curve.
  - Displayed WIS data and Ames data From the First Pass.



Deep-Learning Plan

Objectives of Pavement Distress Recognition

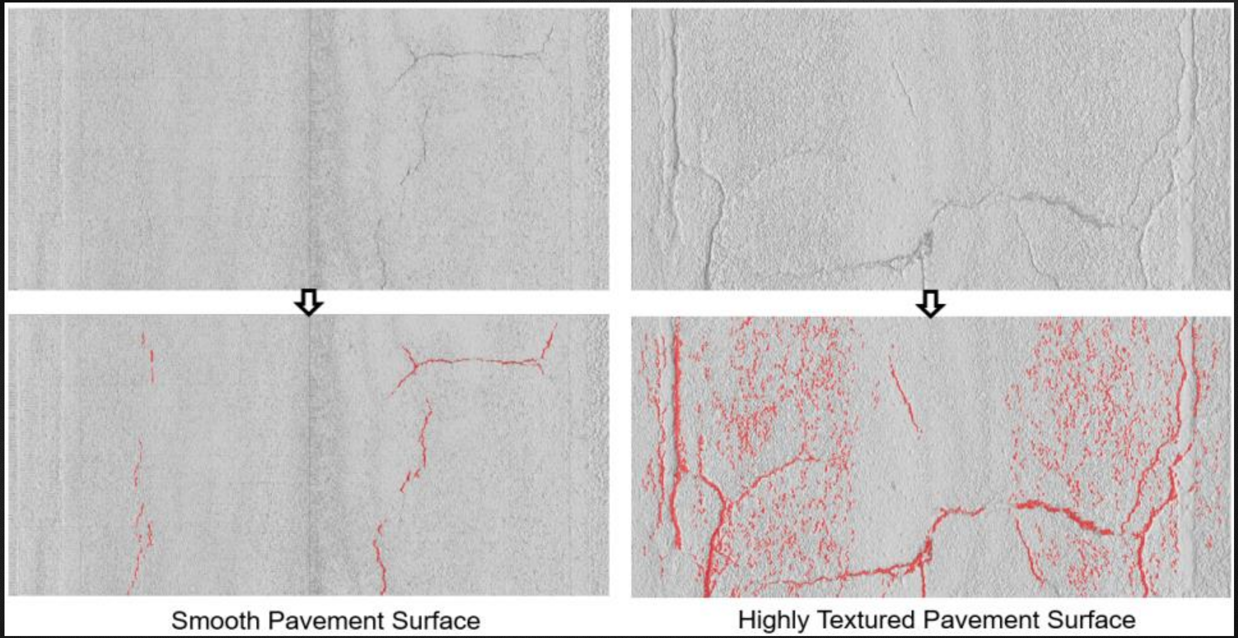
- Detection
  - Find the Actual Location of Distresses with Pixel-Perfect Accuracy
- Classification
  - Label Distress Type

Challenges in Pavement Distress Recognition

- Complexity
  - Pavement Surface: A highly Complicated Environment with A Lot of Uncertainties
  - Distress Identification: Even Human Operator Has to Be Well-Trained
- Diversity
  - Diverse Pavement Surface Textures
  - Various Presences of Pavement Distresses

Common Failures in Distress Automation

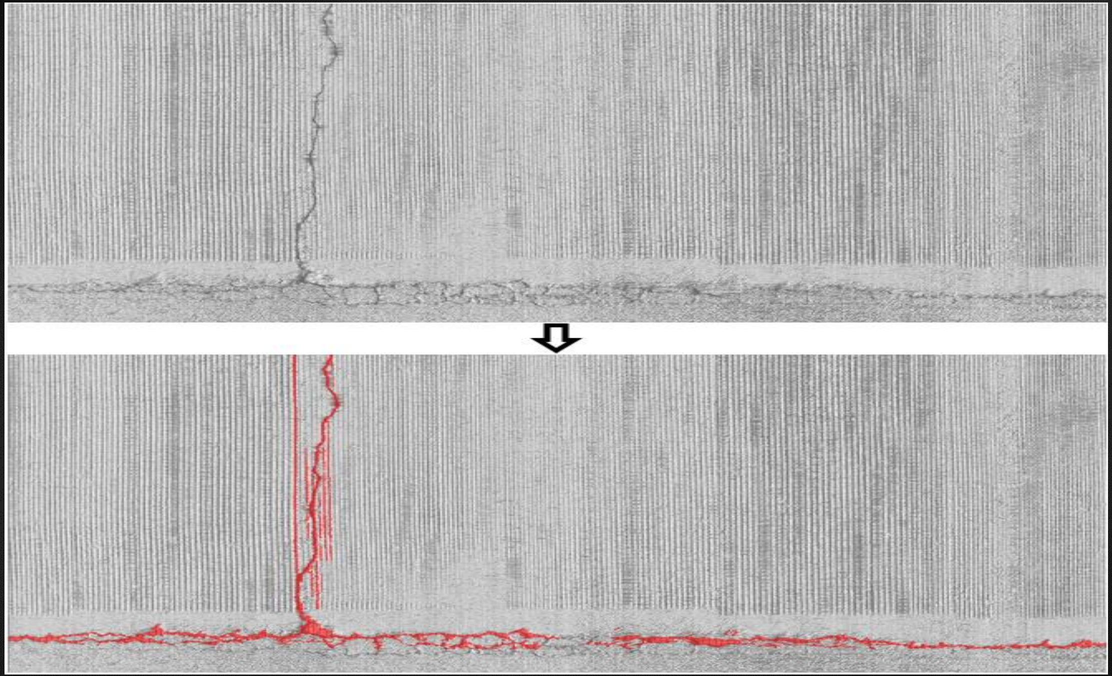
- Inconsistent Accuracies for Different Roads



Cracking Detection on Two Roads Using Same Level of Sensitivity

Common Failures in Distress Recognition

- Interference from Other Patterns



Cracking Detection on Grooved Surface

Deep Learning: Potential for Automated Distress Recognition

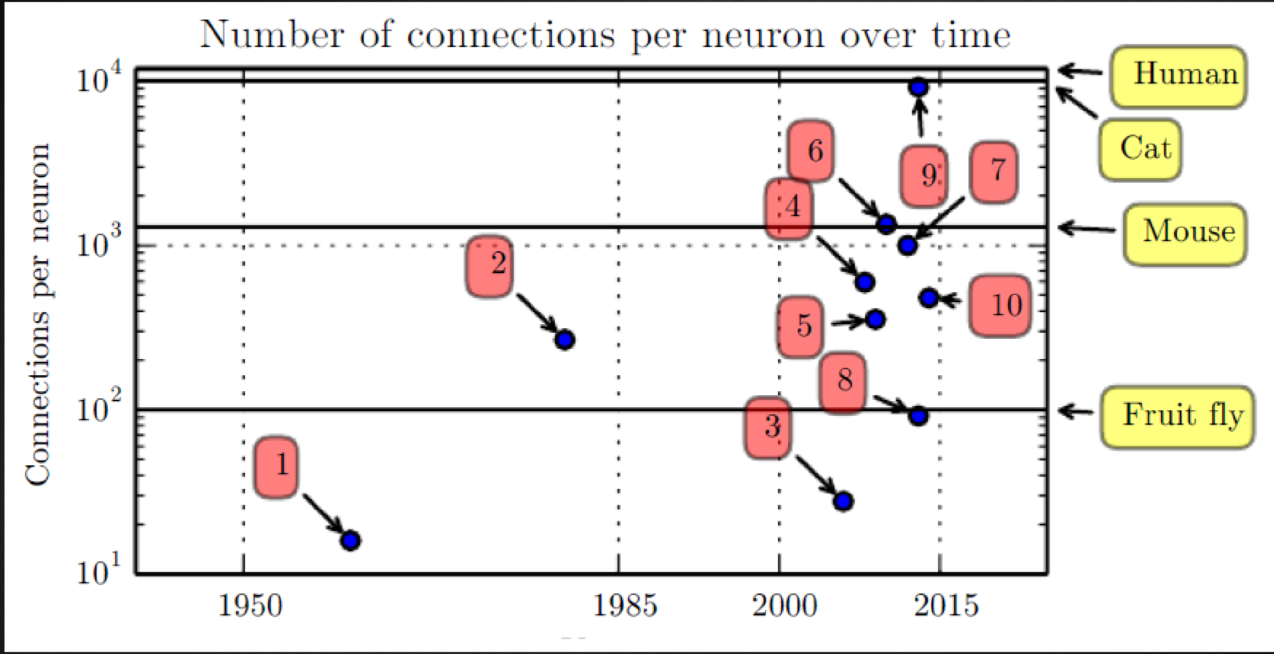
- Strong Learning Ability
  - Learning from Experiences;
  - Exploiting Understanding on New and Unlabeled Examples;
- Versatility
  - A Single Deep Learning Network Can Detect Multiple Types of Pavement Distresses
- Enhanced Reliability
  - Feed with Exhaustive Variations of Pavement Distresses

History of Deep Learning

- 1940s-1960s
  - Cybernetics
  - Biological Learning & Models Using Single Neuron
- 1980s-1990s
  - Connectionism/Neural Network
  - 1 or 2 Hidden Layer
  - Backpropagation
- 2006-Now
  - Deep Learning
  - Many Layers & Massive Neurons

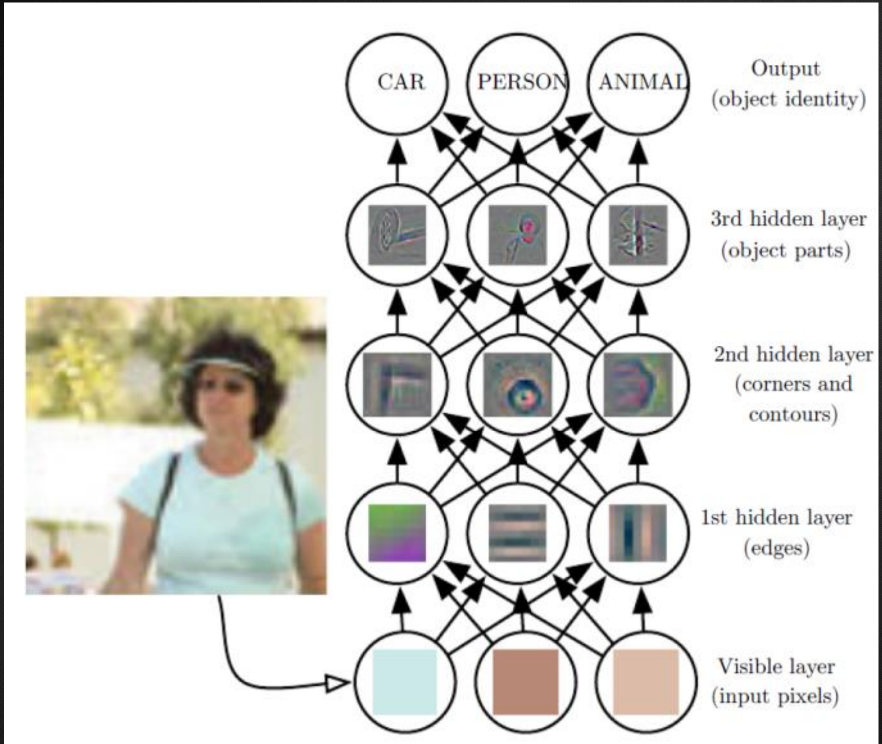
Trends of Deep Learning

- Increasing Model Size



(Goodfellow et al., Deep Learning, 2016)

Compositional Model for Image Recognition



(Goodfellow et al., Deep Learning, 2016)

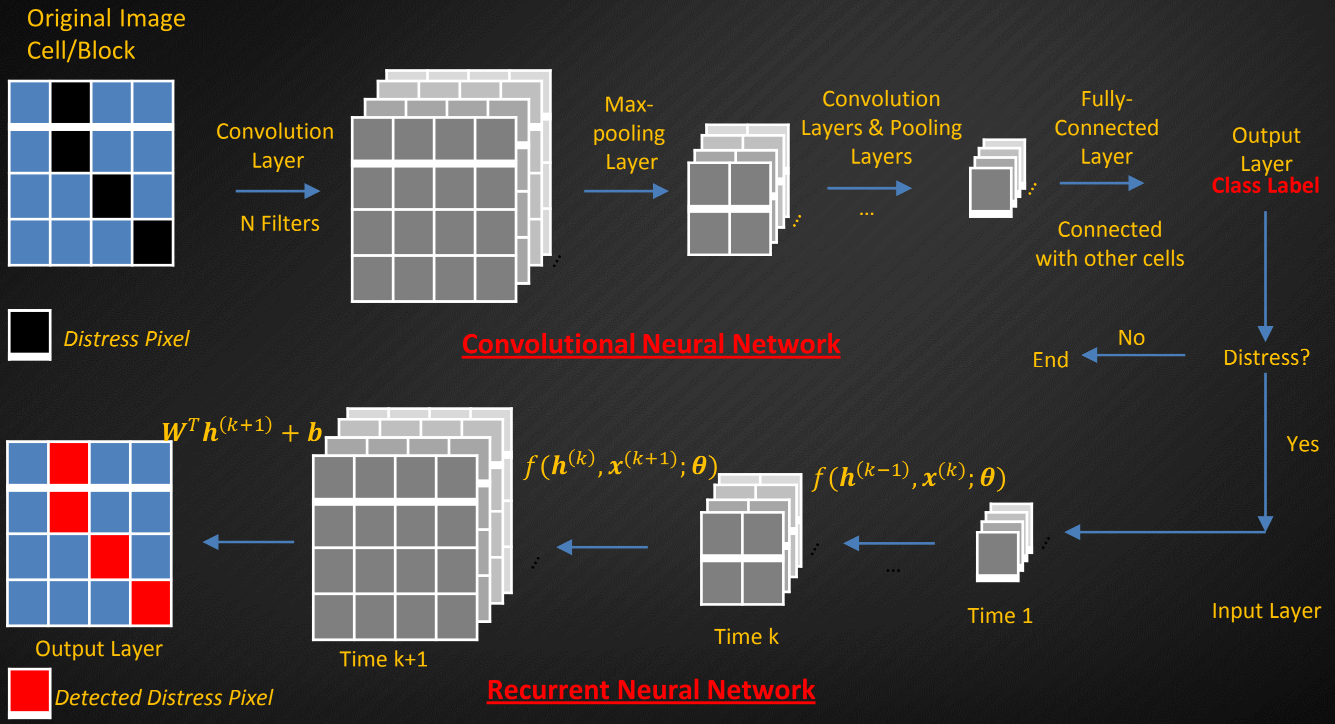
Current Status of Image Recognition Using Deep Learning

- Achievements
  - Give descriptions on what objects have been detected in an image;
  - Detect the bounding box encloses the object and Label the type of detected object within the bounding box
- Limitations
  - Actual location of the detected object is vague;
  - Lack of Pixel-perfect Accuracy

Deep Learning Models for Pavement Distress Recognition

- Alternative #1
  - Deep Convolution Neural Network
    - Feed Forward
    - Detect whether an image cell has distresses
  - Recurrent Neural Network
    - Feed Backward
    - Find which pixels in a detected image cell are very likely to be distress pixels

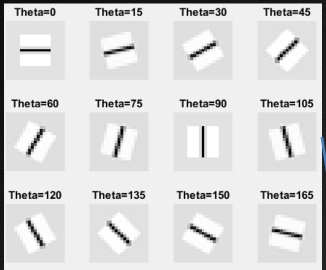
Deep Convolution Neural Network & Recurrent Neural Network



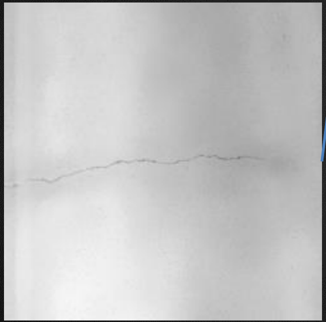
Types of Filters Used in Convolution Neural Network

- Matched Filters
  - Objective: detect the profiles of a crack;
  - Multiple Orientations: detect cracks oriented at various directions;
  - Multiple Filter Sizes and Spreads: detect cracks with various widths.
- Gabor Filters
  - Objective: detect the edges of a crack
  - Multiple Orientations: detect edges oriented at various directions;
  - Multiple Degrees of Smoothing and Enhancement

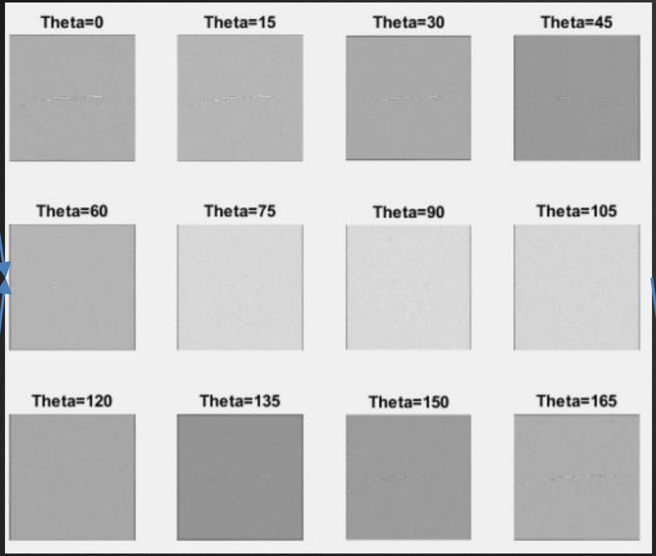
Convolution Using Matched Filter



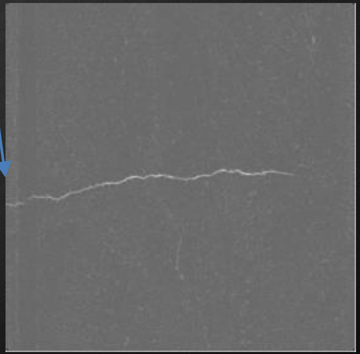
Matched Filters



Raw 3D Image

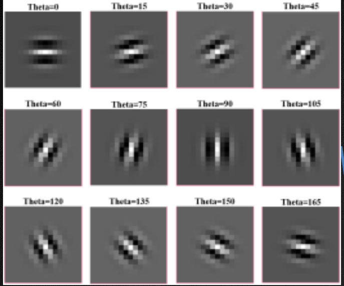


Filtering Responses



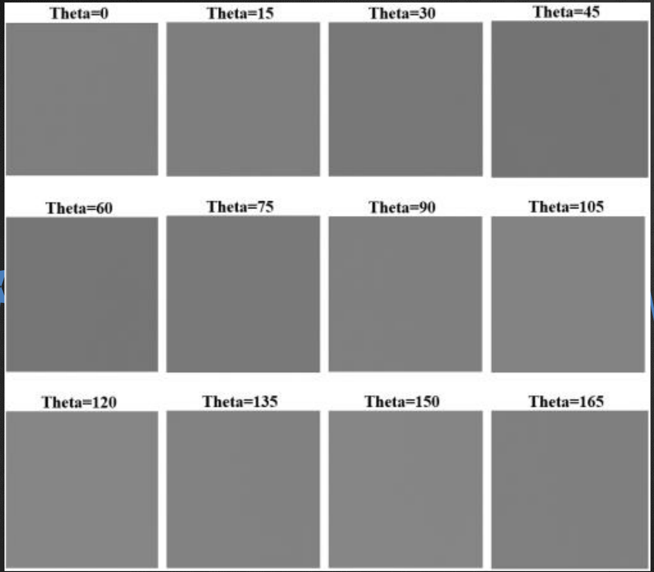
Integrated Result

Convolution Using Gabor Filter

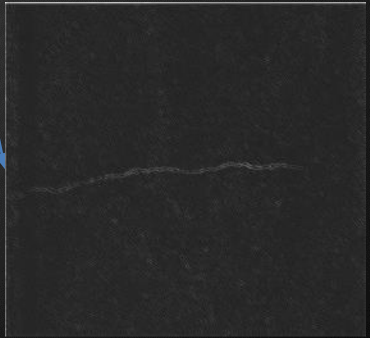


Gabor Filters

Raw 3D Image



Filtering Responses



Integrated Result

Deep Neural Network for Pavement Distress Recognition

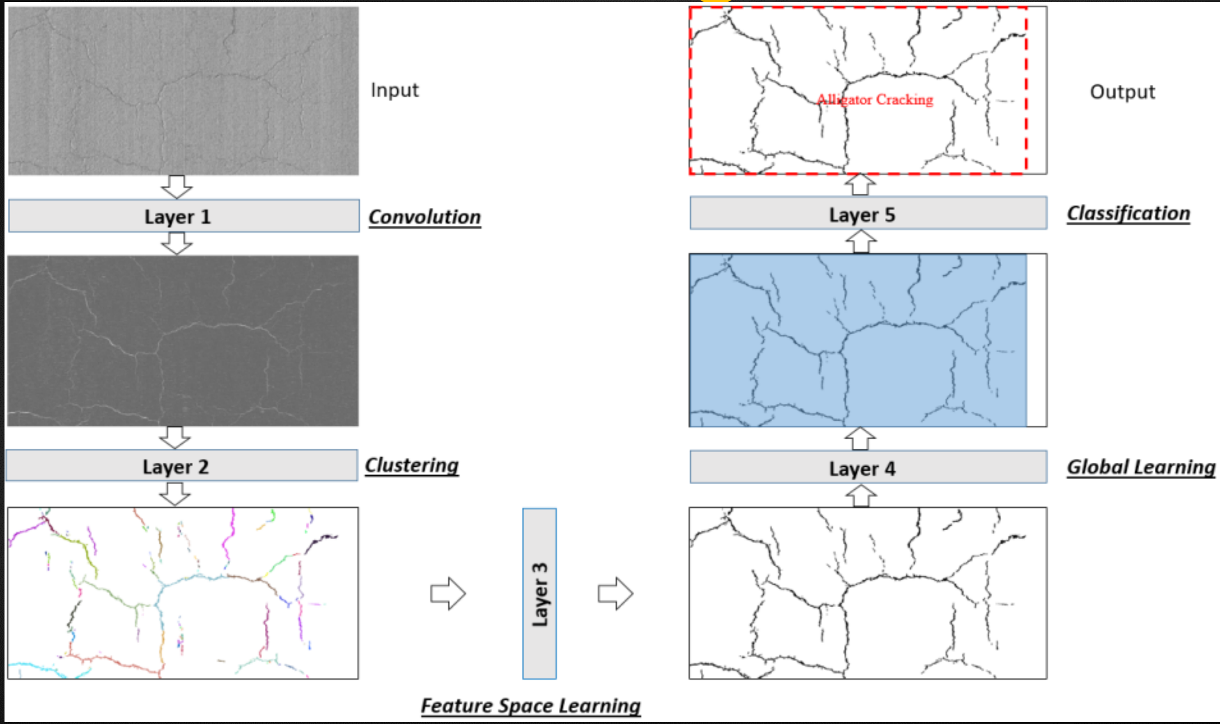
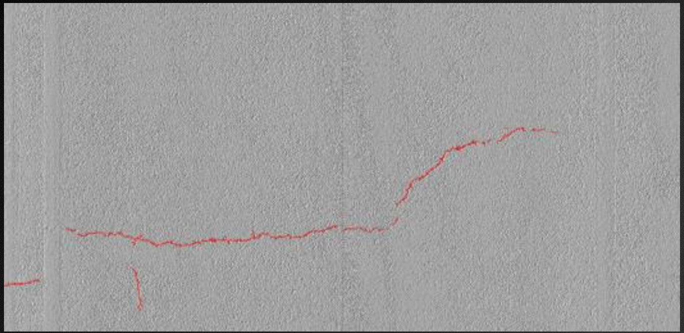
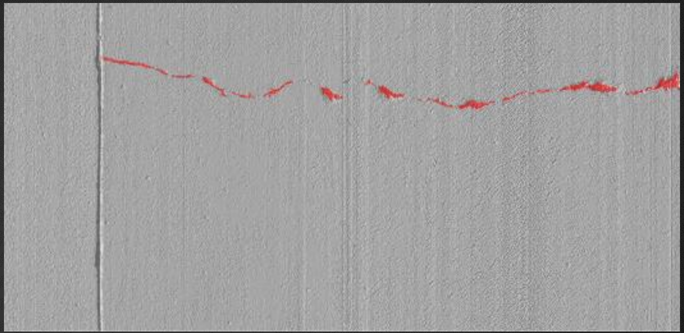


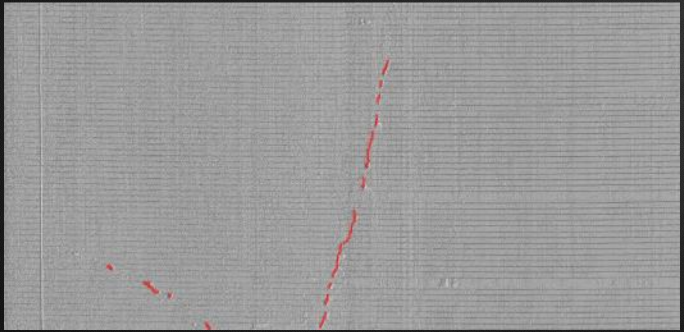
Image Library for Pavement Distress Recognition

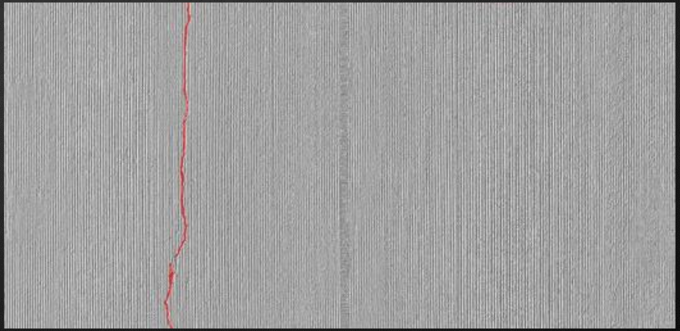
- Data Type
  - 3D Data & 2D Images
- Image Library Size
  - 2016-2017: 150,000 3D Images + 150,000 2D Images
  - 2017-2020: 1,000,000 3D Images + 1,000,000 2D Images
- Ground Truth
  - Manually Marked
- Diversity
  - All Typical Variations of Pavement Distresses

Typical Samples in Image Library









Challenging Tasks

- Architecture of Deep Learning Network
  - Structure of Neurons at Each Layer, Connection between Layers
- Exhaustive Image Library
  - 3D Pavement Data & 2D Pavement Image
  - All Variations of Pavement Distresses, Manually Marked Ground-truth
- Long-term Training & Optimization
  - Training on Each Layer, on Connections between Layers, Entire Network
  - Sufficient Computational Horsepower
- Self-taught Learning
  - Unsupervised Learning from Unlabeled Data;
  - Progressive Improvements in Real-time Applications
- Real-time Application
  - Parallel Computing to Reduce Processing Time

Funding Support

- Federal Highway Administration (FHWA)
- Federal Aviation Administration (FAA)
- University Transportation Centers (UTC)
- Oklahoma DOT, Arkansas DOT, Indiana DOT
- Users in South Africa, Brazil, China, and Europe
- Oklahoma State University

Thank You！