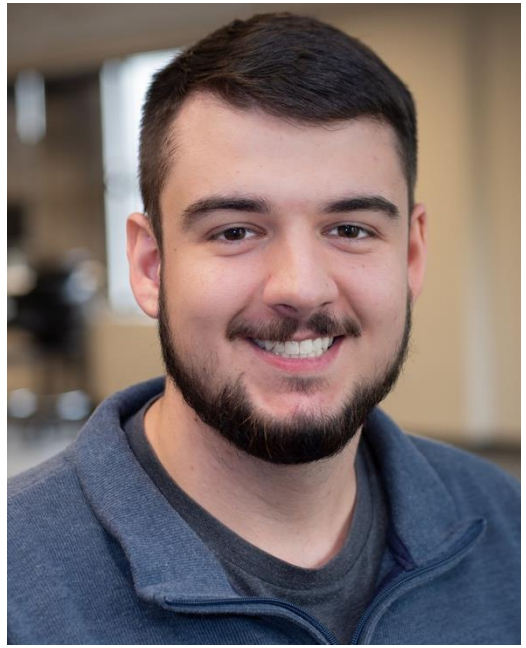
Measuring What Matters: Smart Glass Quality in LED Edge-Lit Sunroofs

Presented by: Danton Bennett

April 21, 2026

Today’s Presenter



Danton Bennett
Business Development Manager

Danton Bennett is a Business Development Manager at Radiant Vision Systems with just under five years of experience in display and lighting measurement solutions. He began his career as an Applications Engineer, where he partnered closely with customers to support proof-of-concept projects, deliver technical training, and develop customized inspection solutions. In his current role on the sales team, Danton leverages his strong technical background to help customers identify the right imaging and measurement technologies to improve product quality and manufacturing efficiency.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RETHINK
WHAT‘S
POSSIBLE

Today's Agenda

- Smart Glass Market
- Technologies
- Applications
- Performance Considerations
- Example Application: Sunroof Inspection
- Challenges Beyond Current Solutions
- Customer Case Examples: Technology Advancement for Superior Inspection
- Q&A

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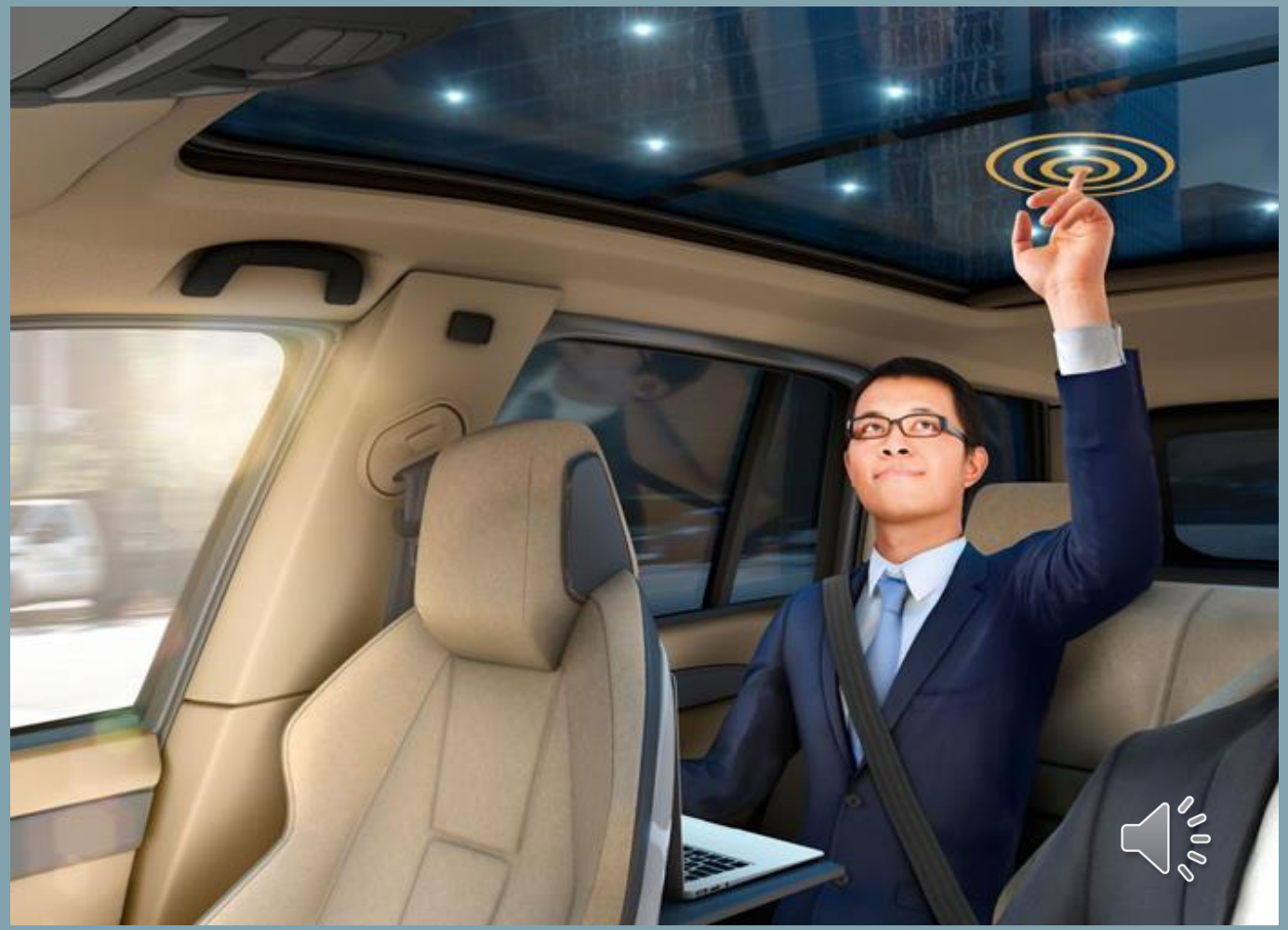
TREND
DIGITIZING VEHICLE SURFACES

WHAT IS SMART GLASS?

AKA, INTELLIGENT, DYNAMIC, OR SWITCHABLE GLASS

- ADJUSTABLE TINT
- HEAT & NOISE BLOCKING
- DISPLAYS
- RAPID DEFROST
- SOLAR POWER

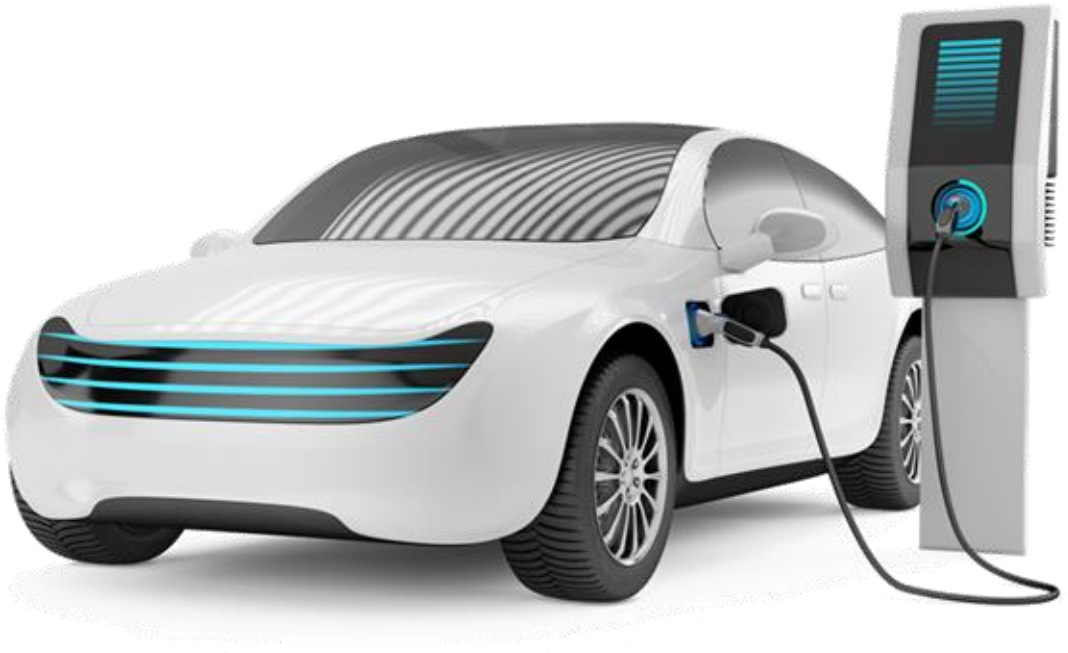


Market Outlook: Automotive Smart Glass

- **Automotive smart glass forecast:**
  - $6.5-7.8B by 2030, 18-20% CAGR*
- **Smart glass adoption:**
  - **Panoramic smart glass sunroofs** – continued strong adoption with ~12–15% CAGR to 2030**

    Windshield AR HUDs – sustained high-growth adoption through 2030, trending toward ~25–30%+ CAGR***

    Touchscreen windows – limited production pilots; commercial adoption emerging around 2028–2030 and broader deployment expected post-2030****
  - **Electric vehicles (EV)** - fastest adoption; premium EVs increasing smart glass penetration aligned with EV platform thermal & UX priorities



** Automotive Smart Glass Market to Grow with a CAGR of 20.02% through 2031F, TechSci Research*
*** Global Smart Glass in Automotive Market Trends Analysis, Market Trends Analysis*
**** Rear-Windshield Head-Up Display (HUD) Market Report 2026, Globe Newswire*
*****Automotive Smart Glass Market Size, Share, Growth, and Industry Analysis, Global Growth Insights*

Smart Glass Technologies

Where Glass Gets Its “Intelligence”

SMART GLASS COMPOSITION

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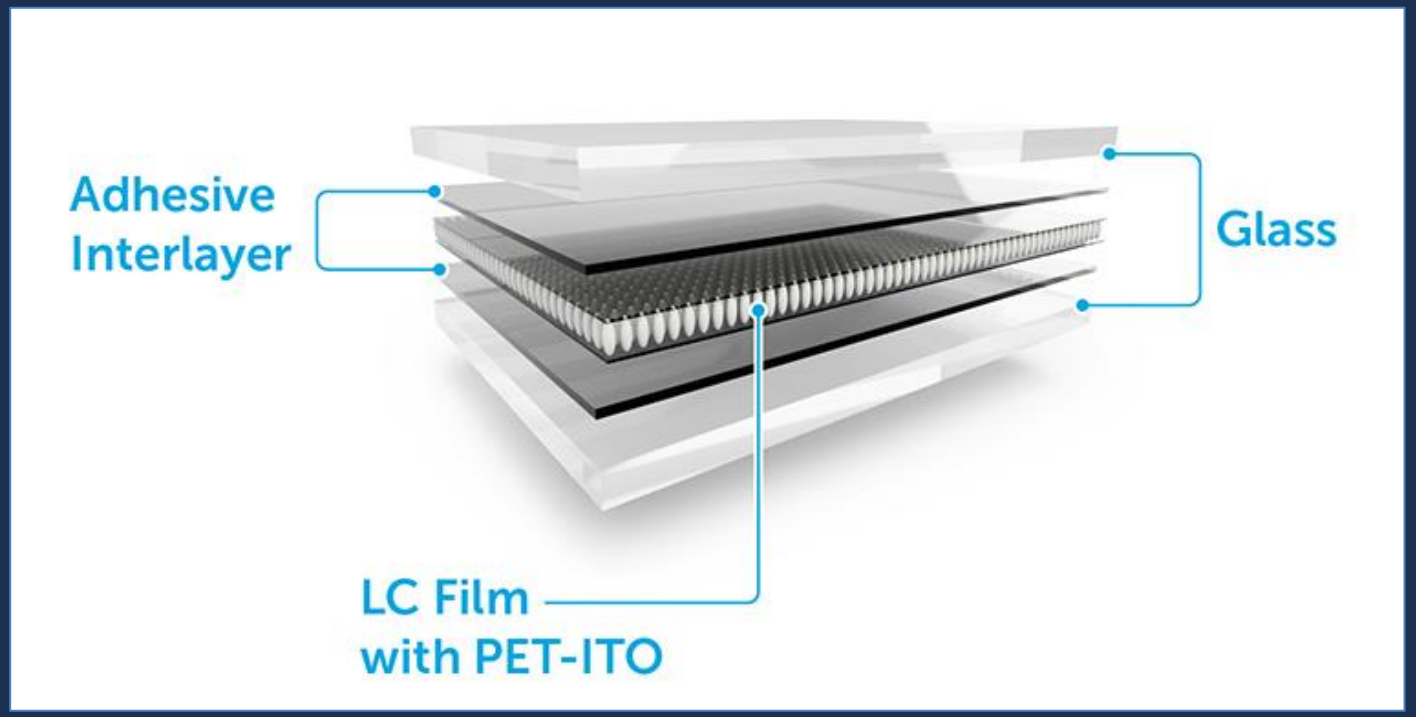
GLASS OUTER LAYERS

ACTIVE INTERLAYERS

- Films
- Liquid crystal/polymer
- Electronics

OTHER LAYERS

- Adhesive
- Air/spacing
- Laminates
- Coatings



SMART GLASS TECHNOLOGIES

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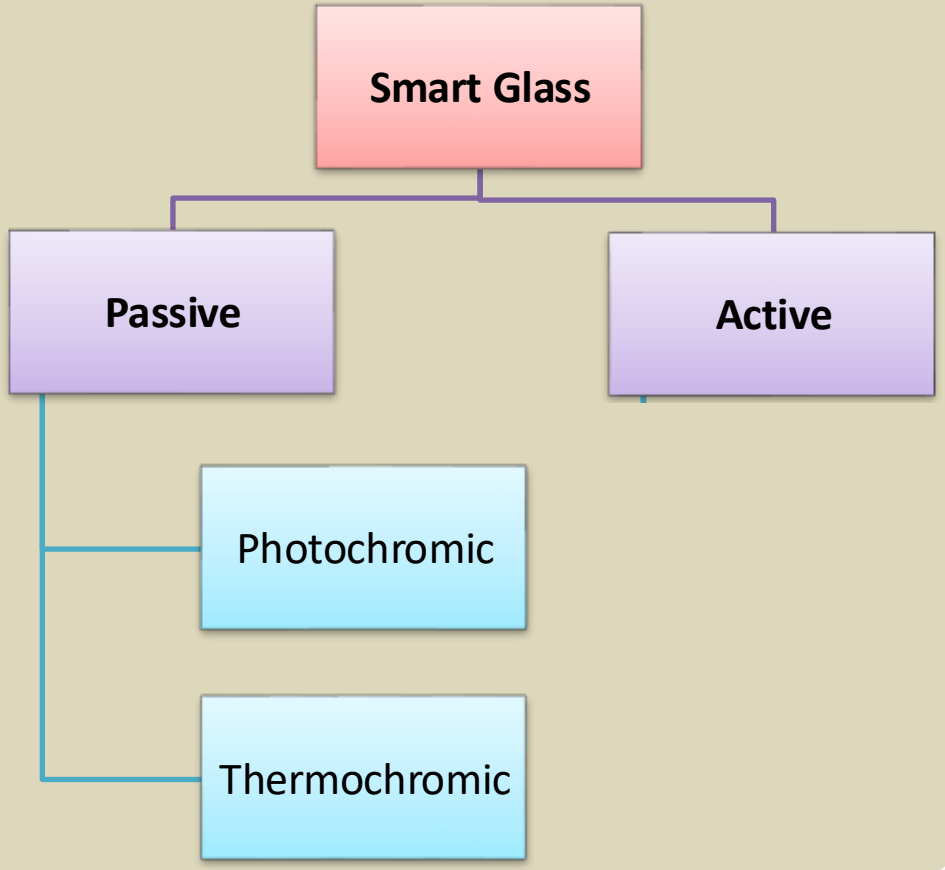
PASSIVE

- Respond to non-electric (environmental) stimuli e.g., UV rays, heat
- Automatic—no manual control

ACTIVE

- Respond to electrical stimulus
- Controlled both manually and automatically



Smart Glass Applications

Where and How Smart Glass is Used in the Vehicle

Smart Glass Applications

Roof/Sunroof

Head-up display (HUD)

Rear-view mirror

Rear window

Side mirrors

Windshield

Side windows

SMART GLASS APPLICATIONS

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ADAPTIVE

Tint

- Visibility
- Sun protection
- Heat reduction

Opacity

- Privacy

DISPLAY

Interior

- HUDs
- Entertainment
- Touchscreen controls

Exterior

- Communicate intention
- Information display
- Advertising

LIGHTING

Interior

- Roofs
- Accents

Headlamps

FUNCTIONAL

Solar collection

Acoustic (noise blocking)

Defog/ defrost

LED Edge-Lit Sunroofs

Electrification of sunroof glass

- LEDs in trim edges
- Etched channels act as waveguide to create illuminated pattern
- Etch is static
- Colors, zones dynamic

Performance Considerations

Ensuring Smart Glass Function and Appearance

QUALITY CONSIDERATIONS: GLASS

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GLASS PANEL QUALITY

- Optical faults (distortion)
- Spot faults (bubbles and deposits)
- Linear/extended faults (surface scuffs/scratches)

FILMS & LAMINATION

- Particles or bubbles trapped between layers

QUALITY CONSIDERATIONS: ADAPTIVE

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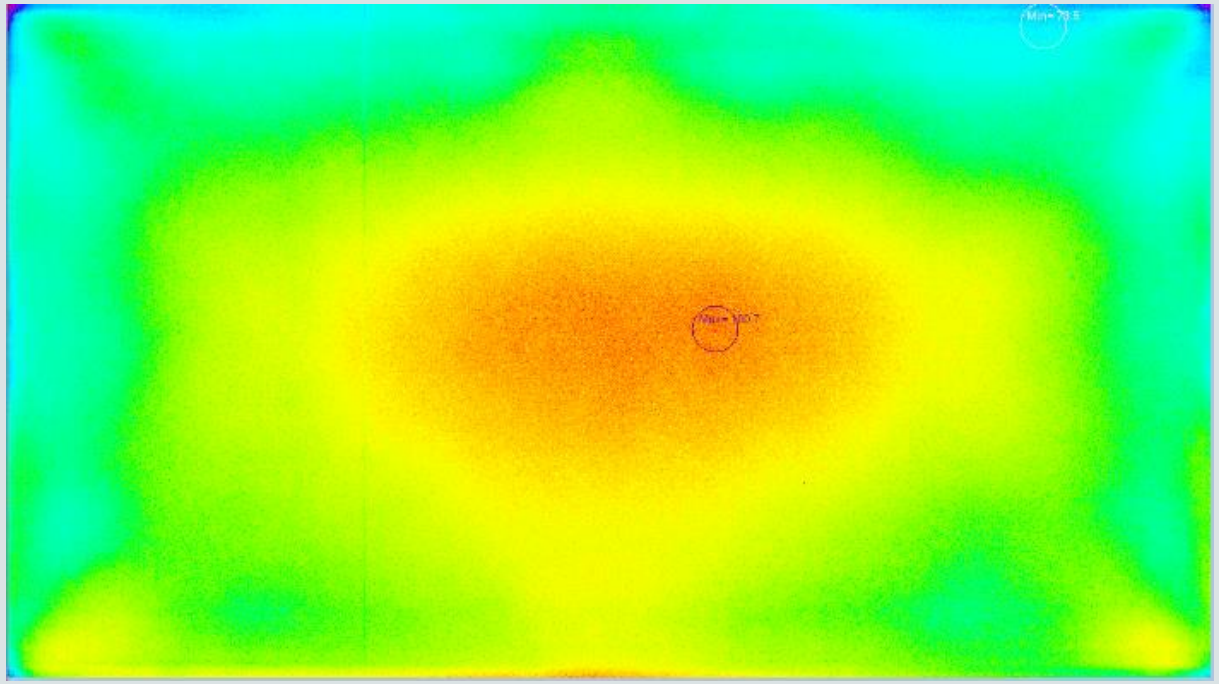
TINT

- Uniformity
- Transmittance and brightness level
- Color (e.g., blue tint)
- Uniform progression (bright edges, corners)

OPACITY

- Uniformity
- Transmittance and brightness level



QUALITY CONSIDERATIONS: DISPLAYS

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IMAGE APPEARANCE

- Brightness, color, uniformity, contrast
- Defects (lines/pixels/blobs)

COMPLEX IMAGERY

- Patterns
- Text and symbols
- Overlapping images

ELEMENTS WITH <1 MM SIZE DETAIL

GLASS CURVATURE

QUALITY CONSIDERATIONS: ILLUMINATED ETCH

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LIGHT QUALITY

- Brightness, color, uniformity

DEFECTS

- Broken/incomplete etch

COMPLEX IMAGERY

- Patterns
- Text and symbols
- Criss-cross lines

Case Examples

Leveraging Display Test Equipment and Methods to Ensure LED Sunroof Quality

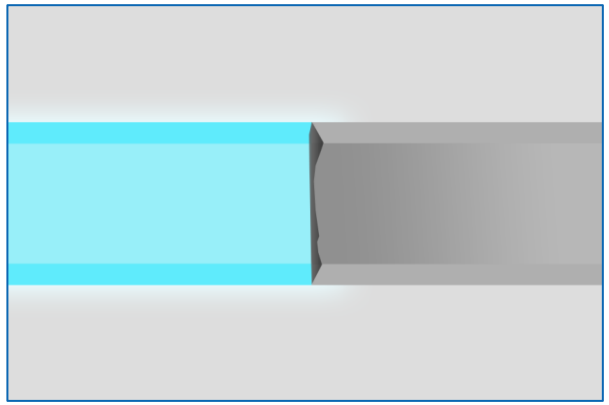
Quality Considerations

Light quality

- Luminance
- Chromaticity
- Uniformity
  - Luminance and/or chromaticity

Defects

- Broken/incomplete etch
- Artifacts/debris in glass



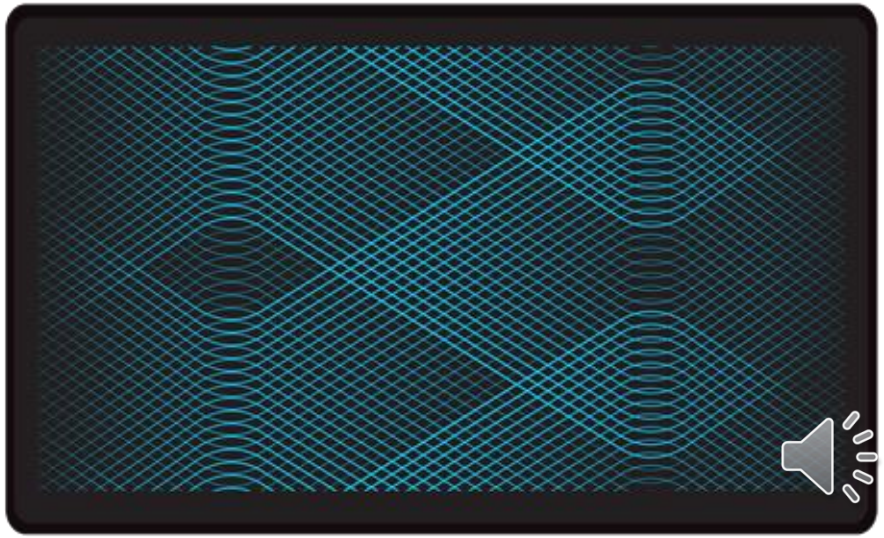
Broken etch example

BMW X7 Sky Lounge; Source: CARJAM TV

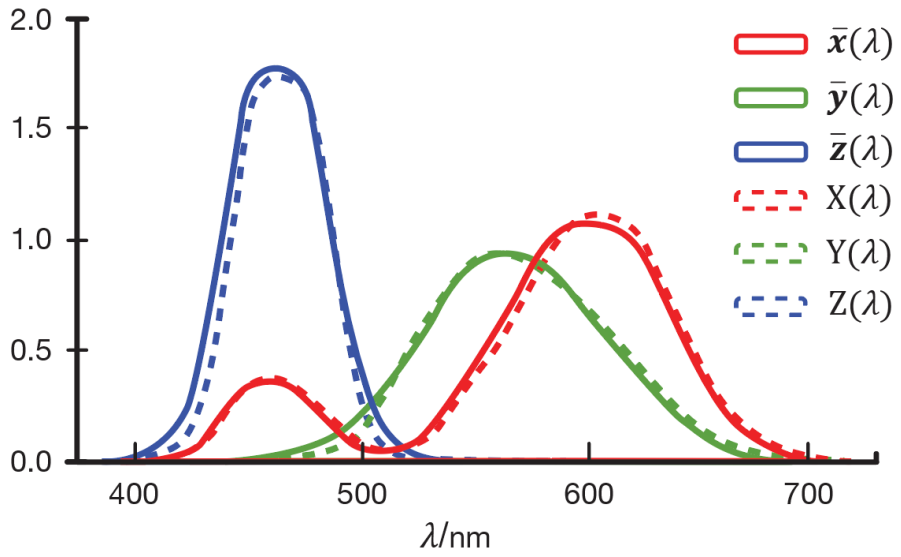
Measuring Sunroofs like Displays

Commonalities

- 2D spatial area
- Relatively flat
- Relatively rectangular
- Illuminated substrate
- Quality influenced by light source
  - Should be consistent/uniform



Like Displays: Photometry/Colorimetry

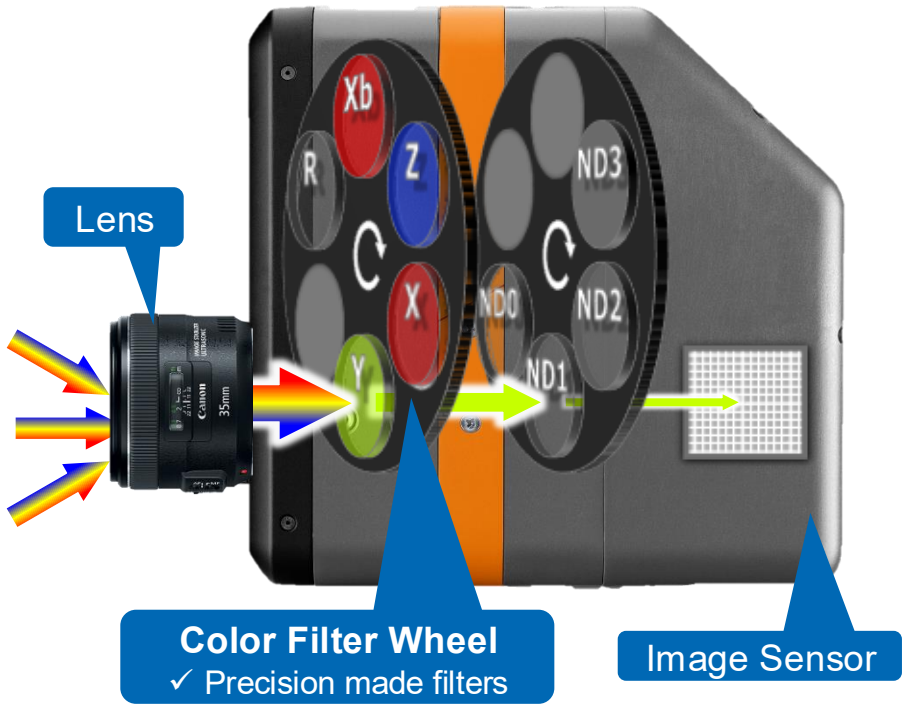


CIE Color-Matching Functions

CIE (solid lines) vs. colorimeter response (dotted lines).

System response must adhere to a model standardized by CIE to ensure accurate luminance and chromaticity measurements.

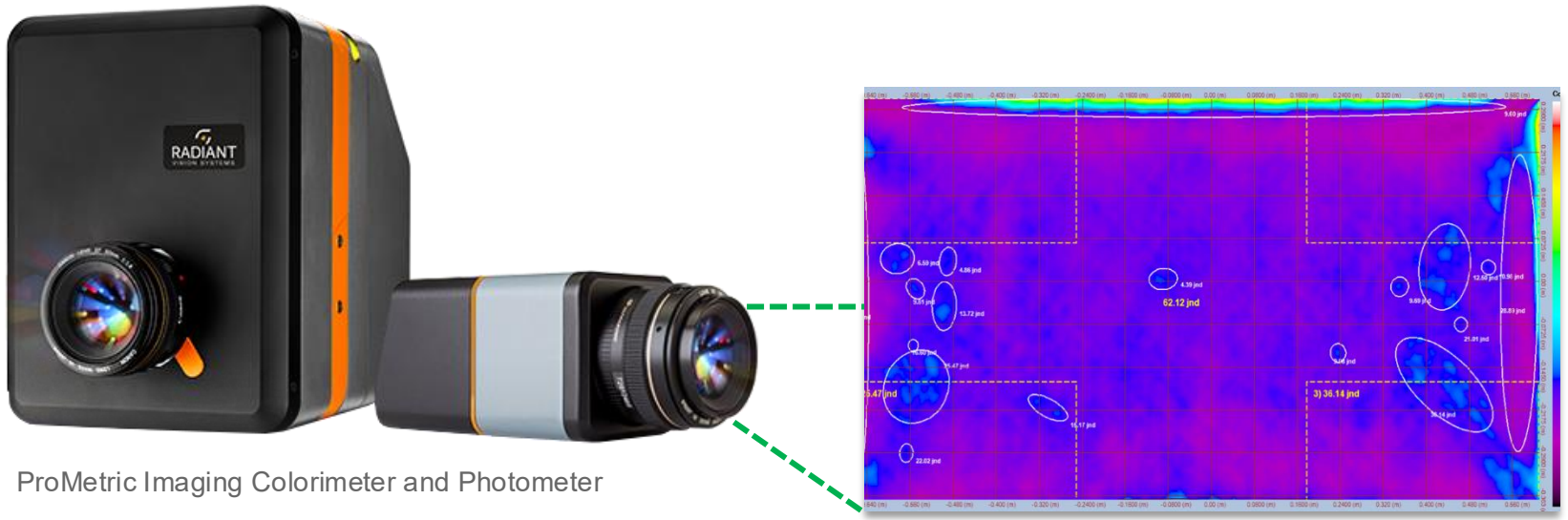
Radiant ProMetric® I Imaging Colorimeter



Like Displays: Imaging

Spatial understanding of all visual qualities at once

Efficient & comprehensive



ProMetric Imaging Colorimeter and Photometer

Necessary for:

- Evaluating uniformity
- Detecting defects
- Evaluating shapes/patterns

Like Displays: LED Calibration

Applied for displays:

- 2D LED screens
- Now, emissive OLED, miniLED, microLED
- Called “pixel-uniformity correction” or “demura”

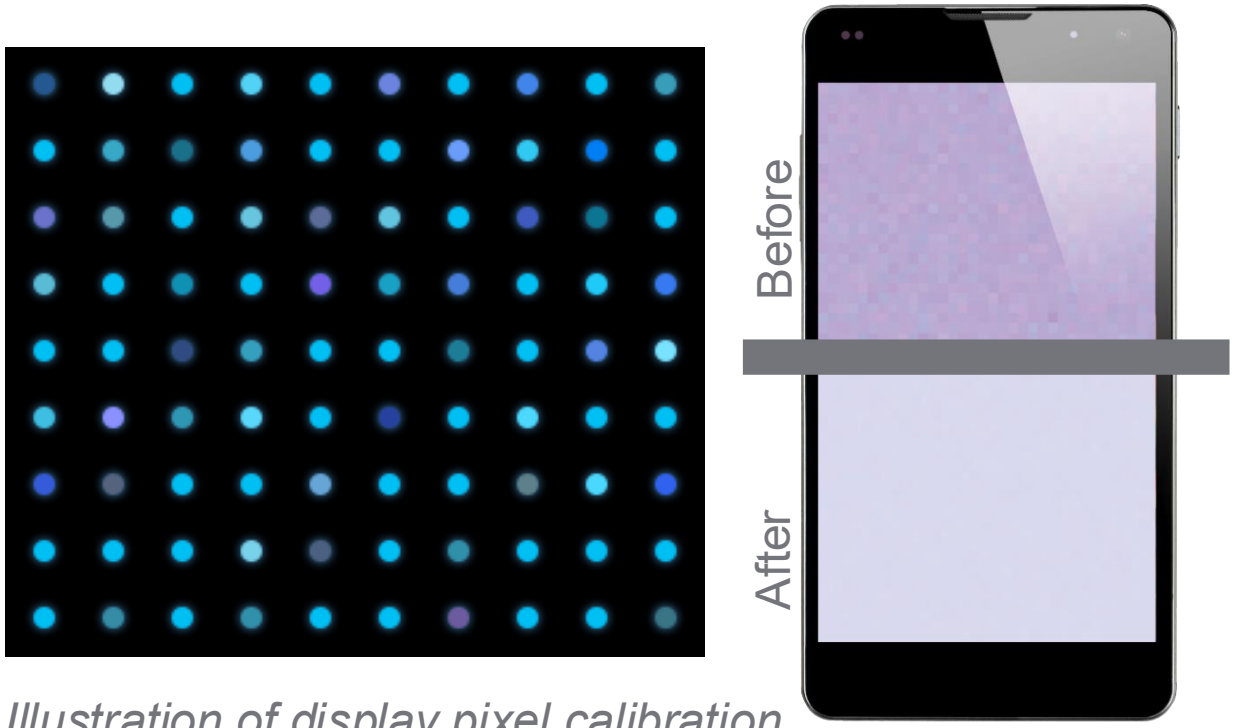
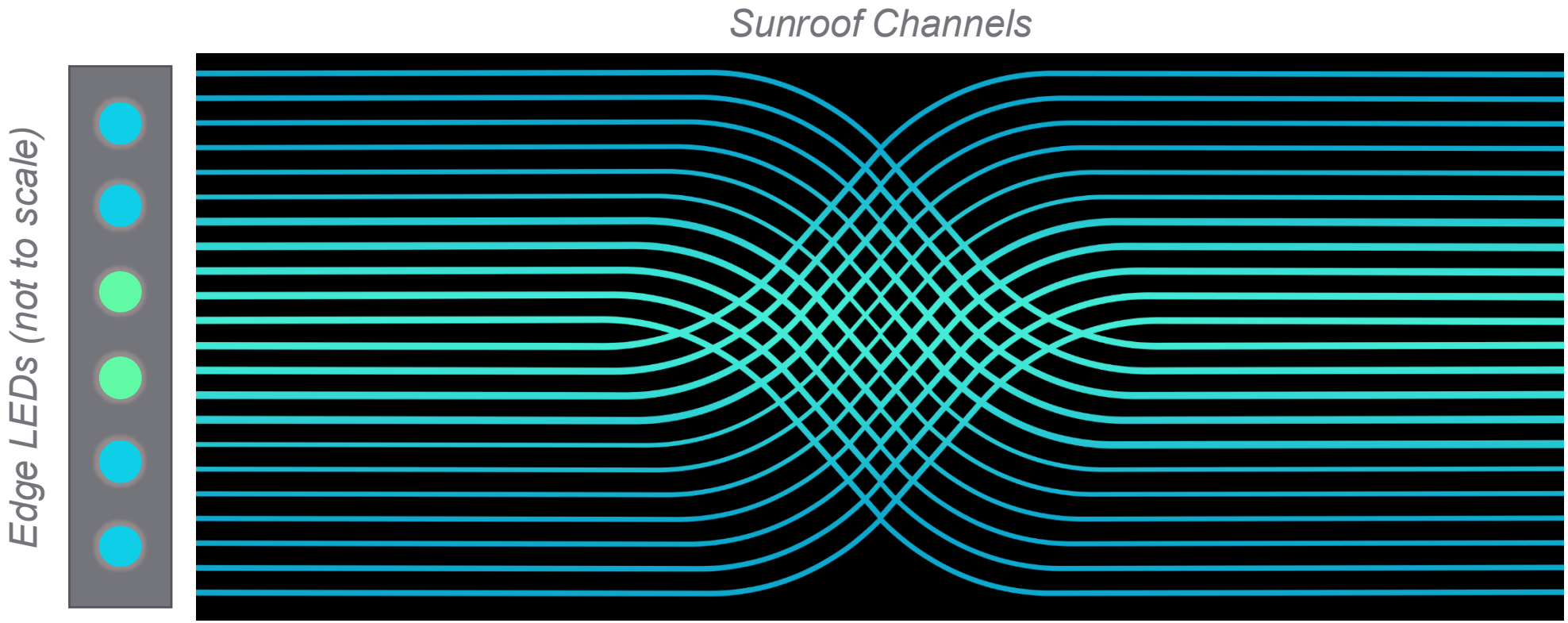


Illustration of display pixel calibration

Like Displays: LED Calibration



Challenges Beyond Current Solutions

Characteristics of Etched Sunroofs Not Addressed by Traditional Display Test Systems

WHY ARE LED SUNROOFS A CHALLENGE?

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PANEL SIZE

ETCHED ELEMENT SIZE

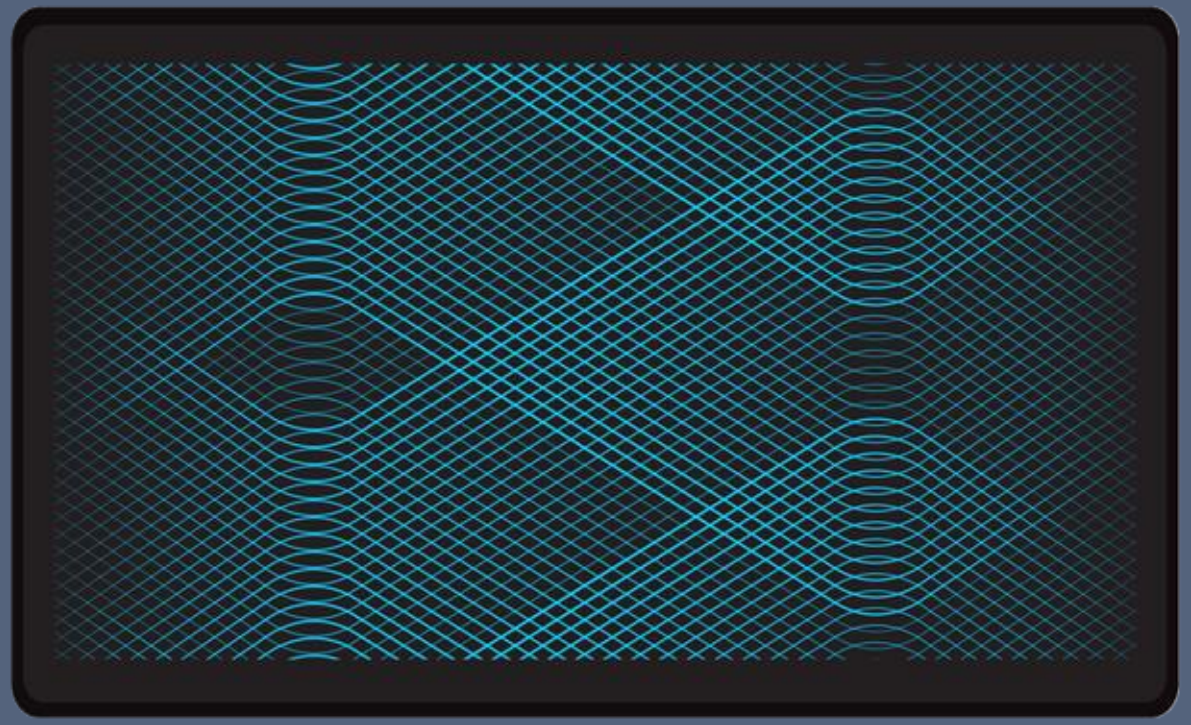
INDEPENDENT ILLUMINATED CONTROLS

- Unique ROI
- Complex directionality

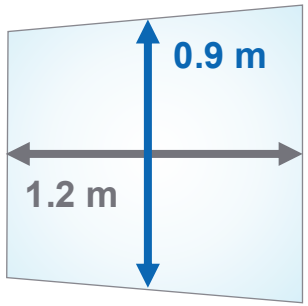
PATTERN COMPLEXITY

- Intersecting elements

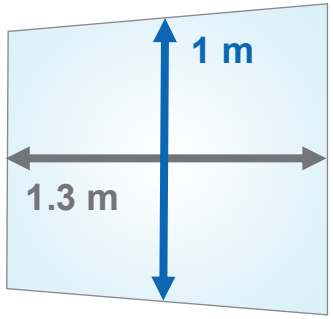
CURVED GLASS



Sunroof sizes (current sedans)



Standard



Large

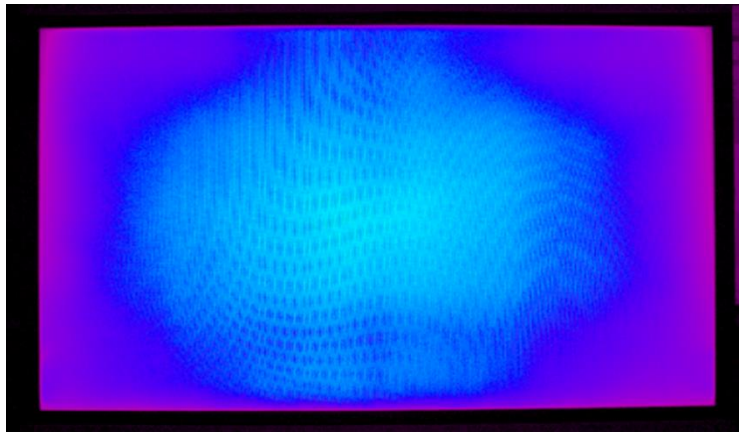
Comparable display size (60” TV)

Sunroof Panel Size

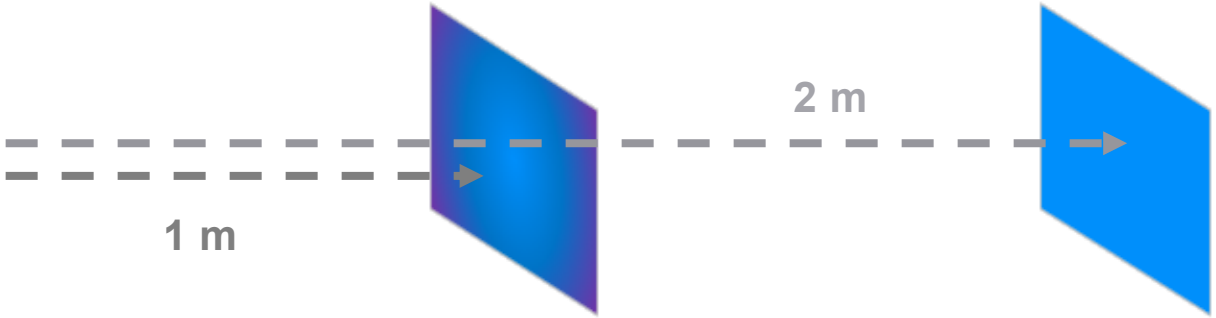
Minimum FOV Requirements

Sunroof size (m)	Working distance (m)	Min. angular FOV
1.2 x 0.9	1	62 x 49°
1.2 x 0.9	**2**	**33 x 25°**

Vignetting due to angular falloff



ProMetric Y Imaging Photometer



Angular FOV of Typical Display Test System

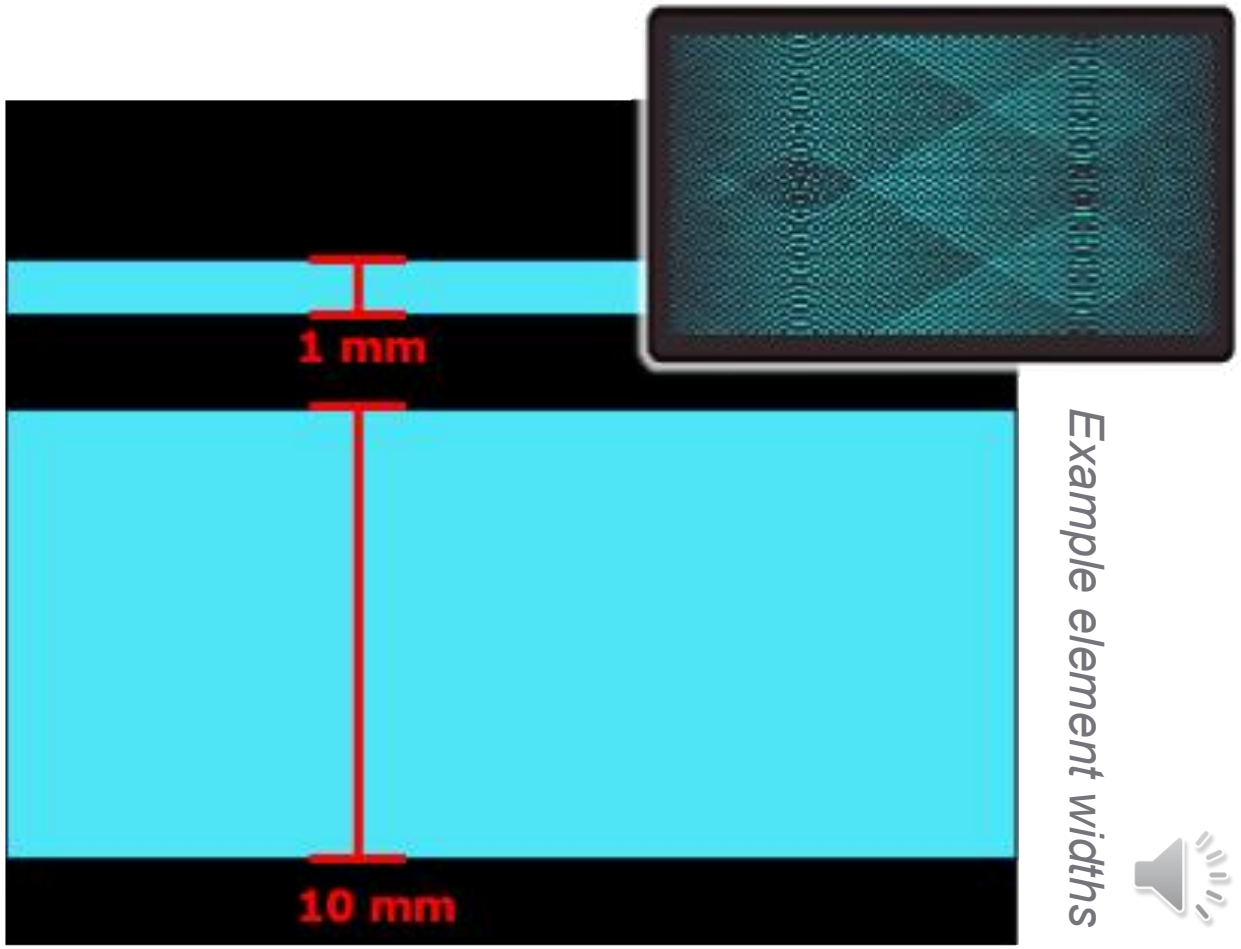
Required for 2 m distance: **33 x 25°**

Sensor resolution	Sensor size (mm)	Active sensor area (mm)	Lens focal length (mm)	Angular FOV
12 MP (a)	15.8	13.2 x 8.8	**14**	**51 x 35°**
12 MP (a)	15.8	13.2 x 8.8	24	31 x 21°
12 MP (b)	17.6	14.2 x 10.4	**14**	**54 x 41°**
12 MP (b)	17.6	14.2 x 10.4	**24**	**33 x 25°**

Etched Element Size

Higher imaging resolution ensures:

- Detail for registering each channel's ROI
- More light for better SNR and accuracy

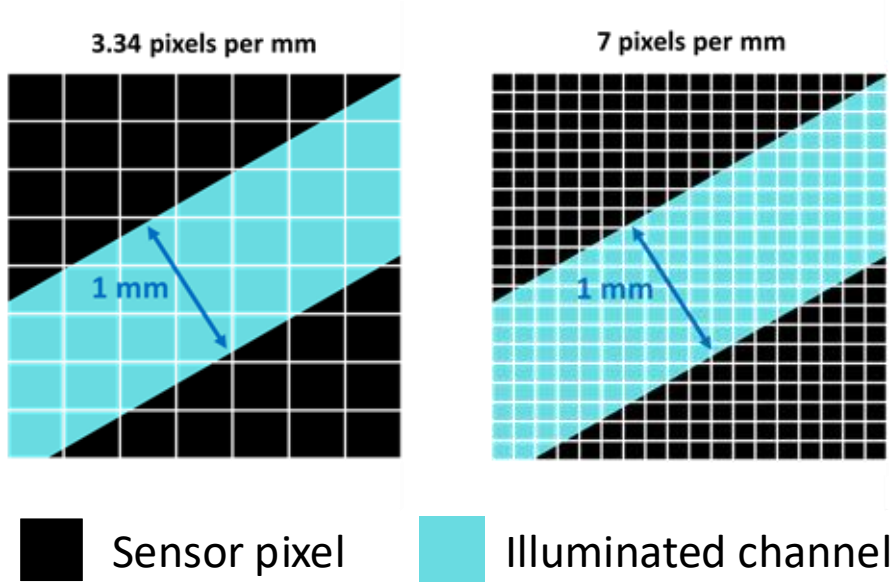


Example element widths

Pixels/mm for Typical Display Test Systems

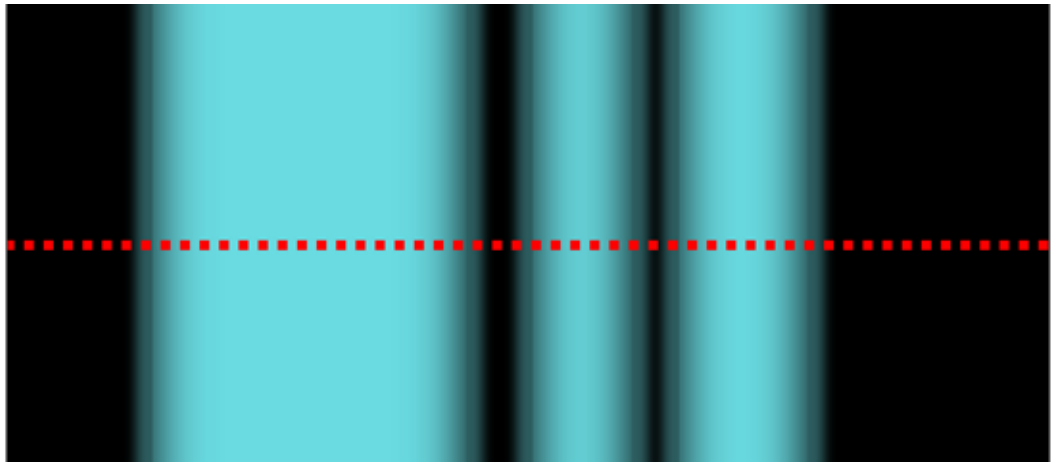
Sensor resolution	Sunroof panel (mm)	Applied sensor pixels	Pixels per mm
12 MP (a)	1200 x 900	3784 x 2838	**3.15**
12 MP (b)	1200 x 900	4010 x 3008	**3.34**
30 MP	1200 x 900	5460 x 4095	**4.55**

Required for detail: **7-10 pixels/mm**



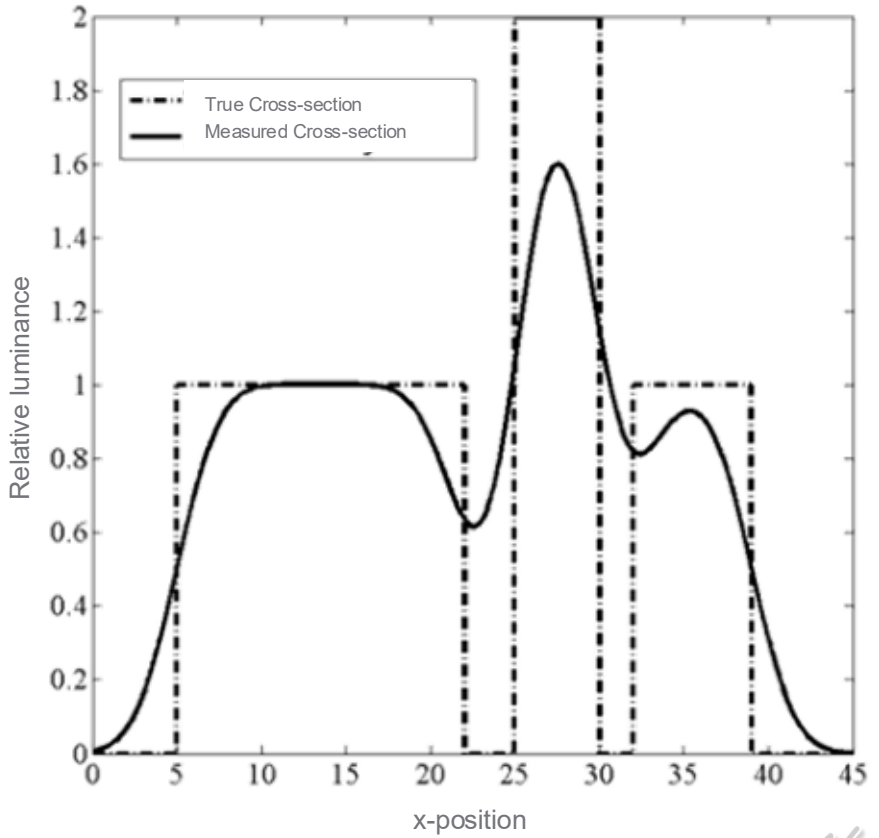
PVE = Partial Volume Effect

- Low resolution results in blurring at channel edges
- Measured luminance < actual luminance



Example illustration of PVE

Example PVE Plot



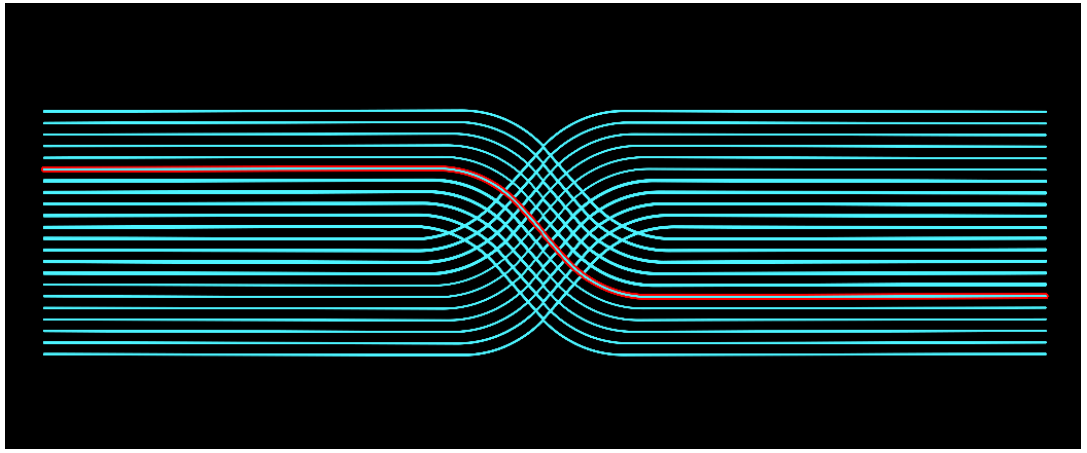
Data source: Prior, 2014

Independent Illuminated Regions

Successful measurement depends on:

- **Registration:** Ability of measurement software to define ROI
- **System Calibration:** Ability of measurement system to measure multiple areas with different output

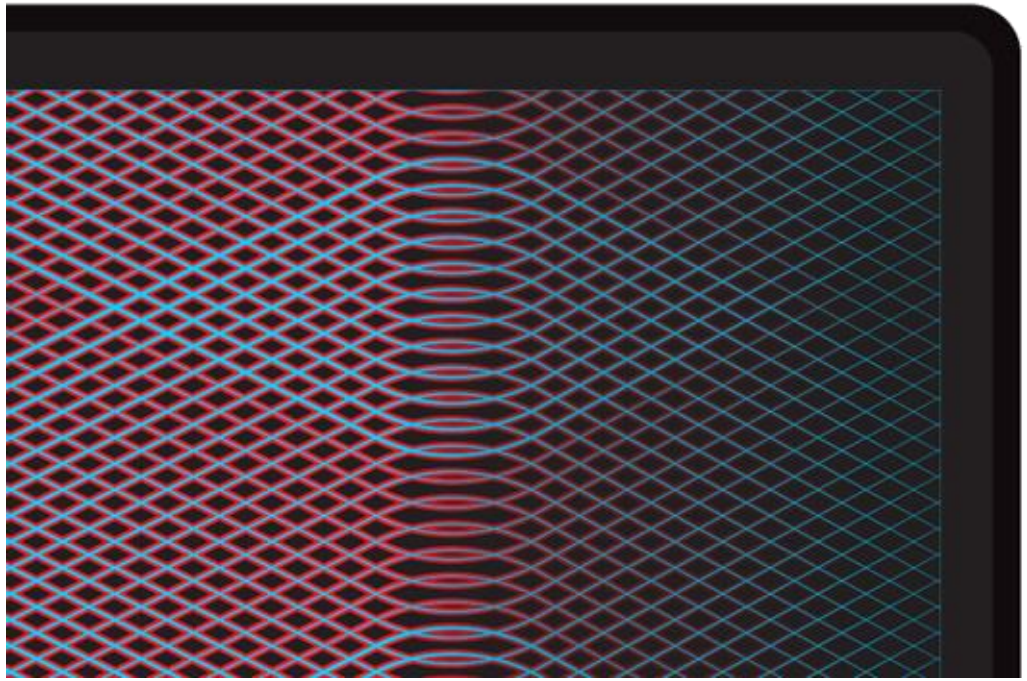
Example channel registration



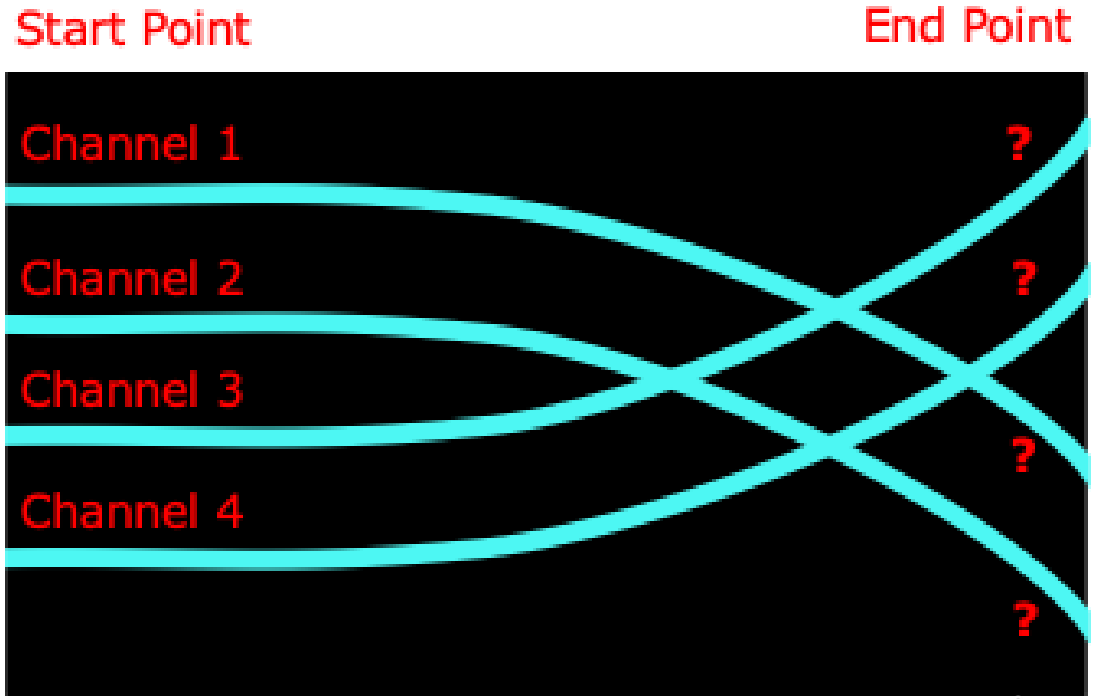
Speedometer regions registered by measurement software

Issues with traditional registration:

- Global thresholding



Example luminance threshold: too limited

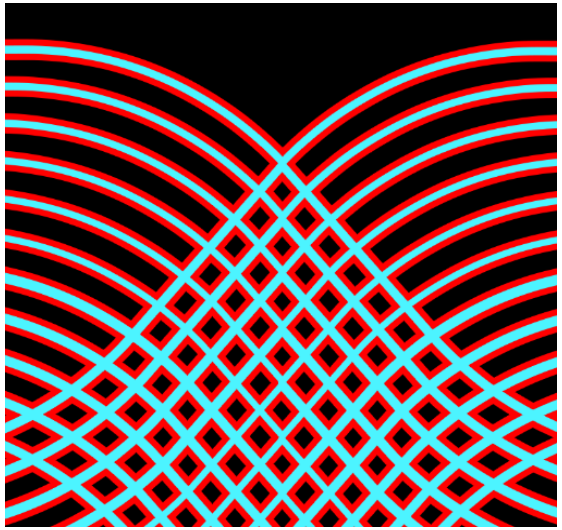


Example identify channel start/end points

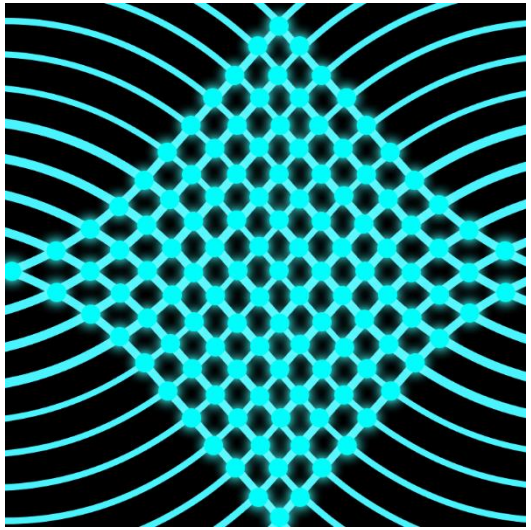
Intersecting Patterns

Measurement Challenges:

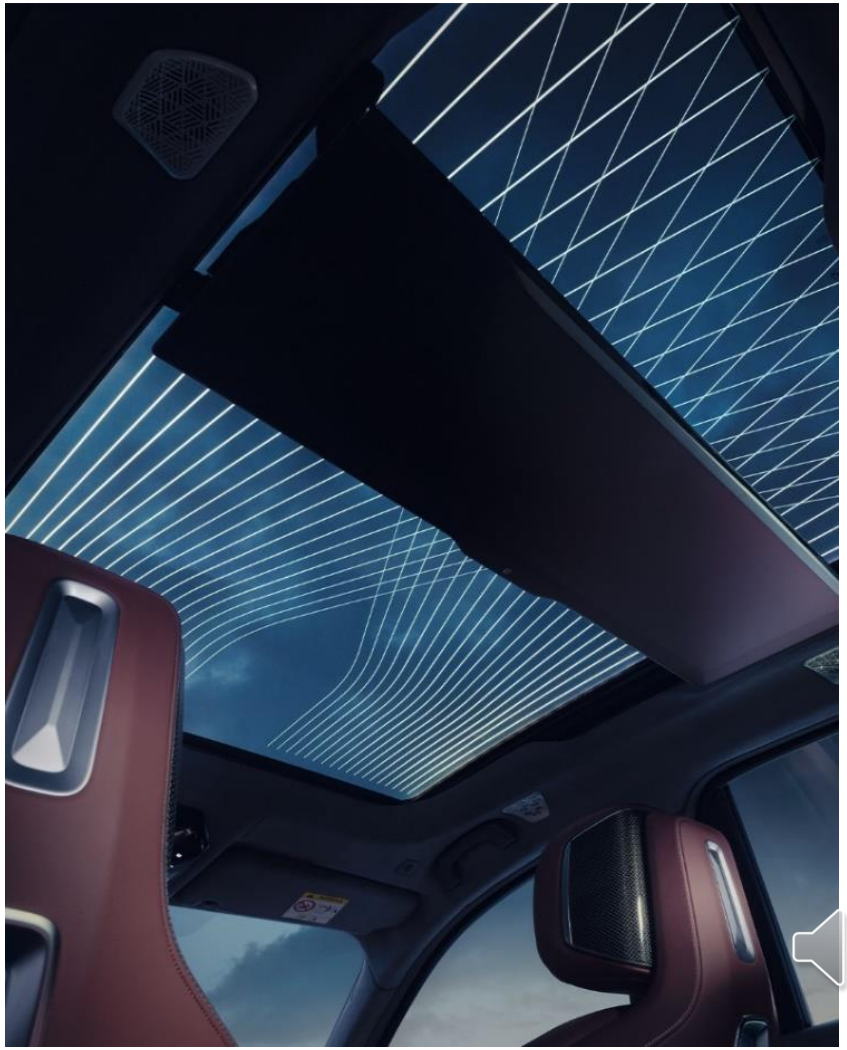
- Registration
- Changes in brightness/color



Example “meshed” ROI



Example “starry night” effect



2023 BMW i7 Sky Lounge; Source: BMW

Issues with traditional measurement systems:

- Cumbersome calibration process

Example channel variability

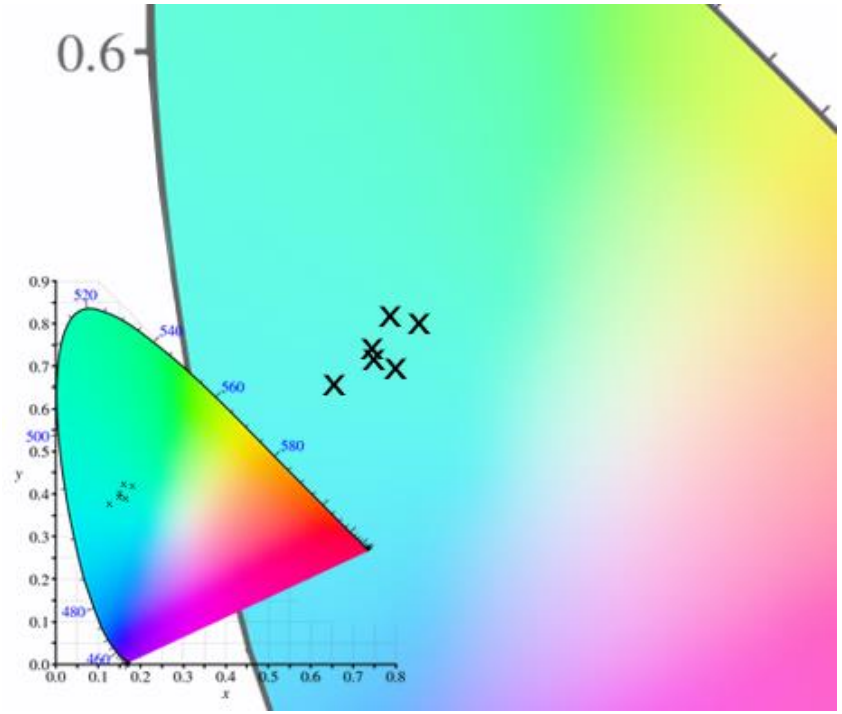
2019 BMW X5 Sky Lounge; Source: The Wheel Network

Example changing color states

Issues with traditional measurement systems:

- Cumbersome calibration process

Example channel variability



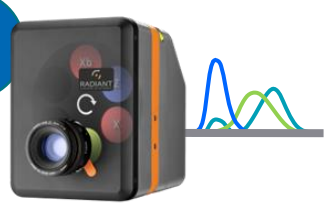
Example system accuracy range

Spectrum

1

Calibration

2



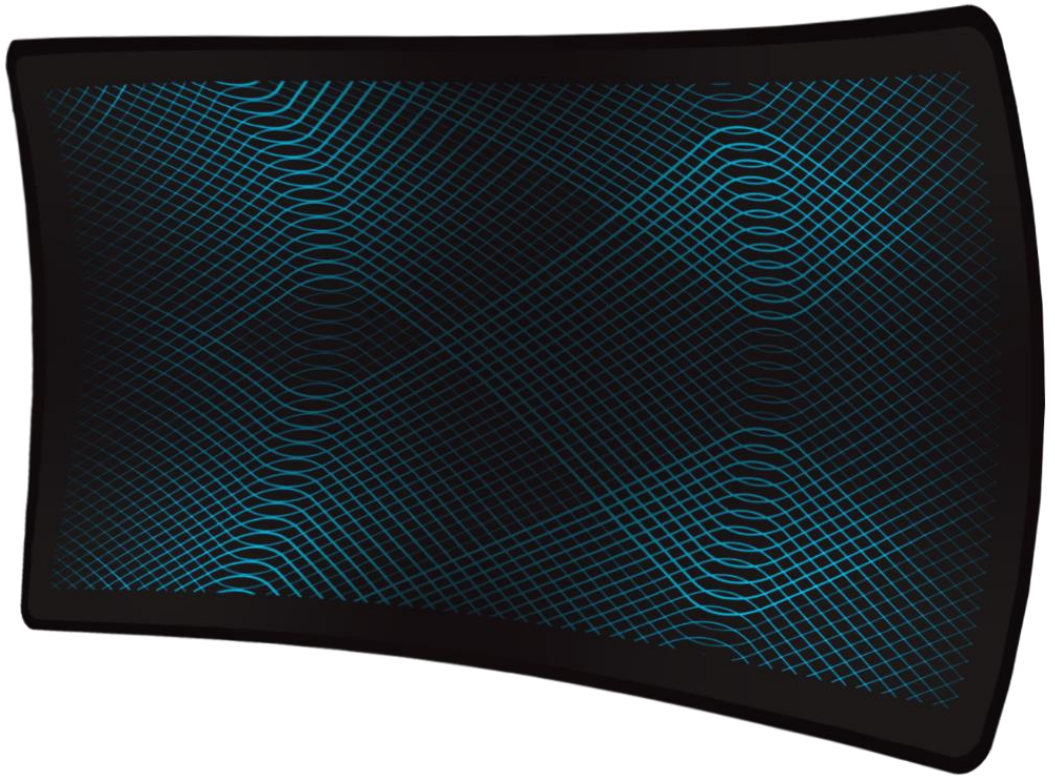
Measurement

3

Curved Glass

Successful measurement depends on:

- **Depth of Field (DOF):** Range of depths where the imaging system can capture objects in a single image as equally in-focus
- **System Calibration:** Ability of measurement system to measure multiple areas with different output

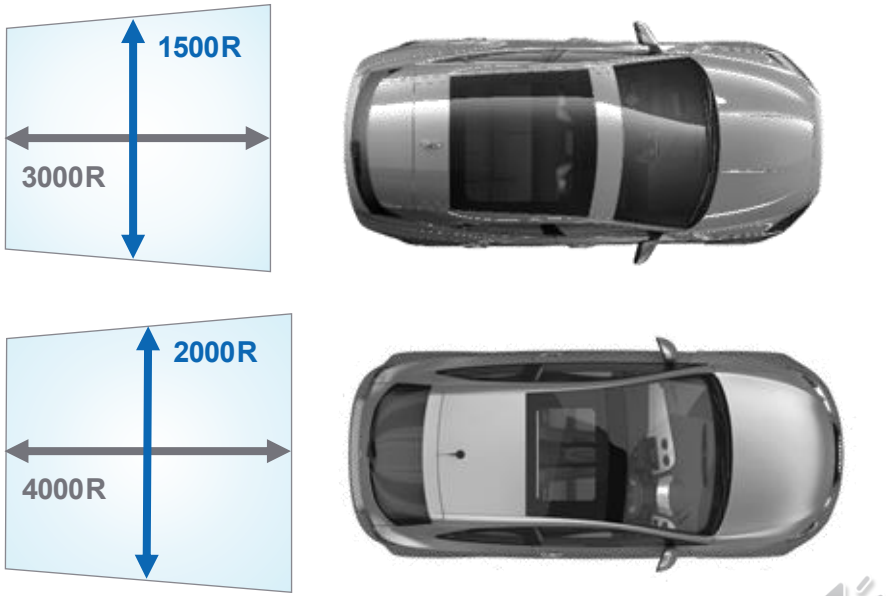


Depth of Field (DOF)

- Requires a combination of high resolution & high DOF

Required for imaging:
- f/13+
- Or, f/8+ & high-res

Pixel defects captured in an image of a 1500R curved display from 0,0 perpendicular position (poor resolution/DOF applied)



Example curvature of average sunroofs

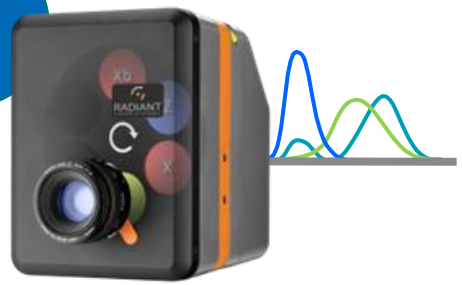
System Calibration

- Need to calibrate to accurately measure multiple areas with different output

Example angular dependency of light per channels due to glass curvature

1 Acquire Spectrum with Spectrometer

2 Calibrate Imager



3 Capture Image for Measurement

Technology Advancements for Sunroof Inspection

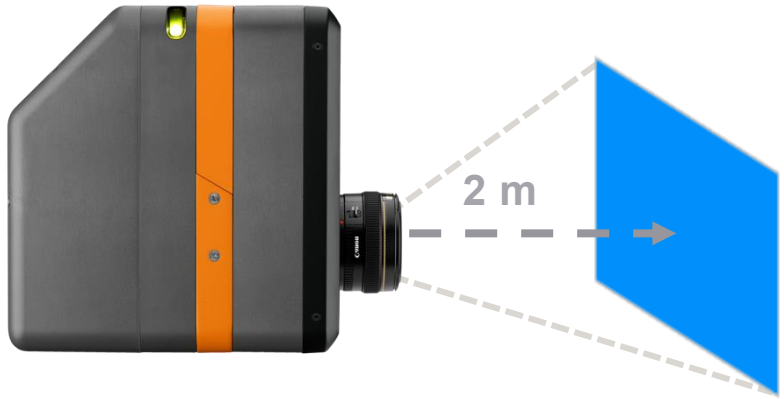
Optimizing Measurement System Specifications and Methods

Pixels/mm for Various Test Systems

Sensor resolution	Sunroof panel (mm)	Applied sensor pixels	Pixels per mm
12 MP (a)	1200 x 900	3784 x 2838	**3.15**
12 MP (b)	1200 x 900	4010 x 3008	**3.34**
30 MP	1200 x 900	5460 x 4095	**4.55**

Required for detail: **7-10 pixels/mm**

Required for 2 m distance: **33 x 25°**



Radiant ProMetric I61 Imaging Colorimeter

Resolution: 61 MP

FOV: 40 x 28° *(50 mm lens)*

Depth of Field

Radiant ProMetric I61 / Y61 Imaging Systems

Factory calibrated apertures:

Standard: f/2.8, f/3.3, f/4.7, f/8

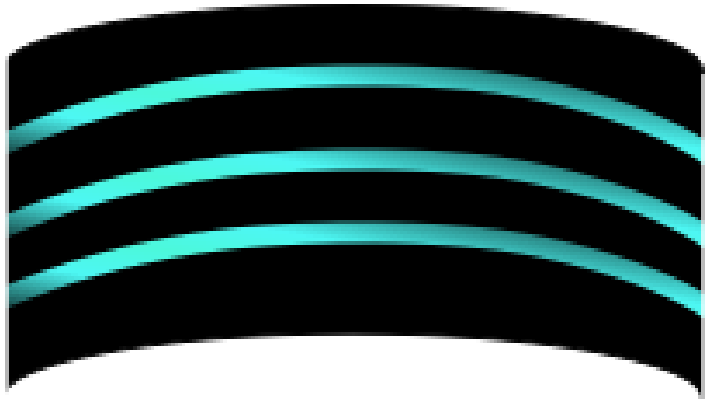
Applied: f/11, f/13, f/16, f/22

Required for imaging:

- **f/13+**
- **Or, f/8+ & high-res**

Example measurement setup; ProMetric I Imaging Colorimeter measuring curved glass from 0,0 perpendicular position.

Example channel variability



Radiant ProMetric I61-SC

Imaging colorimeter + integrated spectrometer

- Spatial (cd/m², CIE x,y) and spectral (CCT, CRI) data
- Capture, store, and apply color calibrations in-line

Other advantages:

Adaptive/smart calibration

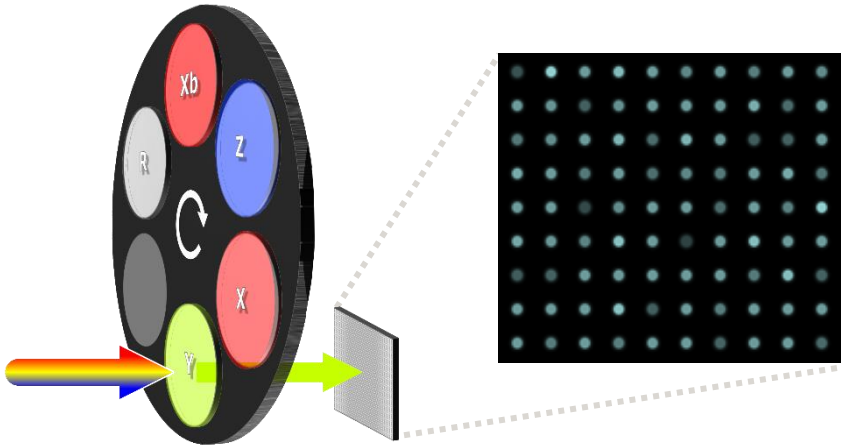
- Automatically apply a stored calibration based on unique signal received at each pixel
- System response is adjusted pixel by pixel across FOV

Multi-point calibration

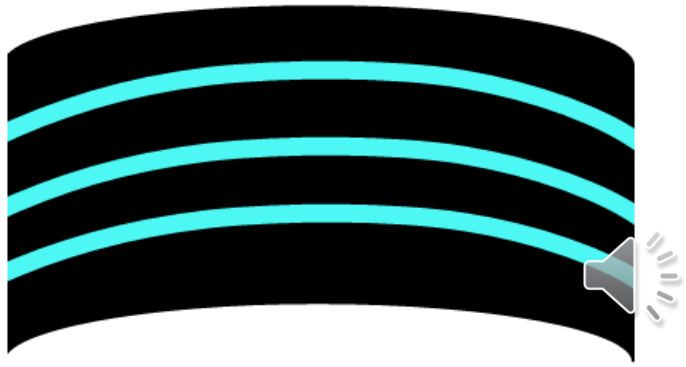
(US Patent No. 6,982,744)

- Apply regional scaling to calibrate out variations across FOV
- Characterizes falloff and adjusts measurement image as though no curvature is present

Example pixel calibration

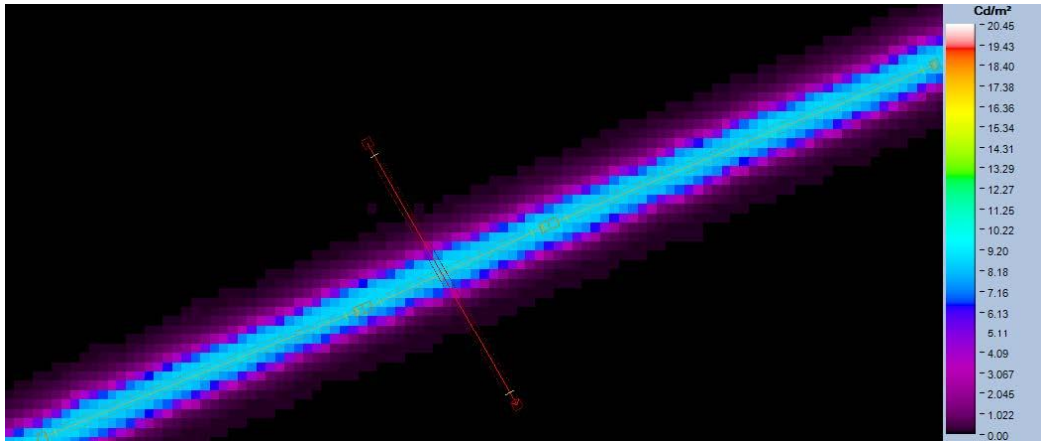


Example multi-point scaling

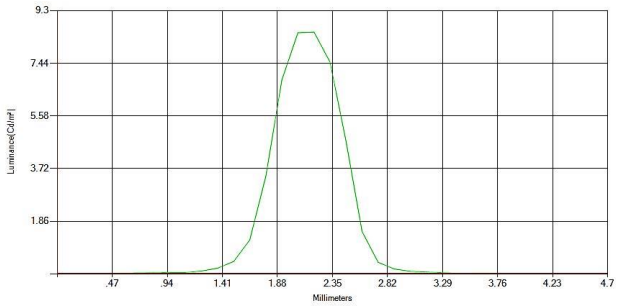


Registration Capability

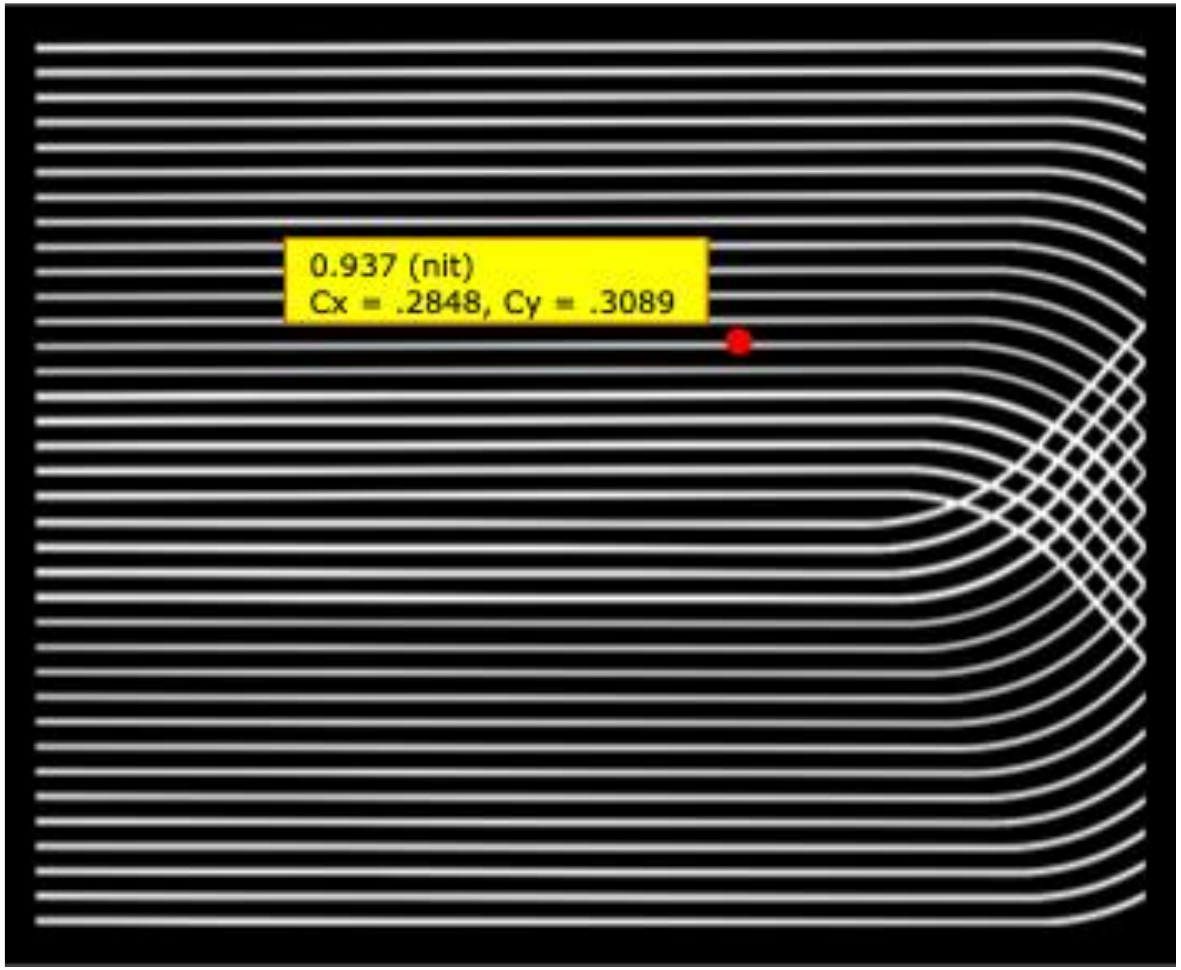
- **Must be adapted for each sunroof pattern**
- **Providers with experience can pull from existing algorithm libraries**
- **Existing algorithms can be refined to create custom software packages**
  - Channel count
  - Channel size
  - Pattern directionality
  - Curvature
  - Color states



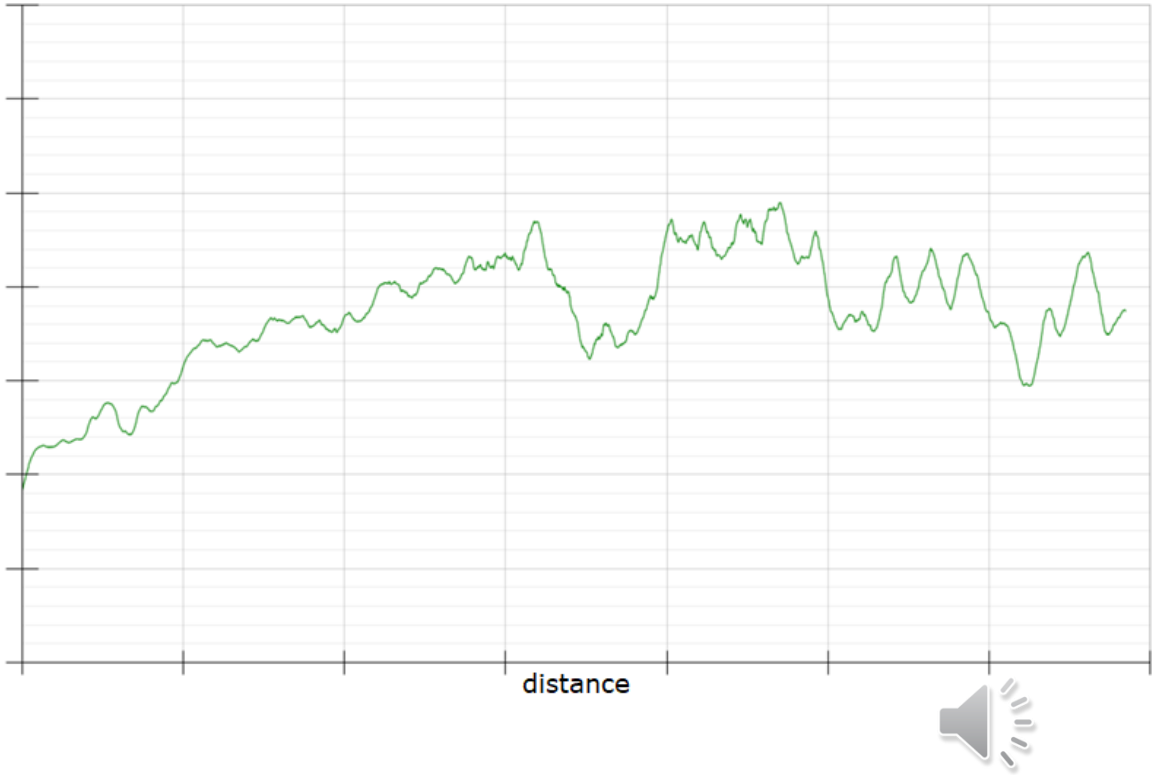
Measurement image applying custom algorithm to calculate center and thickness of a single channel



Plot of luminance at cross-section in above image



Single Line Histogram



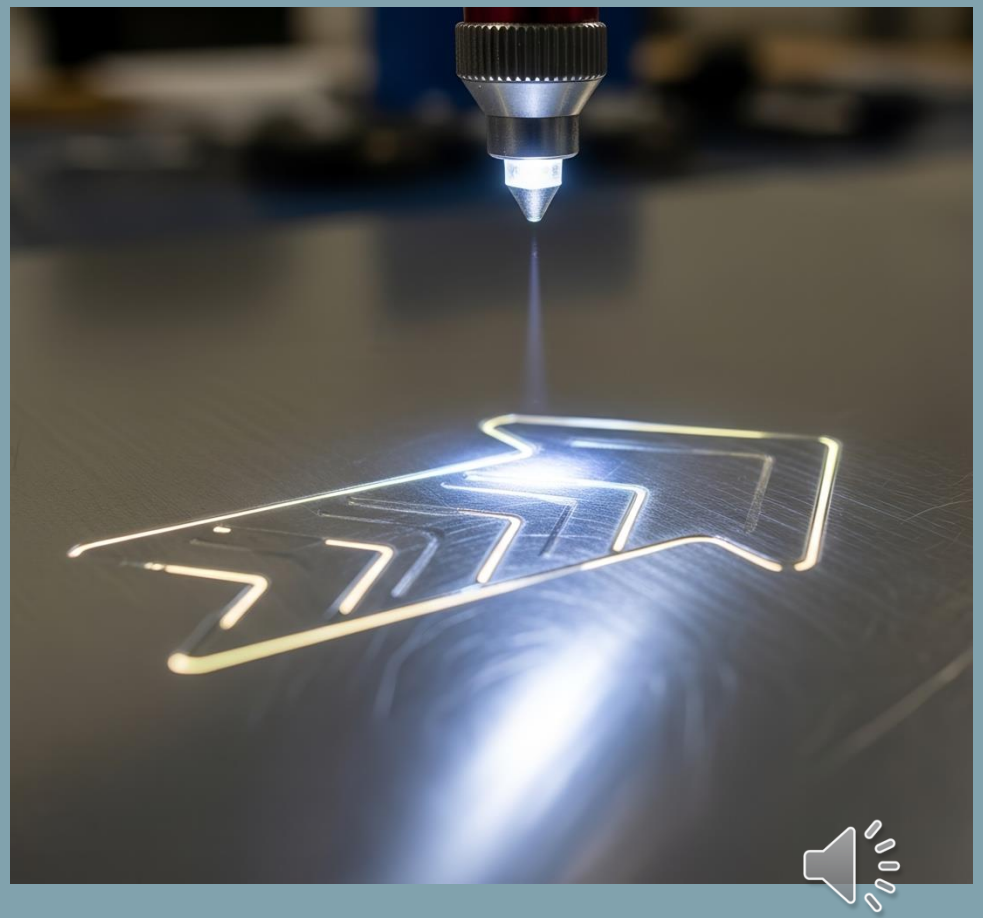
EXAMPLE
ETCHED EMBLEM

QUALITY CONSIDERATIONS

- Luminance, chromaticity
- Etch integrity (exclusions/inclusions, rotation, size)

MEASUREMENT CHALLENGES

- Registering unique shapes
- Relative positioning of measurement system – consistent application of registration region



MEASUREMENT SOLUTION

VIP™ (Vision Inspection Pack) Software

DYNAMIC REGISTRATION OF UNIQUE SHAPES AND SYMBOLS

- Easily train to register bespoke regions
- Registration region aligns regardless of symbol position, orientation, size (w/in FOV)

MEASUREMENT AND INSPECTION

- Luminance, chromaticity, uniformity
- Defects (exclusions/inclusions)

Software Customization

A knowledgeable solution provider can work with you to develop a custom software package and algorithms to:

- Determine image processing needs
- Establish calibration routines
- Collect and store calibration data
- Determine channel directionality
- Manage intersections
- Register unique channels
- Mitigate curvature

Measurement Solution

Imaging System	**Type**	Photometric/colorimetric
	Resolution	61MP+
	Lens	50mm+
	DOF	f/8+
	Integration	Imager/spectrometer
Software	**Processing**	Auto image scaling
	Registration	Custom-defined ROI
	Calibration	Smart; multi-point, etc.
Other	**Support**	Software customization
	Interfaces	Ethernet; API / SDK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Thank you!
Any Questions?


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