

TOWARDS STANDARDIZED PAVEMENT SURFACE TEXTURE SPECTRAL ANALYSIS AND EVALUATION

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INGIOS GEOTECHNICS



HONORING THE PAST. PAVING THE FUTURE.

OUTLINE

- BACKGROUND
- TEXTURE MEASUREMENTS, SMART WAVE, AND SPECTRAL ANALYSIS
- CONCLUDING REMARKS AND FUTURE WORK



Pavement Friction Management

- Great progress has been achieved in standardizing continuous friction measurements and their use in safety assessment.
- Still challenged with the physical systems need for water and tires, and the inconsistency between different systems.



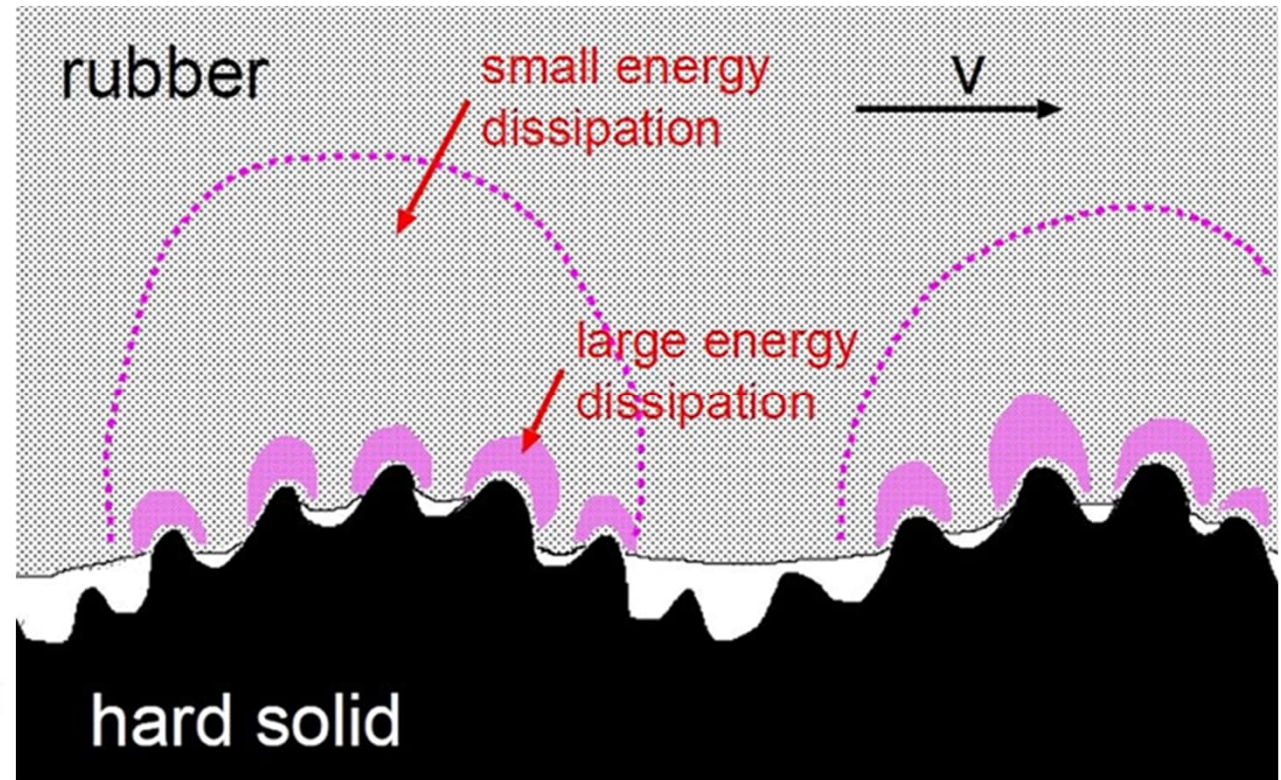
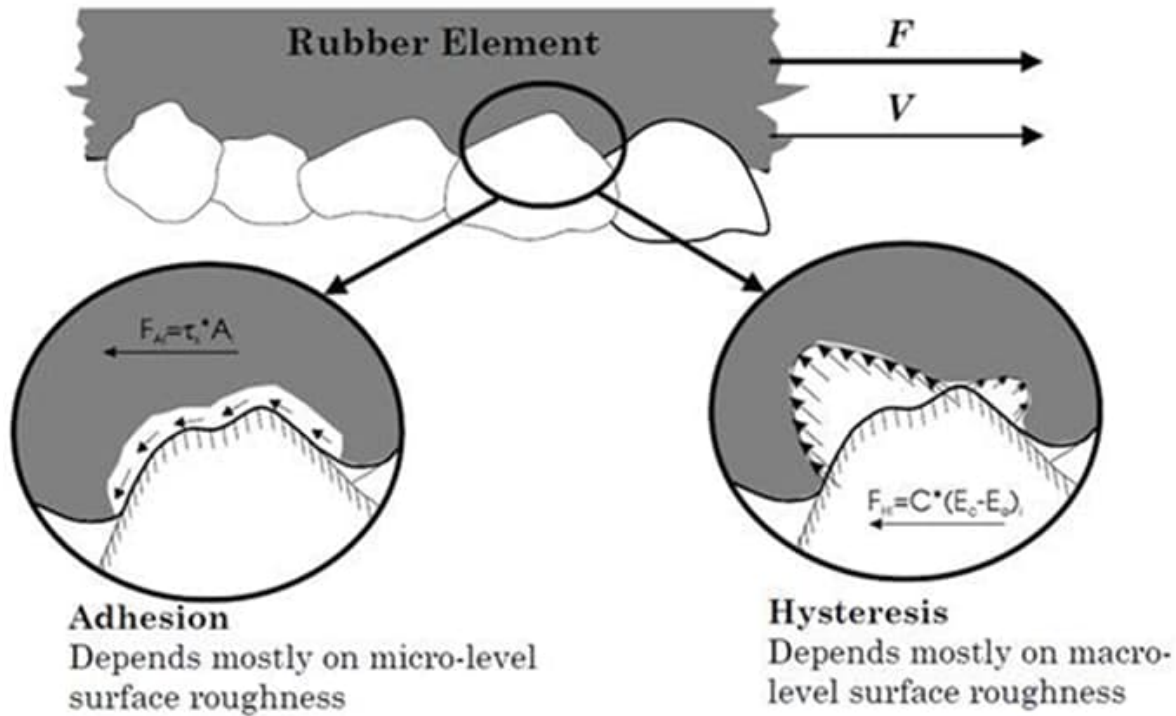
SCRIM, WDM USA



LWST, Iowa DOT

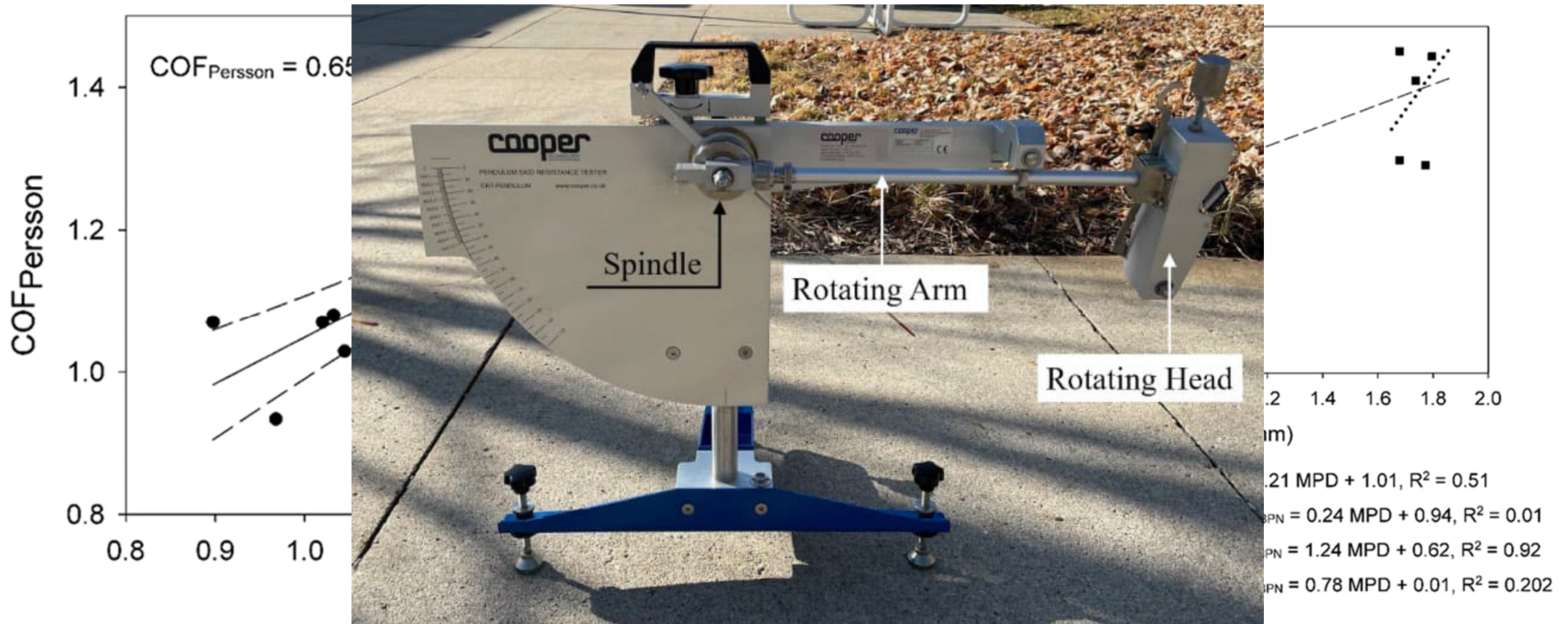
Pavement Texture Scanning

- ⦿ Persson's friction model provided a robust physical and analytical solutions for a simple rubber block.

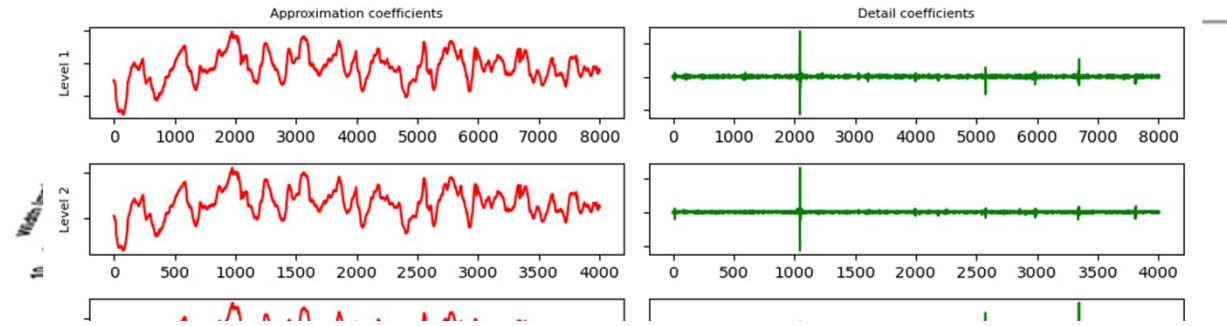


Testing the Theory

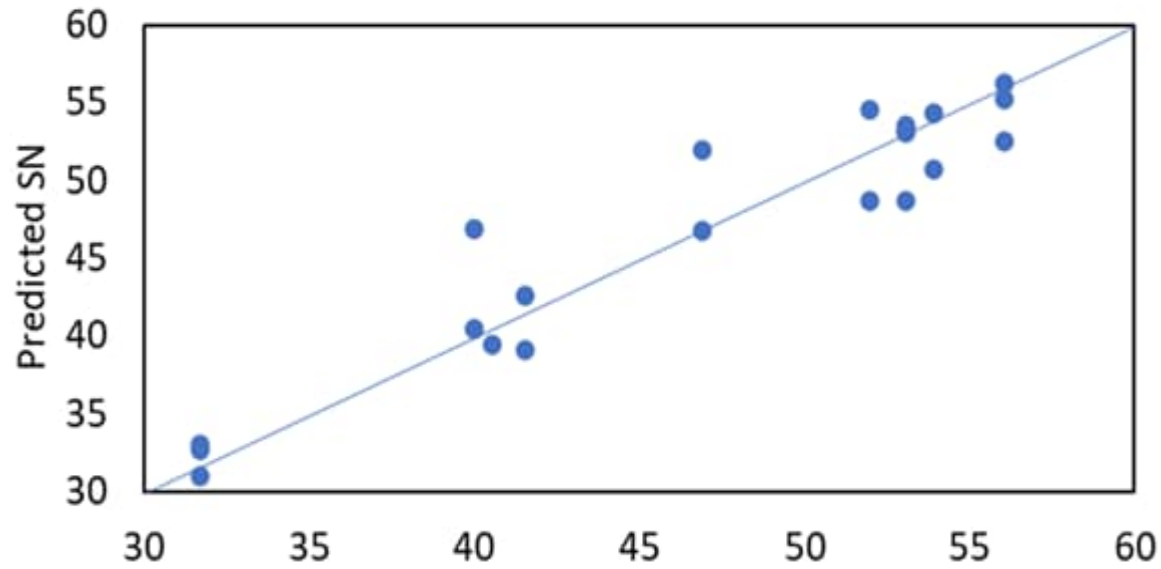
- Persson's friction model provided a robust physical and analytical solutions for a simple rubber block (British Pendulum).



Implementing A Concept



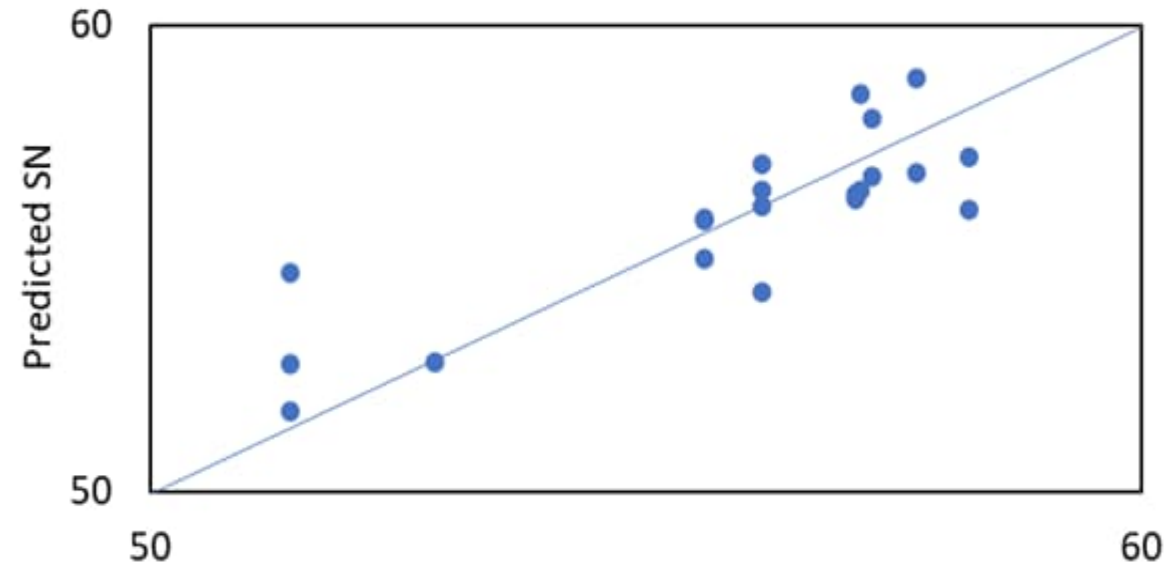
Predicted vs Measured (Average, Smooth, 40 mph)



Measured SN

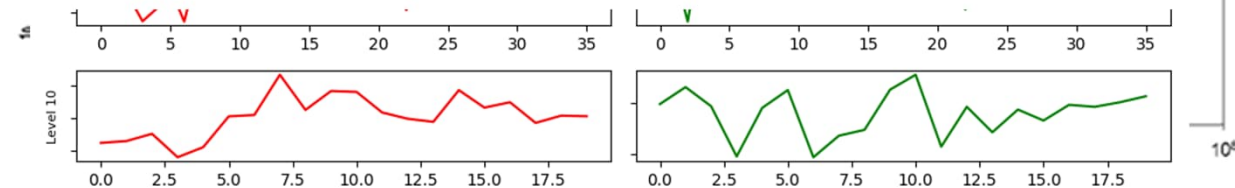
Measured SN

Predicted vs Measured (Average, Ribbed, 40 mph)



Measured SN

Measured SN



(C)

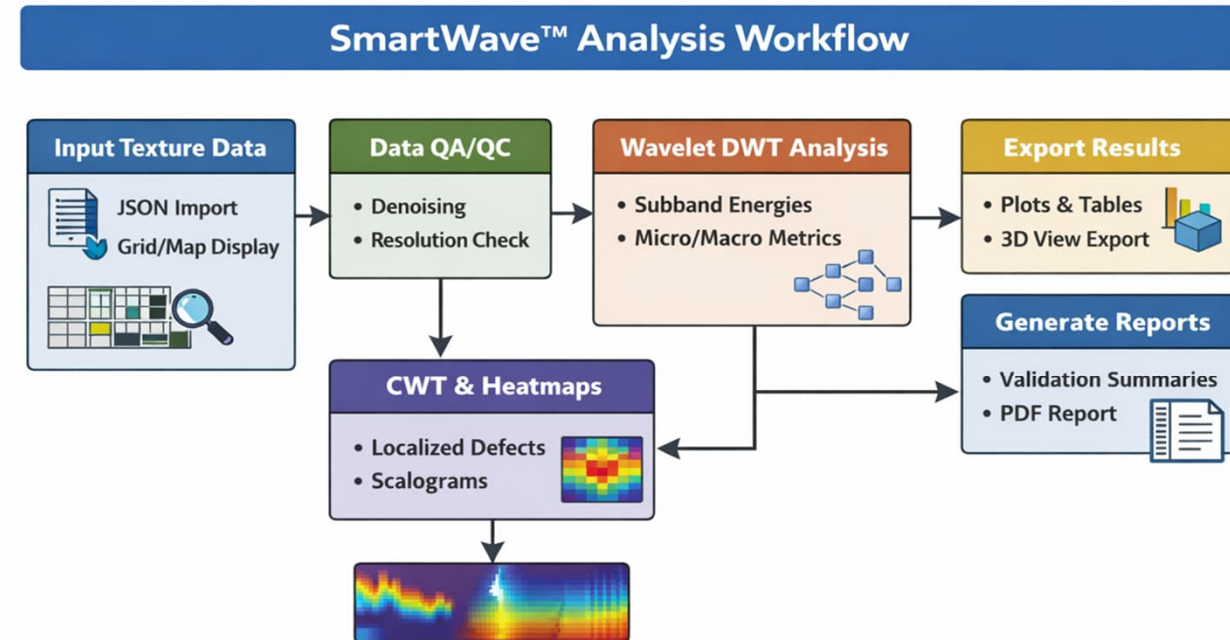
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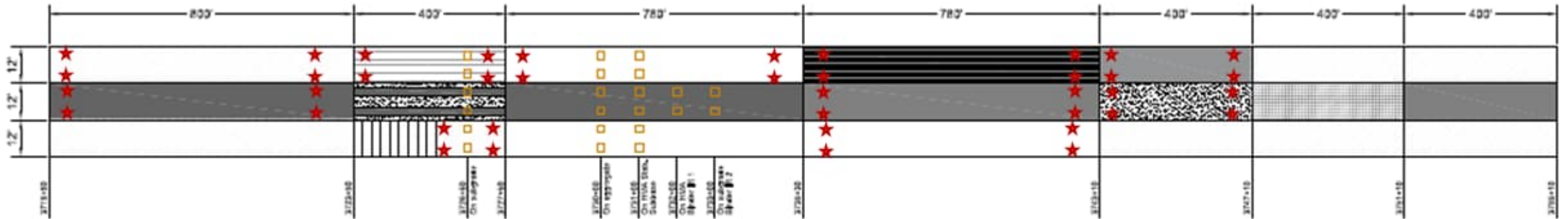


Pavement Texture Data Standardization

- To move towards contactless tire-pavement friction we need improved standards for texture data and analysis.
- Smart Wave™ is a proprietary platform capable of supporting analysis and friction of texture and friction data.



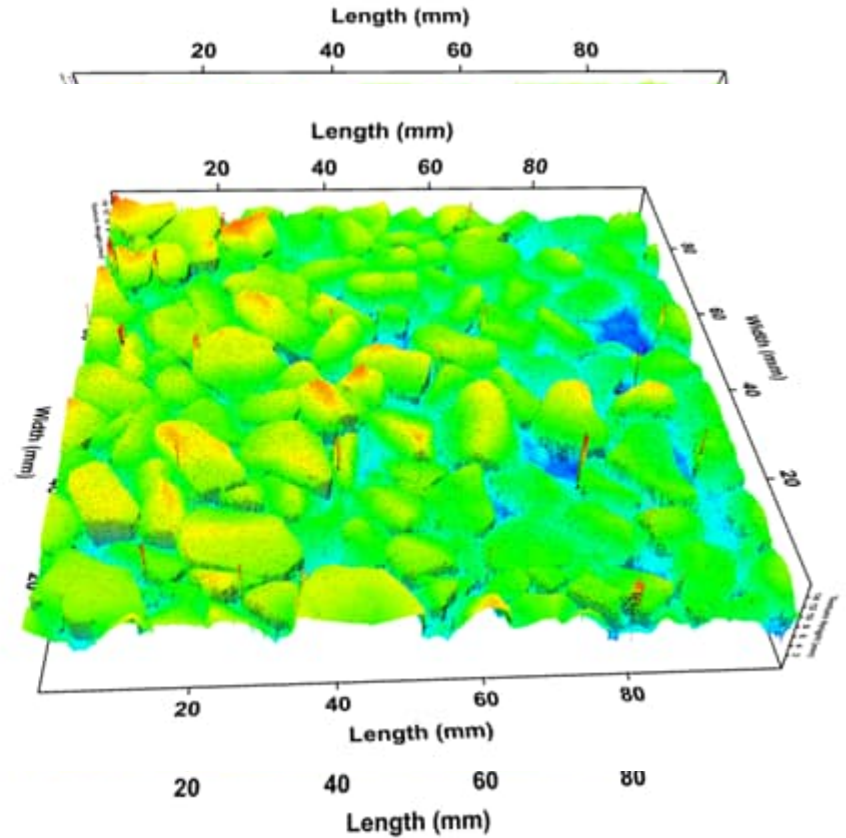
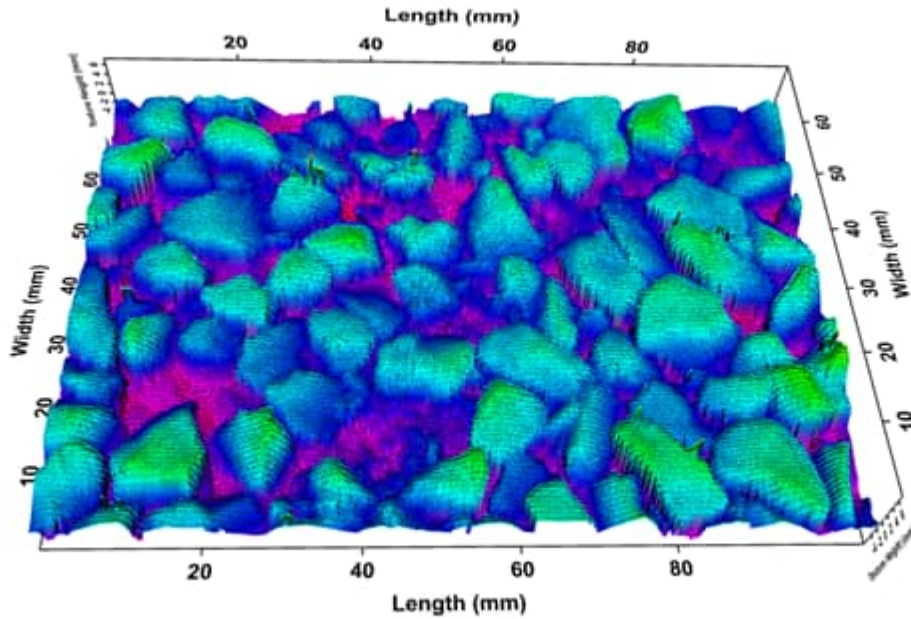
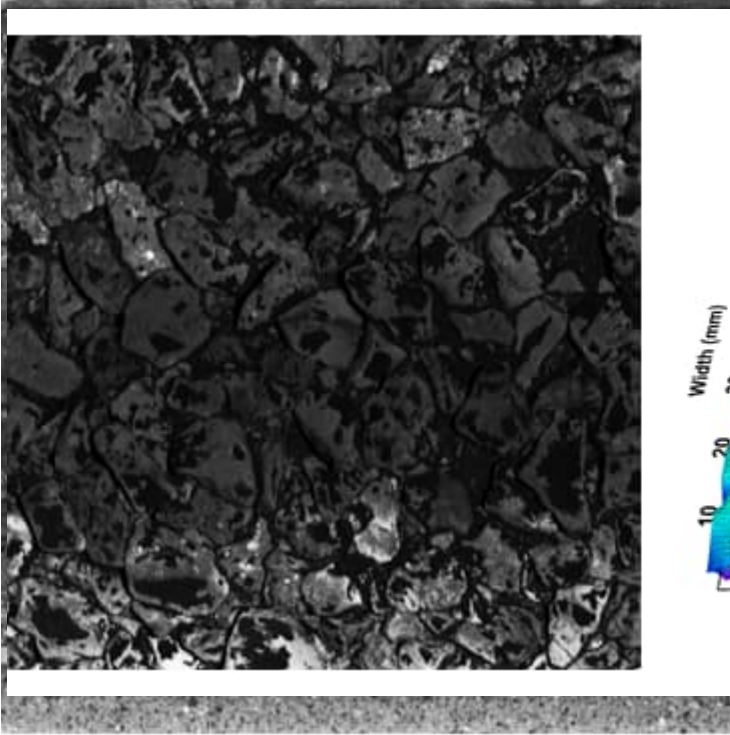
ICART Data Collection



8.5" CRCP - Turf Drag Finish	Smooth Finish with General Grooving	Turf Drag Finish w/ Diamond Grooving	Smooth Finish with Diamond Grinding	Smooth Finish	Turf Drag Finish	Turf Drag Finish
11.5" 12.5 mm SMA	Artificial Rutting	12.5 mm SMA	9.5 mm Dense Graded HMA	Microsurfing with 30% Colloidal Silica & 70% Silica	Single Chip Seal	1.5" Dense Graded HMA
8.5" JPCP - Turf Drag Finish	Artificial Faulting	Longitudinal Tining	Transverse Tining	Turf Drag Finish	Turf Drag Finish	Turf Drag Finish



Included a Wide Range of Surfaces



Smart Wave is a Comprehensive Platform

The screenshot displays the Smart Wave software interface with the following sections:

- Target grid:** Original (may be slow)
- Aggregation:** Mean (bin average)
- Snrap X/Y:** No
- Import progress:** Import complete, Output grids: 816x1024 - dx=0.09942mm - dy=0.12459mm
- Buttons:** Load bundled demo JSON, Export metrics JSON, Export current tab PNGs, Export all PNGs
- 2) Analysis settings:**
 - Wavelet family: Daubechies 3 (db3)
 - Levels (2D DWT): 4
 - Denoise: None
 - Threshold scale: Universal (sigma*sqrt(2) In)
 - Buttons: Run analysis, Reset
 - Status: Analysis complete, Wavelet=db3, levels=4, denoise=none, thr=0.000000
 - Notes: For multi-level analysis, SmartWave(TM) pads to the next power-of-two size (infect padding) to avoid edge artifacts. Band "wavelength" is reported using a consecutive mapping: lambda = 2 * (level+1) * dx (or dy).
- Cross-section settings:**
 - Direction: Along X (row)
 - Index: 0
 - Window avg (profiled): 1
 - Zoom start (mm): 0
 - Zoom length (mm): 80
 - Buttons: Update cross-section
 - Raw: 0.1104, Rq (RMS): 0.1247, Ra: 0.7617, RIr: 0.623, Rku: 0.222
 - Note: If a baseline JSON is loaded (Compare tab), this view will overlay baseline vs device profiles when indices match.
- Profile cross-section:** A line graph showing height (mm) scaled by 100 vs distance (mm) from 0.0 to 80.0.
- Height distribution:** A histogram showing height distribution (counts) for ranges 4.570 to 10.100 mm.
- 3D surface viewer (color + contrast shading):** Interactive 3D visualization of the texture map using WebGL. Uses height-based color with Lambert shading from a directional light.
- Viewer controls:**
 - Downsample: 4x
 - Vertical exaggeration: 1
 - Contrast: 1.8
 - Colormap: Heat
 - Light azimuth (deg): 315
 - Light elevation (deg): 45
 - Buttons: Build / Update 3D, Reset view, Export 3D PNG
 - Mouse drag to rotate - Wheel zoom - Shift+drag pan
 - Status: Mesh ready (756x204 points)
- 3D display:** A 3D perspective view of the textured surface.

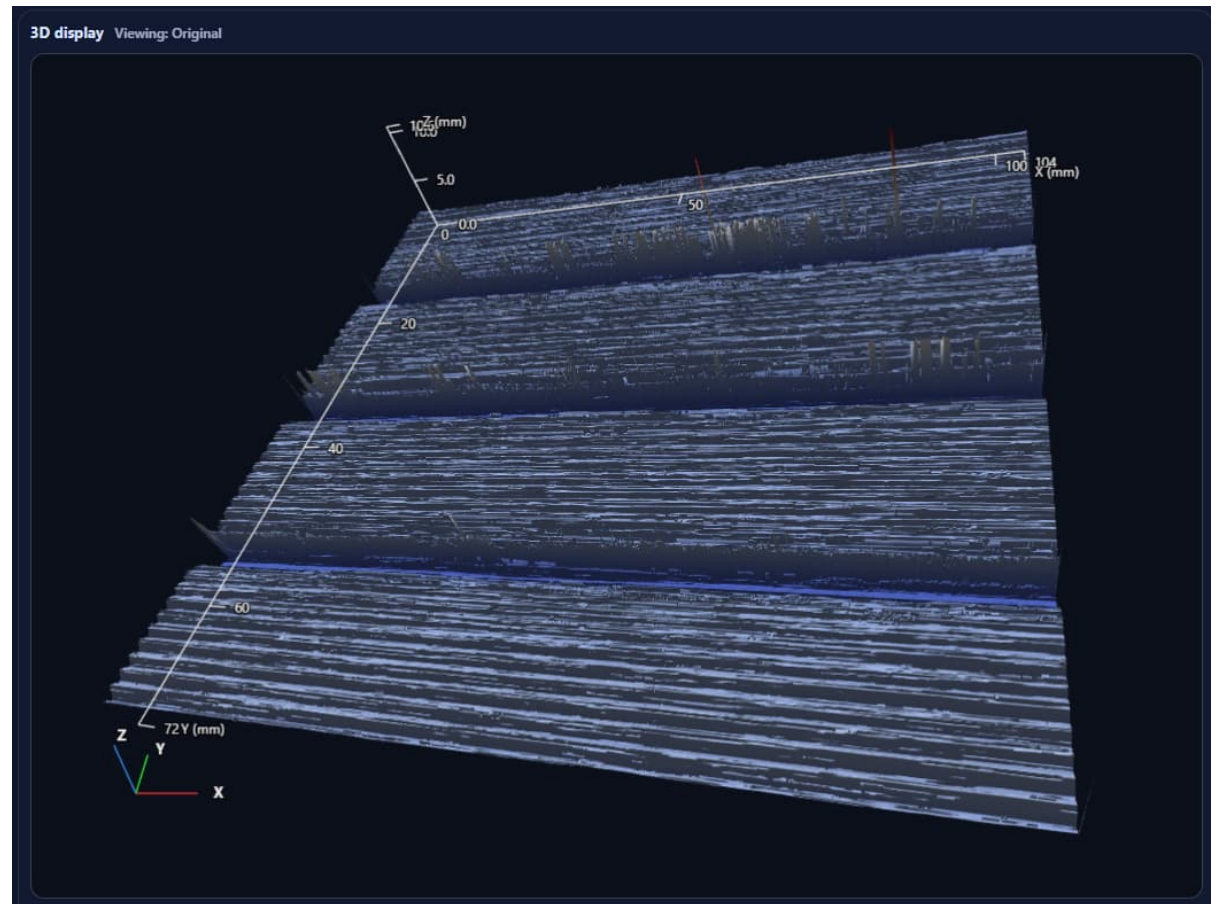
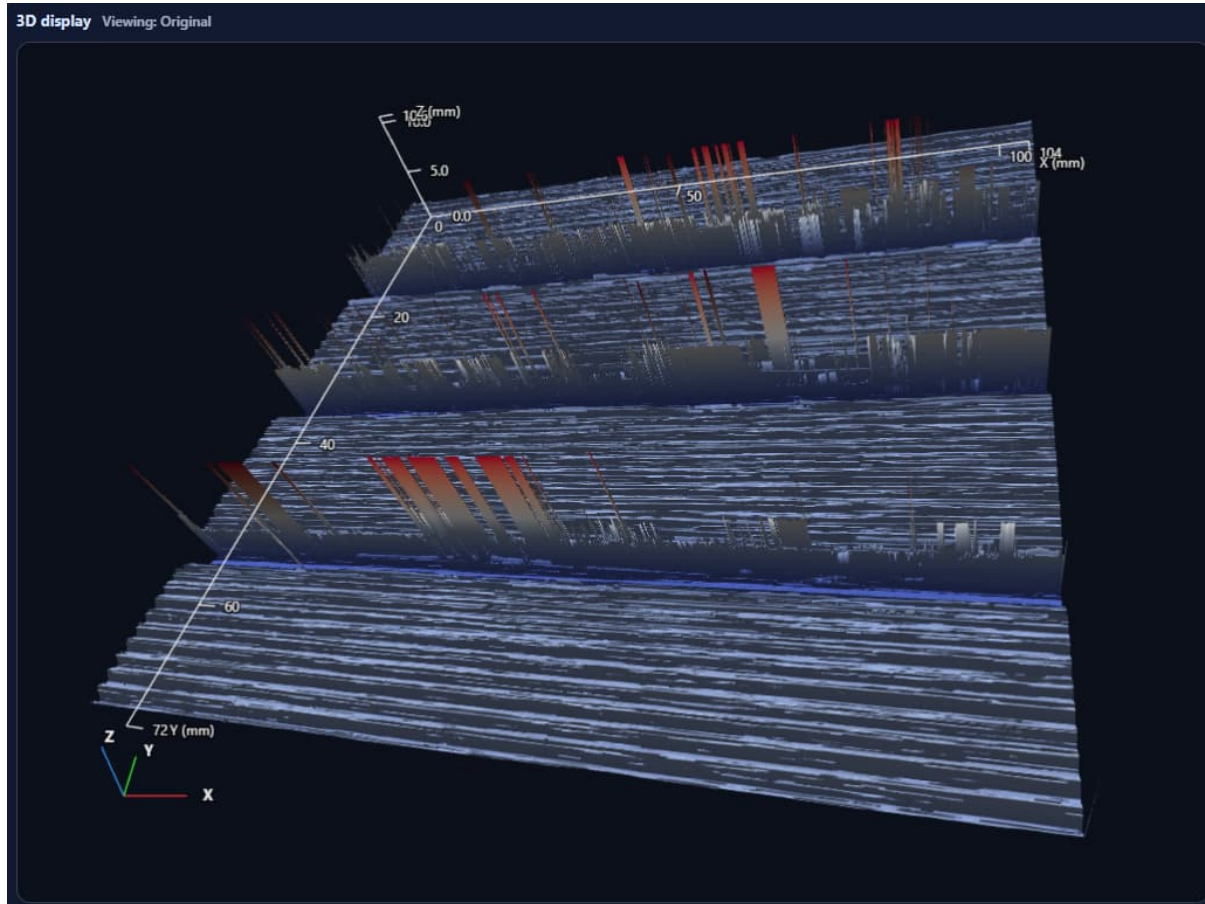
The detailed analysis results are as follows:

- Profile cross-section:** A line graph showing height (mm) scaled by 100 vs distance (mm) from 0.0 to 80.0. The y-axis ranges from 5.190 to 9.740.
- Height distribution:** A histogram showing height distribution (counts) for ranges 4.570 to 10.100 mm.
- A vs B statistical comparison:** A bar chart comparing statistical values for A and B. The values are:

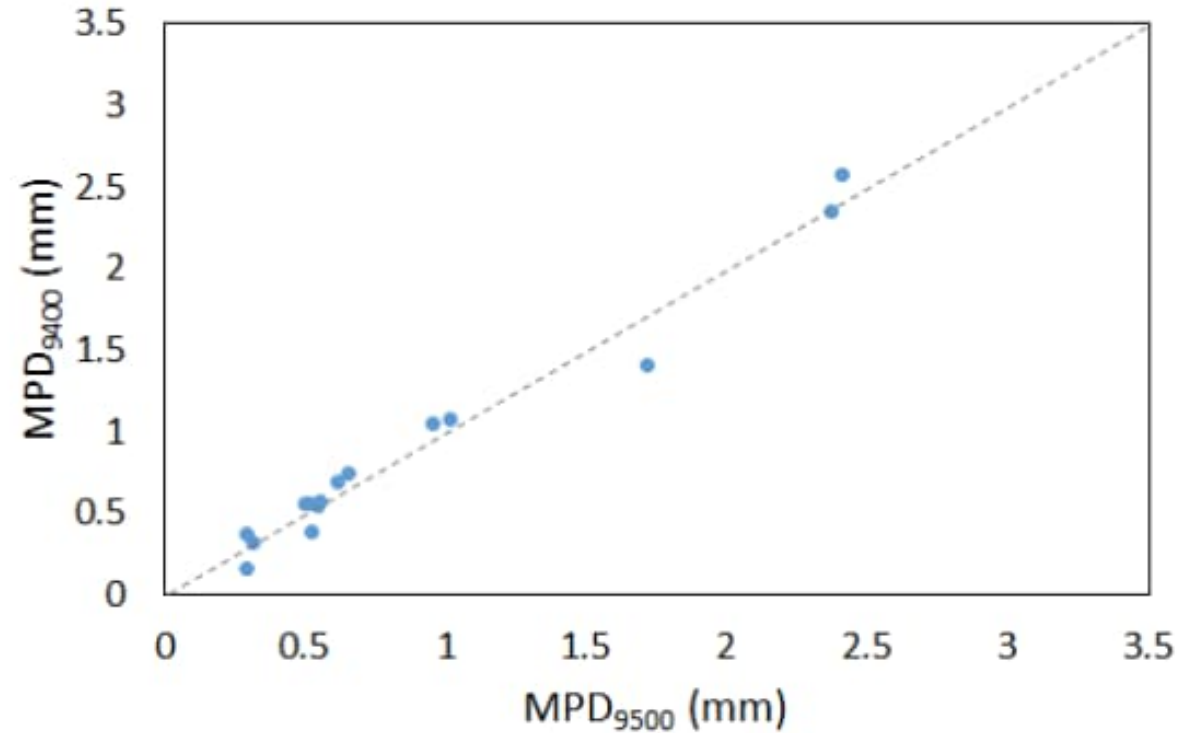
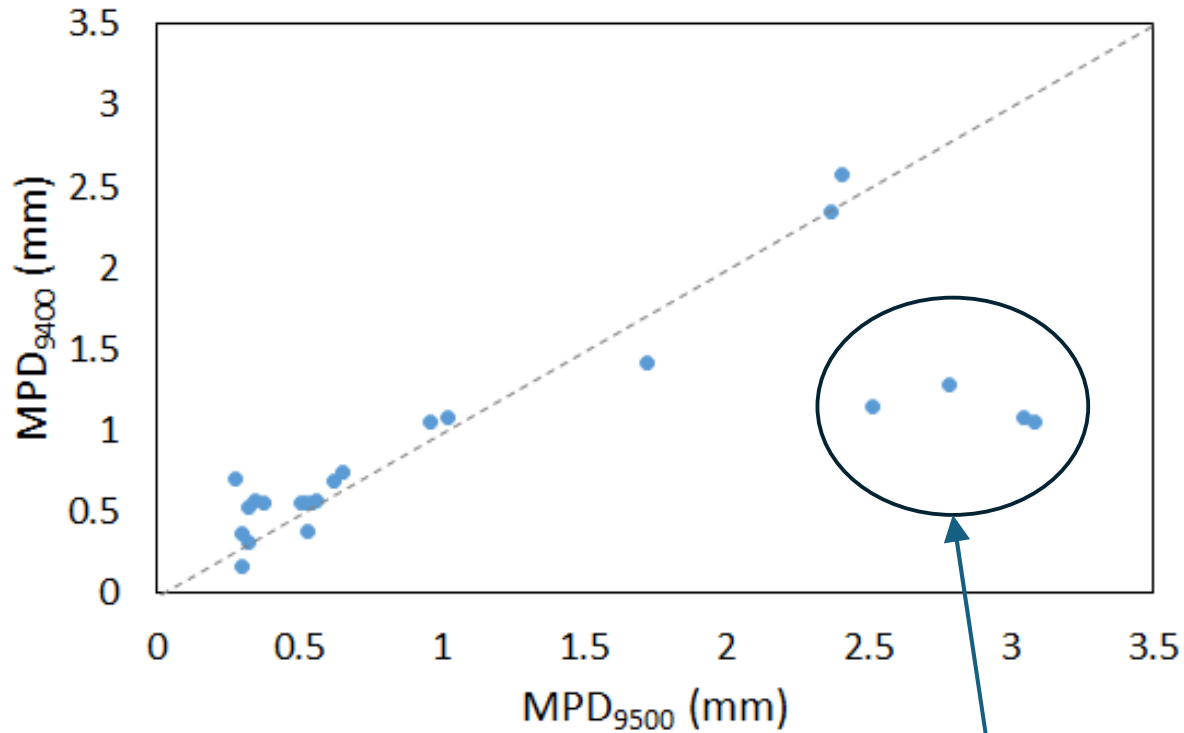
Statistic	A	B
Ra	0.1245	0.1796
Rq	0.1104	0.1247
Rq'	3.81855	1.5400
Rz	0.9062	0.1885
MPD	0.9250	0.3500
ETD	31.4420	-1.699
TPI	116.9418	-0.419
Rsk	-1.699	4.172
Rku	4.172	5.269
- Power Spectral Density (PSD):** A log-log plot of PSD vs Wavelength λ (mm). The x-axis ranges from 1e-1 to 1e2, and the y-axis ranges from 1e-5 to 1e1. Two curves are shown: A (blue) and B (yellow).

PSD is computed on the detrended profile (linear regression removed) using a Hann window and an FFT-based periodogram. X-axis is wavelength (mm, log), Y-axis is PSD (log; units are $\text{mm}^2 \cdot \text{mm}^{-1}$ for the periodogram scaling).

Filtering Varies Based on Laser Type and Surface Texture

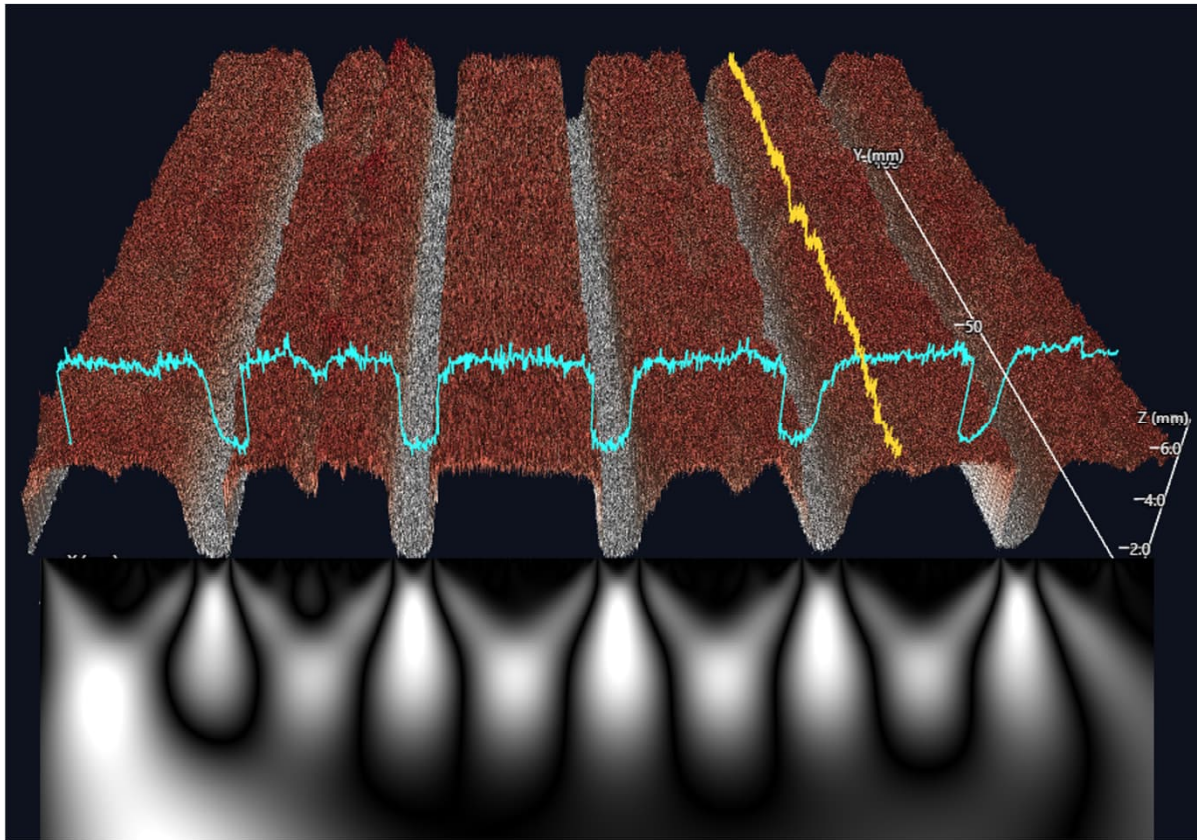


MPD is Highly Sensitive to Different Laser Measurements



Transverse Grooving

Wavelets Decompose Macro and Micro Texture



SmartWave(TM) — 2D Wavelet Texture Analysis

Alpha demo (offline HTML) Haar / db2 / db3 / sym2 / sym3 / coif1

1) Load data

JSON input: Choose File 2026-04-09...-11.P1

CSV import: Auto-detect (AE9500)

Target grid: Original (may be slow)

Aggregation: Mean (bin average)

Swap XY: No

Import progress: Import complete. Output grid=816x1024, dx=0.09942mm, dy=0.12456mm

Buttons: Load bundled demo JSON, Export metrics JSON, Export current tab PNGs, Export all PNGs

2) Analysis settings

Wavelet family: Daubechies 3 (db3)

Levels (2D DWT): 4

Denoise: None

Threshold scale: Universal ($\sigma \cdot \sqrt{2}$ In)

Buttons: Run analysis, Reset

Status: Analysis complete. Wavelet=db3, levels=4, denoise=none, thr=0.00000.

Notes: For multi-level analysis, SmartWave(TM) pads to the next power of two size (refers padding) to avoid edge artifacts. Band "levellength" is reported using a conservative measure: $\text{band} = 2^{(\text{level}+1)} \cdot dx$ for dx .

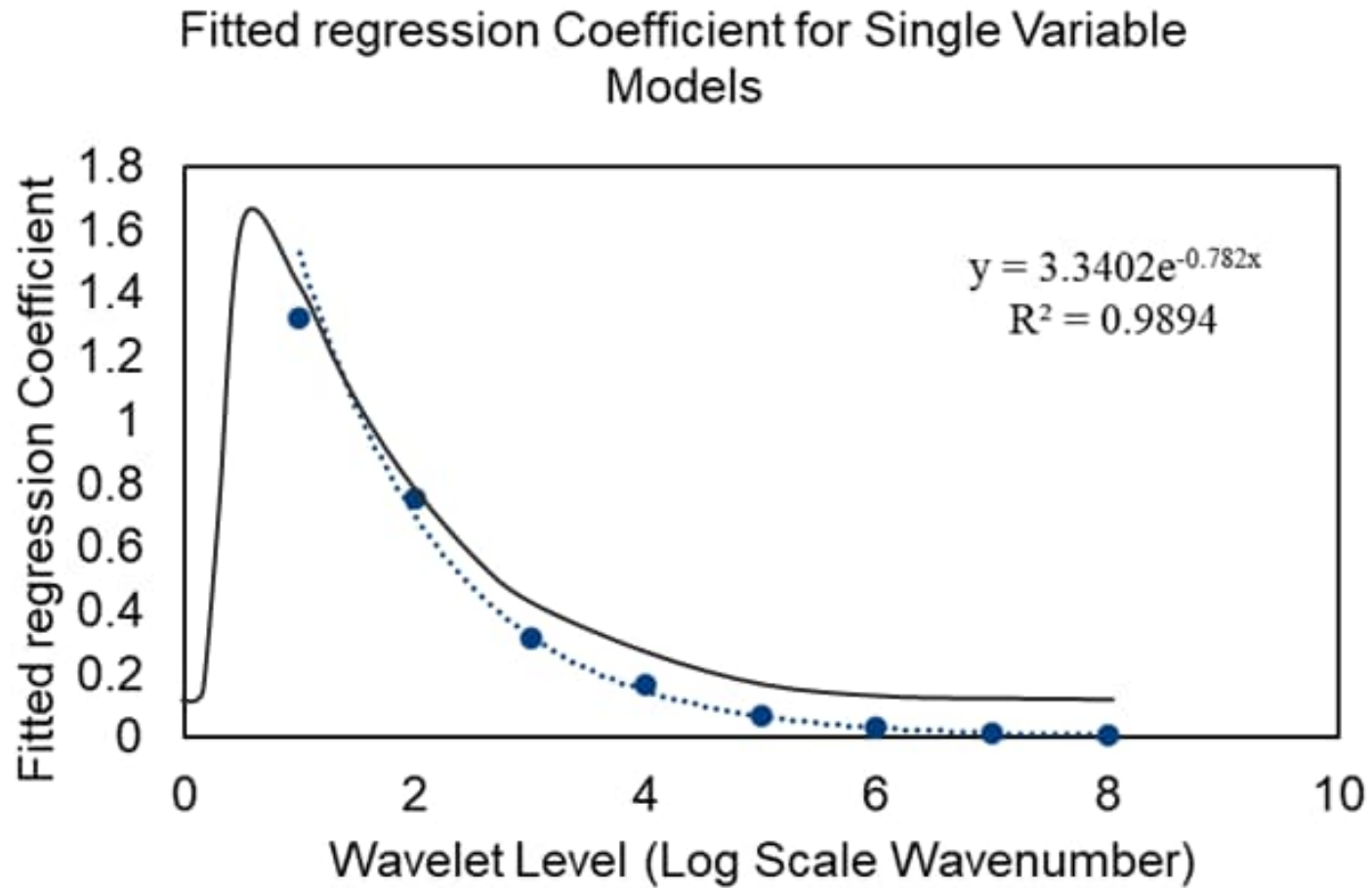
Visualization: 3D Viewer, Metrics, Compare to baseline, CWT (localized defects)

Original texture map

Denoised / reconstructed (LL + details)

Detail magnitude (HH at last level)

Wavelets Decomposition Can Estimate the Impact of Texturing



Towards a Global Friction Model

$$F = F[S, V, A, W, T, F_s]$$

F_s is the base friction measurement (used LWST at 40 MPH for now)

S tire slip ratio operator

V nominal vehicle speed impact ratio operator

A tire angle impact

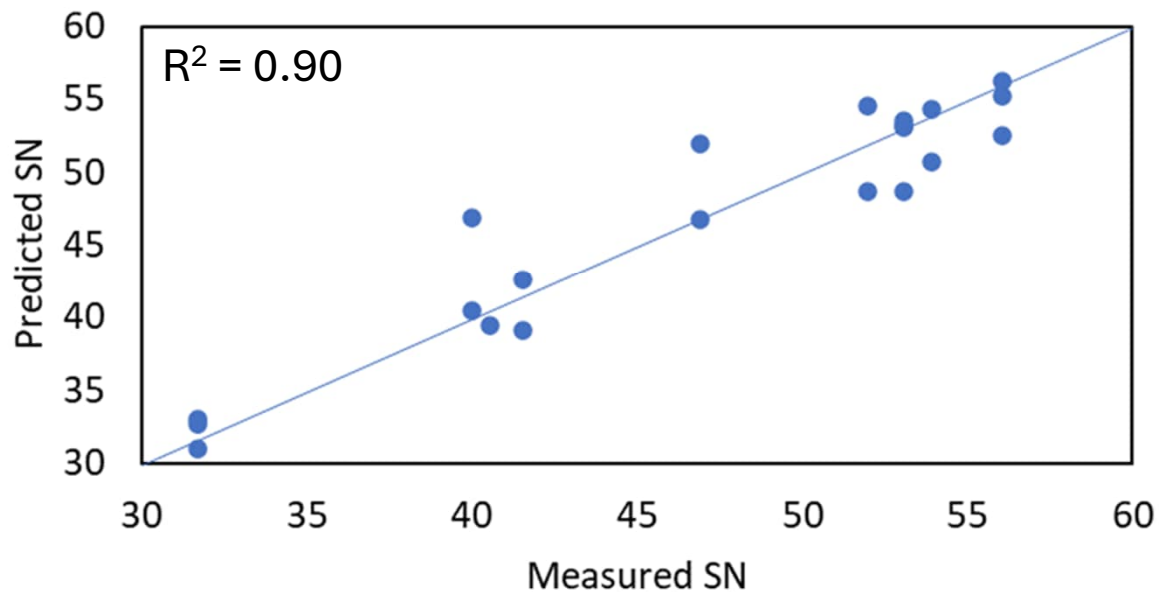
W wet conditions operator

T tire characteristics operator

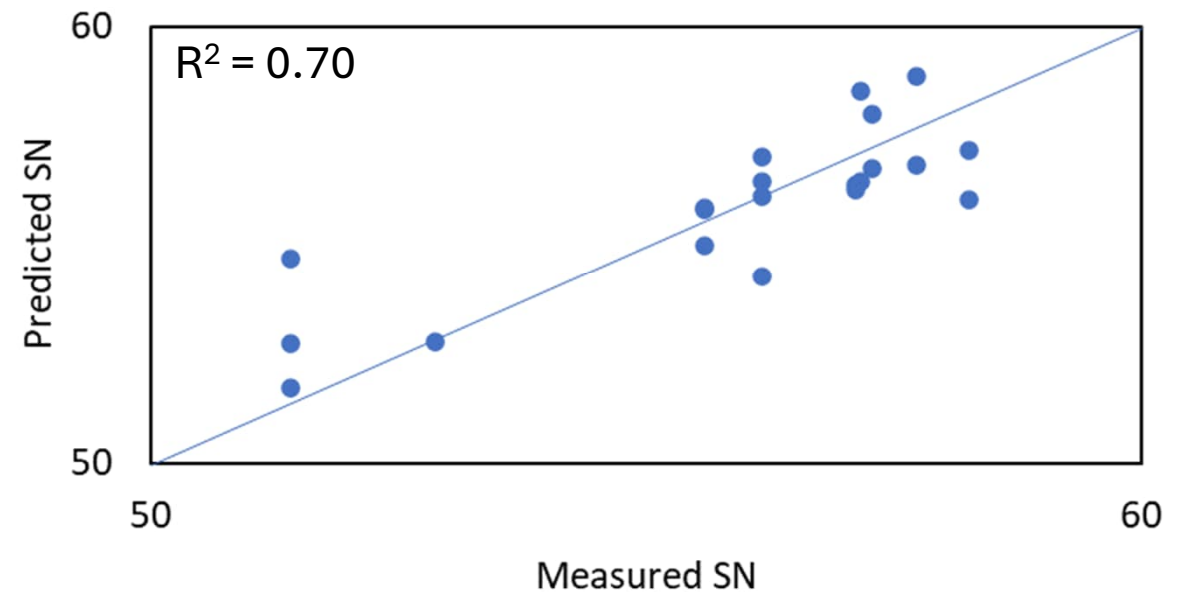
Base Friction Measurements

- Wavelets energy showed a strong to very strong correlations with LWST measurements.

Predicted vs Measured (Average, Smooth, 40 mph)



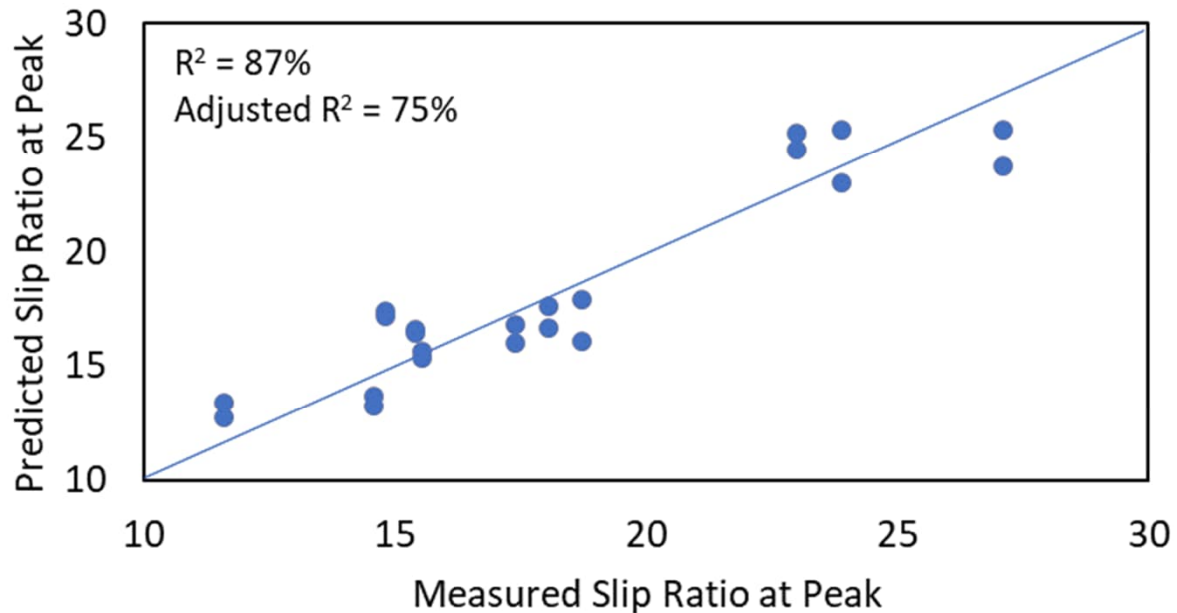
Predicted vs Measured (Average, Ribbed, 40 mph)



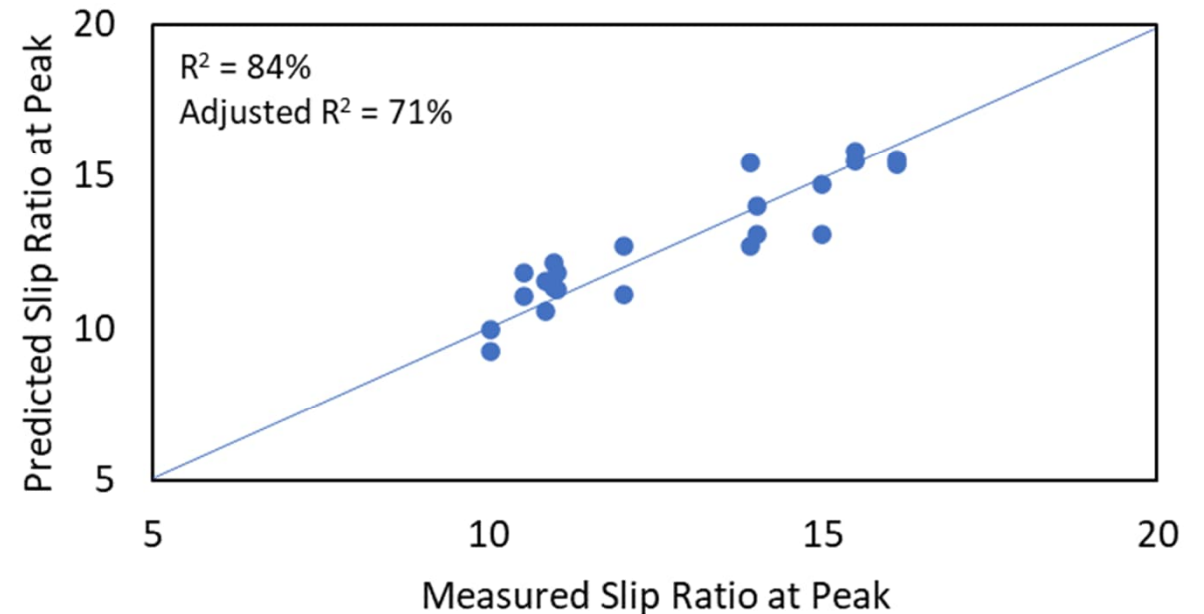
Slip Ratio Impact

- $SR_{Peak} = \sum_{i=1}^n a_{SR,i} E_i$

Predicted vs Measured (Slip Ratio, Ribbed)



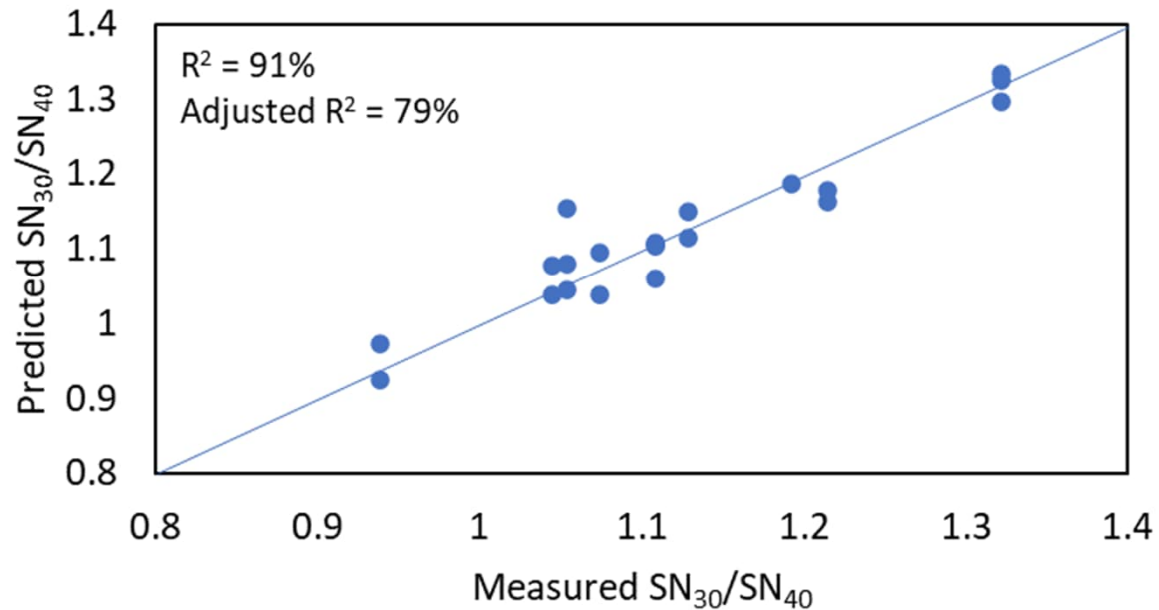
Predicted vs Measured (Slip Ratio, Smooth)



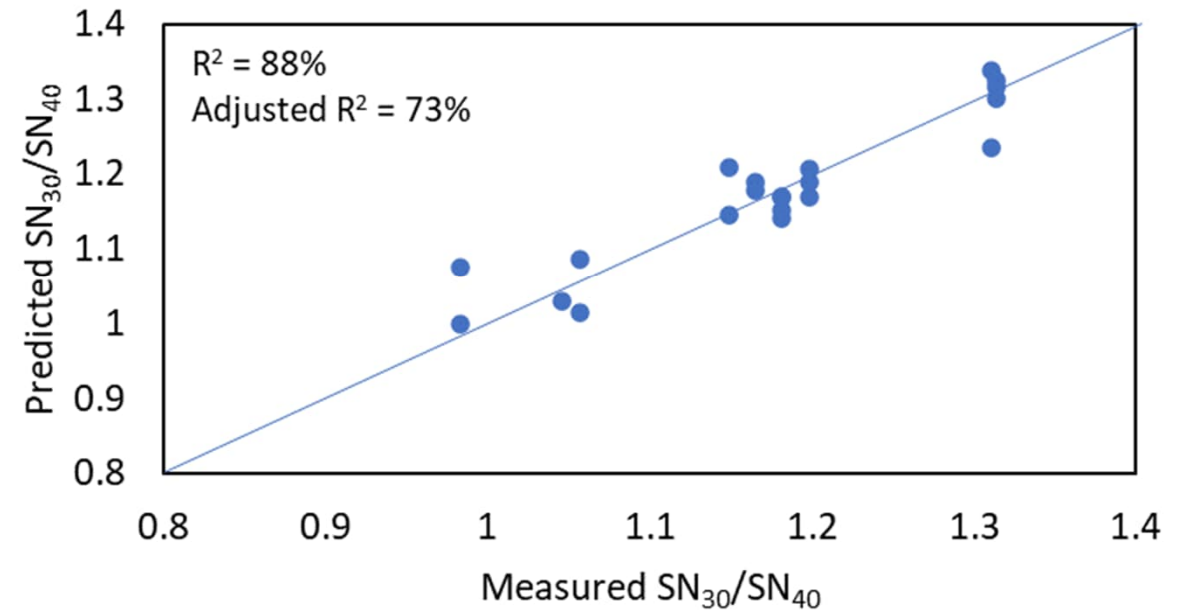
Speed Impact

- $SN_v = SN_v \sum_{i=1}^n a_{v,i} E_i$

Predicted vs Measured (SN₃₀/SN₄₀, Ribbed)



Predicted vs Measured (SN₃₀/SN₄₀, Smooth)



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Concluding Remarks

- Spectral analysis is crucial for filtering, decomposition, and advanced contactless friction models.
- Wavelets analysis allows for more stable and less sensitive analysis to outliers compared to traditional texture parameters.
- Defining ground truth is based on a combination of stable spectral content, measurements from engineered surfaces, and performance in relation to friction predictions.

Engineered Surfaces Provide Stable Ground Truth

The screenshot displays the InGIS Geotechnics software interface. On the left is a control panel with the following settings:

- Isolines: Off
- Isoline step (mm): 0.010
- Tip: Bent Cool Warm is a diverging colormap optimized for shaded 3D surfaces (keeps mid-tones from washing out).
- Colormap: Bent Cool Warm
- Light azimuth (deg): 315
- Light elevation (deg): 45
- Axis triad: On
- Full axes (mm): On
- Axes anchor: Top-left
- Y labels: Increase down (top=0)
- Tip: Y label direction controls whether tick values are referenced from the top (map-style) or from the bottom (Cartesian-style) of the scan.
- Cross-section line: On (single)
- Tip: Cross-section line uses the current Cross-section settings (Visualization tab: direction + index). Click "Build / Update 3D" after changing the cross-section.

Buttons at the bottom of the control panel include: Build / Update 3D, Reset view, Sync to cross-section, and Export 3D PNG. A mouse control tip at the bottom left reads: Mouse: drag to rotate • Wheel: zoom • Shift+drag: pan. Below the tip is the text: 3D print export (STL).

The main view shows a 3D surface scan of a corrugated metal roof. A yellow line highlights a cross-section. A coordinate system is visible with X (mm) ranging from 0 to 10200, Y (mm) at -50, and Z (mm) ranging from 0.0 to 8.0. Below the 3D view is an STL viewer section with a "Choose File" button, "No file chosen" text, and buttons for "Preview last exported STL" and "Reset STL view". The STL file name is "smartwave_surface_ds4_base2mm_z1x.stl" with 1,253,372 tris and a size of 101.43x101.40x10.70 mm. A grayscale cross-section of the surface is shown at the bottom of the main view.



Future Work

- We are working on defining the tuning parameters for the various filters needed for different measuring systems.
- Need consistent definitions, yet flexible enough, to define the spectral and wavelets analysis parameters.
- Global models and procedures require a wider range of data from different texture and friction devices and collected from different locations.

QUESTIONS?

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