

## Windshield Wedge Angle and Layer Thickness Measurements

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### Introduction

In the February 2016 issue of Photonics Spectra, Heads-Up-Display Systems (HUD) for the automobile windshield were reviewed<sup>1</sup>. The focus of this article was on the image display unit and on the types of data and features which are displayed. The present article describes the types and layer structures involved in the construction of the windshield itself and the most common methods of getting ghost free images from automotive HUD displays<sup>2</sup>. This article then describes windshield metrology and more particularly methods to measure the thickness profiles of all of the layers of the windshield simultaneously. As described below, a small wedge angle has been found useful in minimizing ghosting in HUD displays. The metrology system described is also shown to be capable of determining the wedge angle as a function of location on the windshield with a high degree of accuracy as well as determining how much wedge is in each layer.

Presently, automotive windshields are constructed of laminated Safety Glass. In the laminating process two layers of glass are bonded together with one or more plastic interlayers. The most common plastic used for the laminated interlayer is Polyvinyl butyral (PVB). The lamination process is now required by law to be used in all windshields because it minimizes the chance of passengers being injured by the windshield during a collision. The plastic layers cushion the impact during an accident and prevents the windshield glass from separating into shards as a result of an object hitting the windshield, thus reducing the severity of lacerations and other hazards as a result of an automobile accident.

Today, consumers demand quality from every automotive purchase so that windshield manufacturers, vehicle designers and carmakers are being driven to improve safety, aerodynamic and fuel efficiency, driving comfort, electronics connectivity and aesthetics. In practice this means introduction of increasing windshield sizes, reduced thickness to gain component weight loss for improved fuel efficiency, decreasing installation angles, as well as complex windshield surface geometries, coatings for reduced UV and Infrared (IR) radiation and acoustic interlayers for sound insulation. Many windshields today include interlayers composed of multilayer plastics. When acoustic interlayers are used the acoustic absorbing layer is usually sandwiched between a pair of PVB layers. Many windshields today also include coatings for de-icing and demisting, have built-in heaters, integrated antennas for radio, TV, cell phone, navigation etc. integrated rain sensors for automatic wiper activation, as well as other sensors, such as forward obstacle detection, and hydrophobic coatings for improved visibility. Recently, automotive windshields, which are specifically designed for use with Heads-Up-Displays (HUD) to provide ghost free images, are becoming more and more prevalent.

## **HUD Systems and the standard windshield ghosting problem**

At the present time HUD systems in automobiles are becoming more and more popular. The driving forces include improvements in projector technology, the increased use of on-board navigation systems and the many emerging driver assist systems, including forward crash avoidance. A HUD system projects a virtual image at a comfortable viewing distance in front of the driver. A projector located in the dashboard projects the image which, when reflected on the windshield, appears like a virtual image on top of the hood of the car. A typical automobile HUD unit is located on the top of the dashboard on the driver's side of the car. The HUD display unit includes an image light source with a display and usually includes one or more curved mirrors designed to project an image onto the windshield. The image reflects off of the windshield enabling the driver to see a virtual image floating in space just above the steering wheel at a perceived distance of about 2.0 – 2.5 meters in front of the driver. The image is typically about 100 mm x 200 mm in lateral dimensions and may be in full color. The HUD projector can display important information to the driver including vehicle speed, warning signals from the engine management system, fuel gauge and tire pressure readings, navigation system information and can highlight impending road obstacles or lane edges when traveling around sharp curves in the road. The HUD system allows drivers to stay focused on the road instead of glancing at the instrument panel or navigation system to obtain this information. The focal position of the HUD image is designed to be equal to that of the roadway in front of the vehicle so that the driver does not need to refocus his or her eyes to view the HUD information.

If a conventional non-HUD windshield is used the viewer observes two separated images, the virtual image from the inner surface of the windshield closest to the driver and another virtual (ghost) image reflected from the outer surface of the windshield. In order to eliminate this ghosting effect, the angular separation between the two images must be less than the angular resolution of the human eye, which is typically in the range of  $0.013^\circ$  –  $0.020^\circ$ . Figure 1 shows the reflection geometry from a HUD display for a conventional 3 layer windshield and demonstrates the ghosting problem.

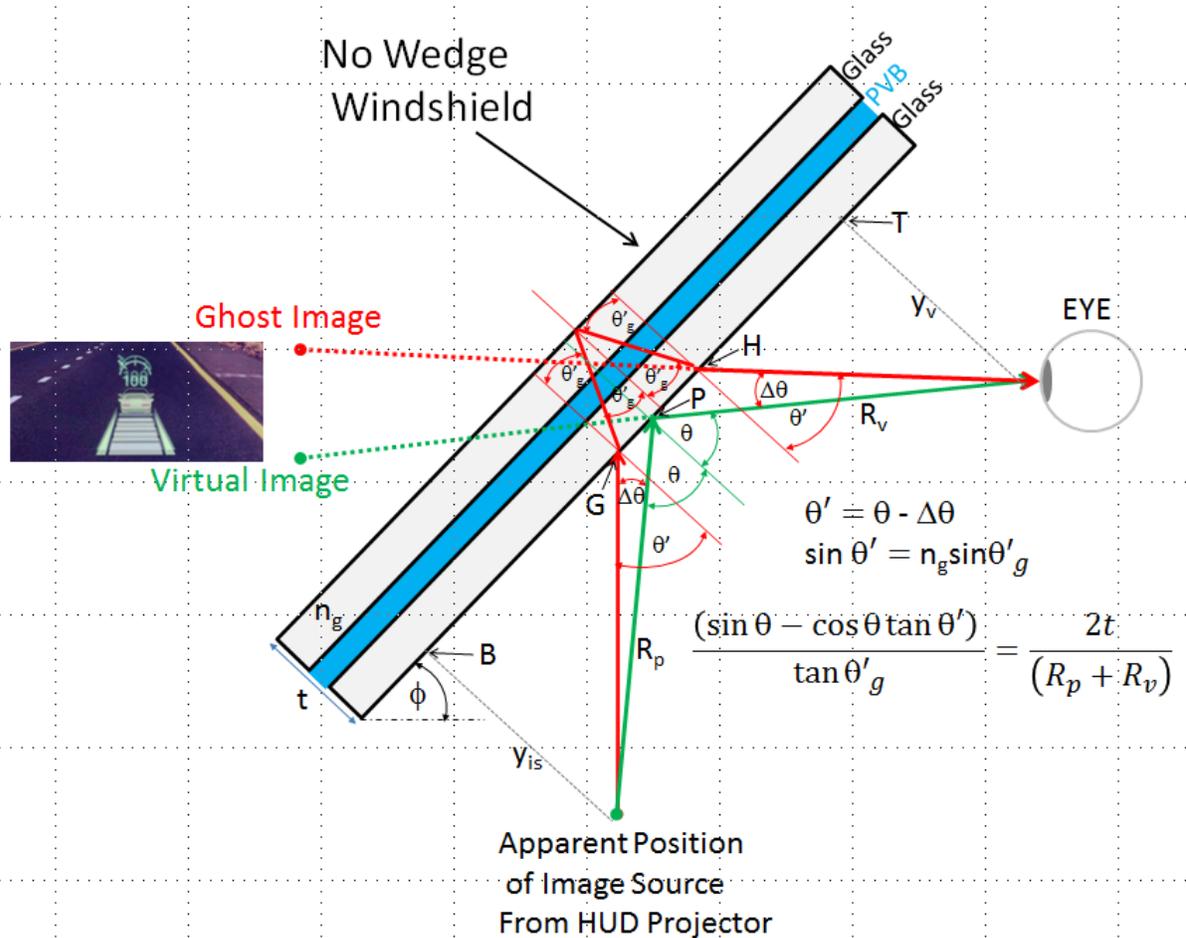


Figure 1. Schematic of a HUD windshield showing ghost image formation in a standard windshield.

The image source of the HUD projector sends out multiple rays of light at different angles from a common image source point. The green ray labeled  $R_p$  shows the path of the central ray from the image source point to point  $P$  on the inner surface of the windshield where it is reflected as the green ray labeled  $R_v$  which is incident on the center of the lens of the viewer's eye. Ray  $R_p$  is incident on the windshield at an angle  $\theta$  with respect to the normal to the surface as is reflected at the same angle  $\theta$  into the center of the viewer's eye. The ray  $R_v$  entering the viewer's eye creates a virtual image of the image source along the same line at an apparent location of the image source. The path of the virtual image is shown by the dashed green line and the solid green dot shows the apparent location of the image source.

Another (ghost) image is formed when the light from HUD reaches the inner surface of the windshield, refracts on that surface, travels through the bulk of the windshield and reflects back at the outer surface of the windshield. As seen in Figure 1, the relationship between the incident angles for the red ( $\theta'$ ) and green ( $\theta$ ) rays is

$$\theta' = \theta - \Delta\theta \quad [1]$$

where  $\Delta\theta$  is the angular separation between the two virtual images. The refracted angle inside the windshield is shown as  $\theta'_g$  with respect to the normal and is calculated using Snell's law by the relationship

$$\sin\theta' = n_g \sin\theta'_g \quad [2]$$

where  $n_g$  is the refractive index of the glass. Another equation is given from the fact that the geometric projection for the green ray onto the windshield surface (BP + PT) is equal to the geometric projection of the red ray (BG +GH +HT):

$$\frac{(\sin\theta - \cos\theta \tan\theta')}{\tan\theta'_g} = \frac{2t}{(R_p + R_v)} \quad [3]$$

where  $t$  is the thickness of the windshield. Typically, the glass layers are each about 2 mm thick with an index of 1.518 and the PVB layer is about 0.7 – 1.0 mm thick and has an index of refraction of about 1.485. Here for simplicity we assume that the inner PVB layer has the same refractive index as the glass. Equations 2 and 3 can then be solved for  $\theta'$  and  $\theta'_g$ , and  $\Delta\theta$  can be calculated from equation 1 as a function of angle  $\theta$ .

As an example, consider the case where  $R_p = 2000\text{mm}$ ,  $R_v = 750\text{ mm}$ ,  $t = 4.9\text{ mm}$ ,  $\theta = 65^\circ$  and  $n_g = 1.518$ . The result is  $\Delta\theta = 0.0643^\circ$ , which is approximately 4 times larger than the angular resolution of the eye. The virtual images at a distance of 2 m in front of the windshield are therefore separated by about 3 mm in vertical direction. The image on the left side of Figure 1 demonstrates the resulting blurry image.

For a conventional flat windshield, the angular separation between images increases with increasing windshield thickness  $t$ , increasing refractive index of the glass, decreasing viewer to windshield distance  $R_v$  or decreasing image source to windshield distance  $R_p$ .

### **Use of wedge to eliminate the ghosting problem**

The ghosting problem in automotive HUD displays can be greatly reduced by the addition of a small wedge angle  $\alpha$  between the inner and outer layers of the glass. It is typically achieved by changing the thickness of the PVB interlayer as shown in Figure 2. As in the case of Figure 1, the green ray path of Figure 2 shows the path for one virtual image created via reflection of the inner surface of the windshield, and the red ray represents the path of the other virtual (ghost) image created via reflection of the outer surface of the windshield. The presence of the small wedge angle  $\alpha$  enables the two rays to coincide on the path to the driver's eye and therefore eliminate the image ghosting.

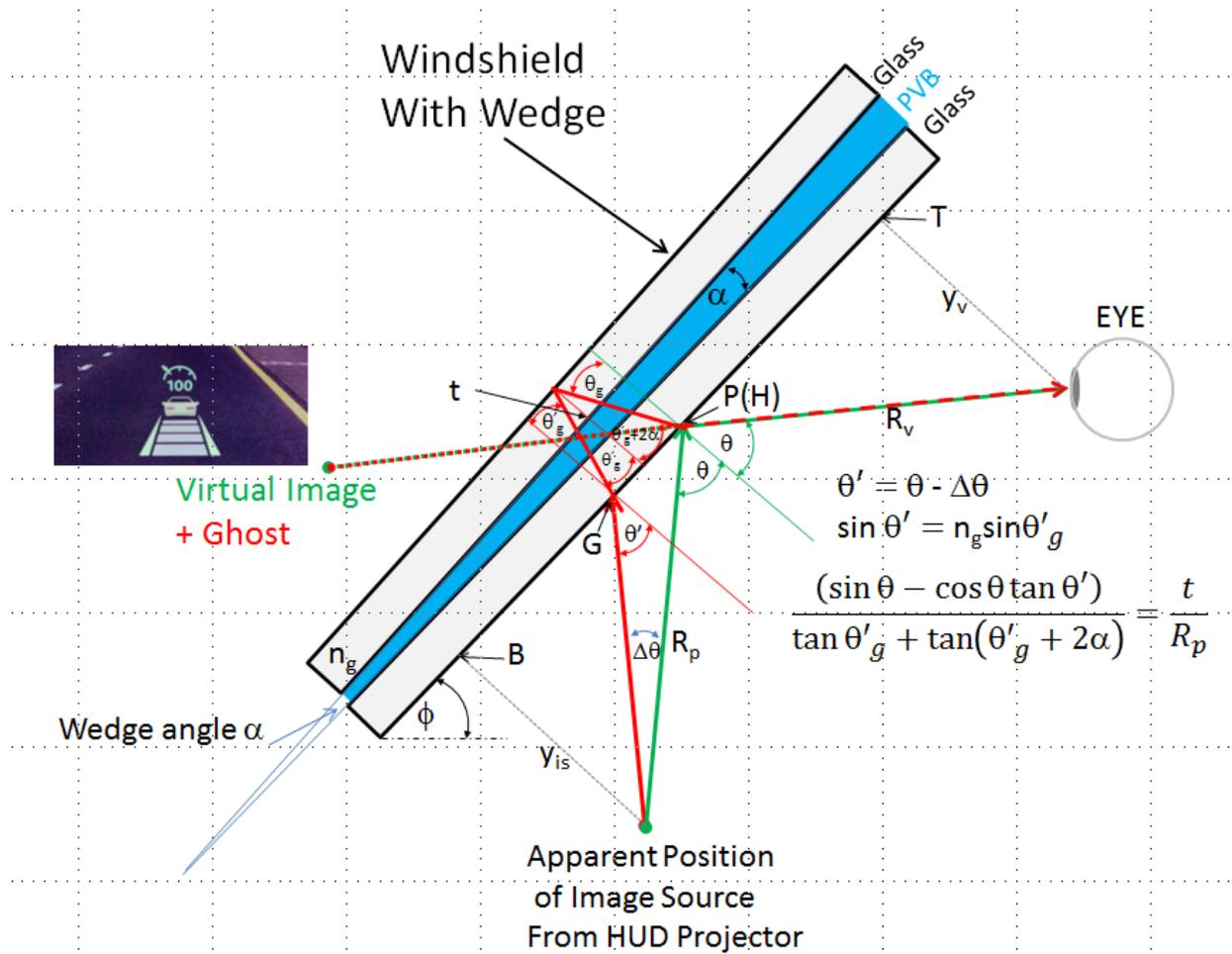


Figure 2. Schematic of a HUD windshield with a wedged windshield showing elimination of the ghost image

In this case, equation (3) becomes

$$\frac{(\sin \theta - \cos \theta \tan \theta')}{\tan \theta'_g + \tan(\theta'_g + 2\alpha)} = \frac{t}{R_p} \quad [4]$$

where  $\alpha$  is the wedge angle and  $t$  is the thickness of the glass at the location of viewing as shown in Figure 2. Equations 2 and 4 form a system that can be solved to find  $\theta'$  and wedge angle  $\alpha$ .

For example, when  $R_p = 2000\text{mm}$ ,  $R_v = 750\text{ mm}$ ,  $t = 4.9\text{ mm}$ ,  $\theta = 65^\circ$  and  $n_g = 1.518$ , the best fit wedge angle is  $0.013^\circ$  for  $\Delta\theta = 0.089^\circ$ . The separation between the two images is therefore below the resolution of the eye, and driver observes a sharp image.

It is important to note, that HUD systems are designed for a nominal driver height and eye distance from the windshield. However, shorter and taller drivers will often experience less than optimal HUD clarity since the wedge angle is not optimized for their viewing conditions.

Most automotive windshields are not simple planar flat structures but usually include slight curvatures in both the horizontal and vertical dimensions. The curvature is usually concave facing the driver. In a curved conventional non-wedged windshield the curvature can help reduce the ghost image separation  $\Delta\theta$ . Having a wedge in a curved windshield increases the range of driver heights that will be able to observe a nearly optimal HUD clarity<sup>2</sup>. In order to obtain optimal viewing conditions for a complete range of driver heights, the wedge angle should be varied as a function of windshield height<sup>3</sup>. For most current automotive windshield designs the optimal wedge angle should thus decrease with the distance from the bottom of the windshield.

Most HUD projectors use only a fraction of the whole windshield to reflect the image. Therefore, the wedge angle is only required in that region of the windshield. Such partially wedged windshields are now becoming popular.

Manufacturers of wedge interlayer films or windshields with such films, include Asahi Glass Company (AGC), Dupont, Eastman Chemical Company, Fuyao Glass Industries Group, Kuraray, Saint-Gobain Sekurit, and Sekisui Chemical Company. Products including partial wedges in the lower part of the windshield include Dupont™ SentryGlas® Wedge, Eastman Chemical Saflex® Q Series HUD interlayer film, and Kuraray Butacite® The Wedge™ interlayer film. Recently Eastman Chemical has begun offering Saflex® VIEW film which can be made with a variable wedge angle for any specific automobile model. Sekisui S-LEC™ S-LEC™ Sound and Solar Film - W combines a wedged shape interlayer film with acoustic and solar absorbing interlayers.

### **Windshield Wedge Angle and Layer Thickness Measurement Technology**

We have performed simultaneous measurements of the thickness of all layers in various automotive windshields as a function of position, using the commercially available dual low-coherence all-fiber optic interferometer (OptiGauge® II by Lumetrics, Inc). The total thickness of all the layers and the local wedge angle can then be calculated as a function of position.

Optigauge® II measurement technology is based on time-domain low-coherence interferometry (Figure 3). The top part of Figure 3 shows a schematic of a Michelson interferometer, where a beam-splitter plate separates the light from a low-coherent light source into two beams, travelling along reference path A and sample path B. A scanning mirror is located at the far end of reference path A, which reflects light back towards the beam splitter. During operation, the mirror is scanned along the z axis to change the path length B in a controlled cycle. The sample is located at the far end of path B. A portion of the light in path B is reflected back from each optical interface in the sample and travels back to the beam splitter. Light reflected back from the reference mirror and from the sample are then combined by the beam splitter and directed to the detector. The detector registers interference between these two beams.

For a low-coherence (also known as short-coherence) light source, the interference occurs when the path lengths of the two arms in the interferometer are equal to within a few coherence lengths  $l_c$  of the light source. The example of the interference signal from the detector is shown at the bottom right part of Figure 3. When sample contains several reflecting surfaces, the interference occurs at several locations of the reference mirror, where the reference path B is equal to the path distance A to the corresponding reflecting surface of the sample. The distance between such adjacent locations of the reference mirror is equal to the optical thickness between the corresponding reflecting surfaces of the sample. Optical distance is defined as the group refractive index multiplied by the physical thickness of the sample material. The Optigaugé® II instrument uses a 1310 nm center wavelength superluminescent light emitting diode (SLED) with a coherence length of  $\sim 15 \mu\text{m}$ . If the sample contains a layer of air, the measured distance between these surfaces is approximately equal to the physical thickness of the layer since the index of refraction of air is very close to 1 (for 1310nm,  $n = 1.0002684$  at room temperature).

The paths in the interferometer inside the Optigaugé® II are completely enclosed into optical fiber. The distance to the reference mirror is modulated by stretching the fiber. The instrument also contains a laser interferometer which precisely measures the changes in the path lengths. Further details concerning operation and performance of the instrument are found in the references<sup>4-5</sup>.

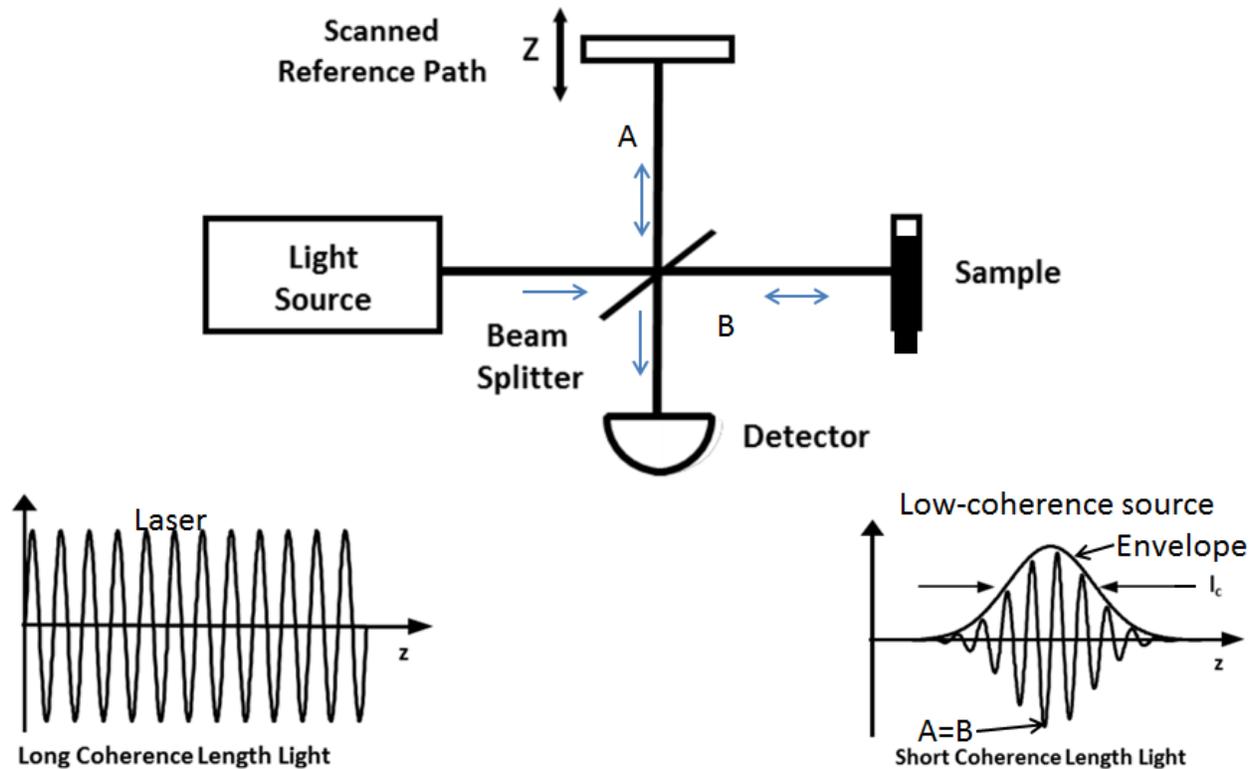


Figure 3. Schematic of a Michelson interferometer (Top) and resulting interferograms for coherent light (bottom left) and low-coherence light (bottom right)

Figure 4 shows the OptiGauge II, a laptop computer and a bench-top optical probe stand. Optical probes focus the light onto a sample, and collect the reflected light, and can be designed to have different working distances and angular tolerances. Probes are small and light, so that they can be readily installed on scanning frames to scan over a line or an area, as shown in Figure 5A. Figure 5B shows a hand-held probe which is attached to a hand-held fixture for measuring non-flat surfaces, such as windshields. Such fixture was used to obtain measurements for this paper.



Figure 4. The Optigauge® II instrument along with a laptop computer for displaying and storing data on its left and a benchtop optical probe with stand on its right

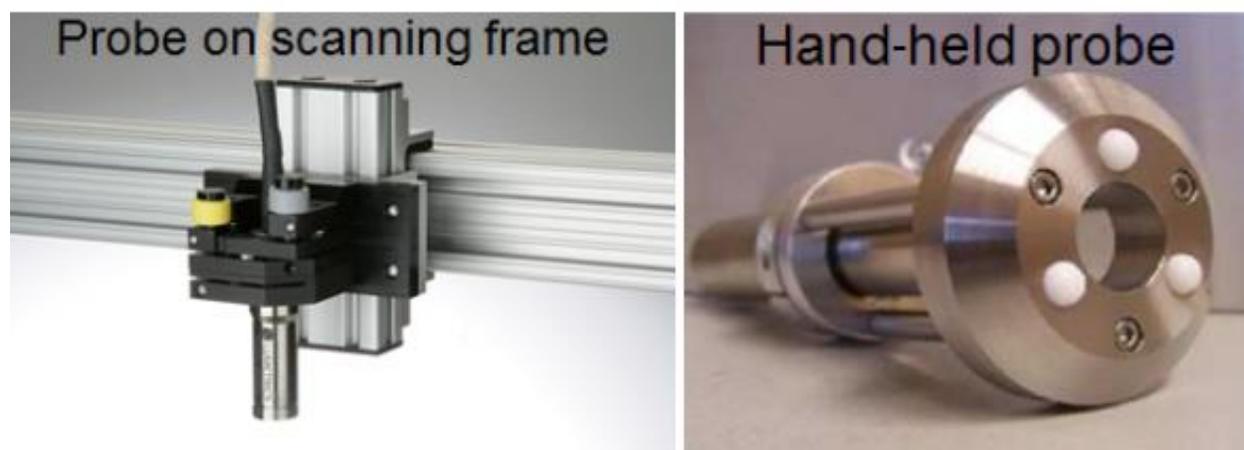


Figure 5. Optical probe examples: A) probe on scanning frame, B) Hand-held fixture

Figure 6A shows how the hand-held fixture is used to measure the windshield of a 2007 Chevrolet Corvette, equipped with a factory installed HUD system. The yellow line is the optical fiber cable that connects the probe to the OptiGauge. One of the advantages of the Optigauge II is that this fiber cable can be of any length up to ~ 2 km.

Figure 6B shows the thickness profile of each layer within the windshield. During the measurement, the probe is moved at an approximately constant velocity for the bottom to the top of the windshield, therefore the distance scale in the graph is approximate. The change in the thickness of the PVB layer indicates presence of the wedge as required by HUD.

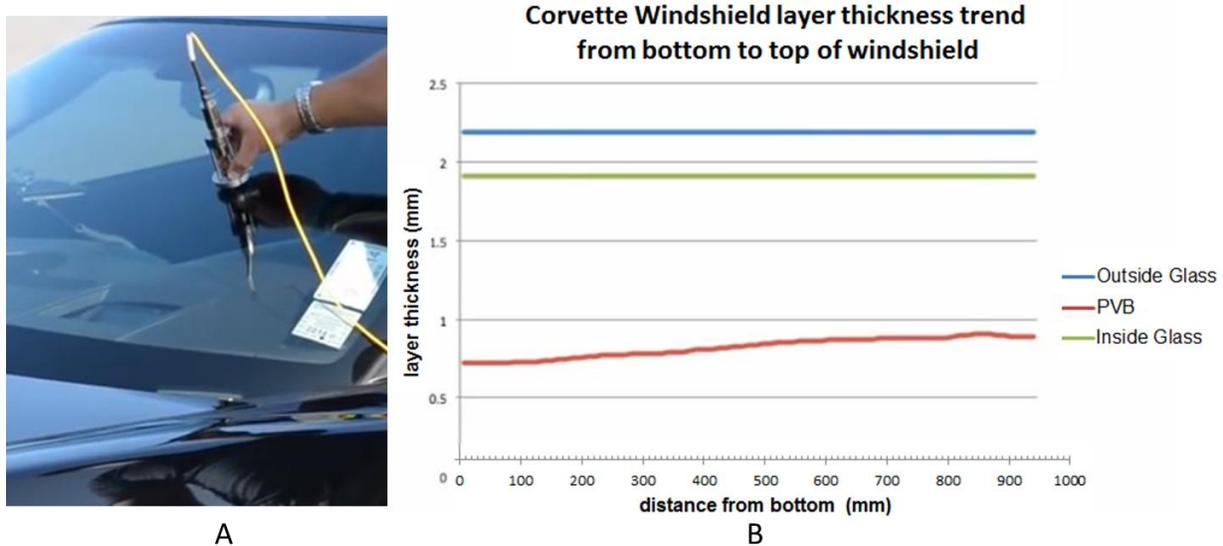


Figure 6. A: Image of a 2007 Corvette with a windshield scan in progress using a hand-held probe. B: Thickness profile of each layer as a function of distance from the bottom of the windshield. Notice the change in PVB layer thickness as the probe moves in the vertical direction.

Figures 7A and 8A show graphs with the processed interferometric scan from OptiGauge II, obtained at a single location of a windshield. The horizontal axis corresponds to the travel of the reference mirror of the interferometer. The peaks in the signal correspond to the interferometric signal registered by the detector, where the path length to the reference mirror is equal to the path length to the corresponding interfaces within the sample. The signal has been demodulated and compressed before it is plotted. The distance between the adjacent peaks is equal to the optical thickness of the corresponding layer. Figure 7A shows signals for a 3-layer windshield, while Figure 8A corresponds to a 5-layer windshield. The 5-layer windshield contains an acoustic layer and an additional PVB layer, as compared to the 3-layer windshield.

Figures 7B and 8B schematically visualize the cross-section of the windshield layers and show corresponding refractive indices. The interfaces are numbered, with the number 1 interface corresponding to the left-most signal peak on the interferometric graphs. Interface 4 on Figure 7B corresponds to the right-most signal peak on Figure 7A. Similarly, peak 6 corresponds to the right-most signal peak on Figure 8A.

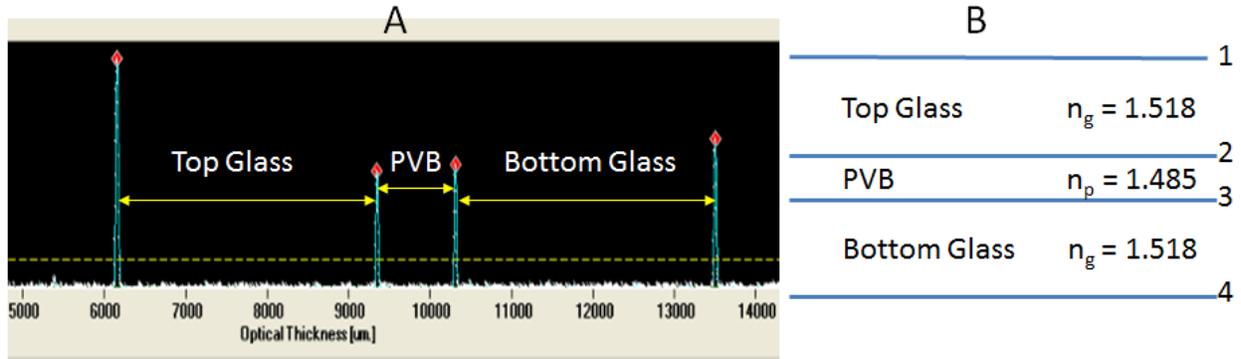


Figure 7. A: Interferometric signal obtained for a 5-layer laminated windshield. B: Schematic of the layer structure of the windshield.

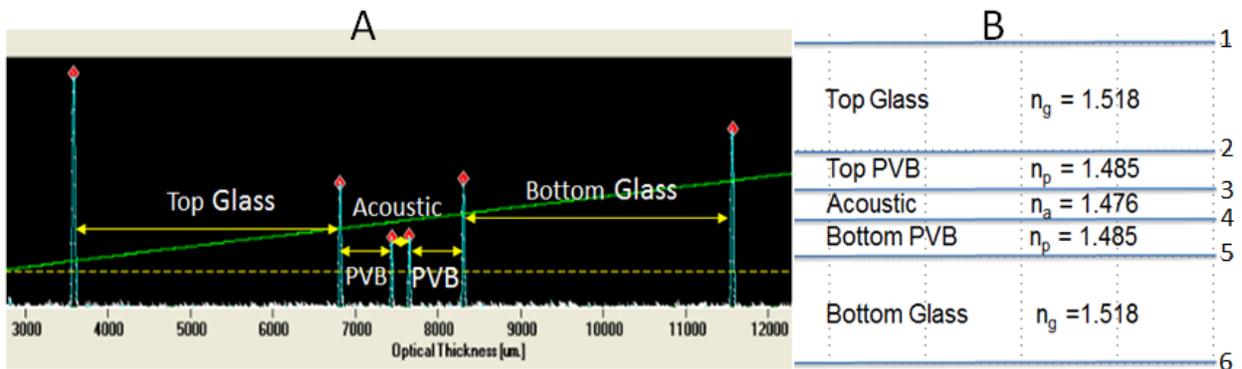


Figure 8. A: Interferometric signal obtained for a 5-layer laminated windshield. B: Schematic of the layer structure of the windshield.

Tables 1 and 2 show statistical analysis of the windshield measurements. We have acquired 100 thickness measurements at the same location. Each measurement is a 3-second average (corresponding to 150 scans of the interferometer). Physical thickness is calculated using the refractive indices of each layer shown in Figures 8 and 9. Tables include the layer number, layer ID, refractive index, mean thickness and the standard deviation.

Table 1. Statistics for 100 repeat measurements of a 3-layer windshield acquired at the same location.

Layer #	layer ID	n	thickness ( $\mu\text{m}$ )	stdev ( $\mu\text{m}$ )
1	Top Glass	1.518	2103.60	0.010
2	PVB	1.485	647.52	0.014
3	Bottom Glass	1.518	2101.67	0.010

Table 2. Statistics for 100 repeat measurements of a 5-layer windshield acquired at the same location.

Layer #	layer ID	n	thickness ( $\mu\text{m}$ )	stdev ( $\mu\text{m}$ )
1	Top Glass	1.518	2125.89	0.011

2	Top PVB	1.485	420.53	0.036
3	Acoustic	1.476	144.78	0.050
4	Bottom PVB	1.485	440.46	0.036
5	Bottom Glass	1.518	2145.22	0.013

Figure 9 depicts a cross-section of a 5-layer wedged windshield. The cross-section is assembled by measuring thicknesses of all layers while manually scanning the hand-held probe fixture along the windshield. Curves I1-I6 correspond to the surfaces 1-6 shown in Figure 8B. The bottom surface I6 is used as a flat reference surface. The location of each successive optical interface is obtained by adding thicknesses of the layers between that surface and surface I6. The curve for interface I1 is therefore equivalent to plotting total thickness of the windshield. The scan was conducted in 13.3 seconds and the probe fixture was moved at an approximately constant velocity of 58.5 mm/s.

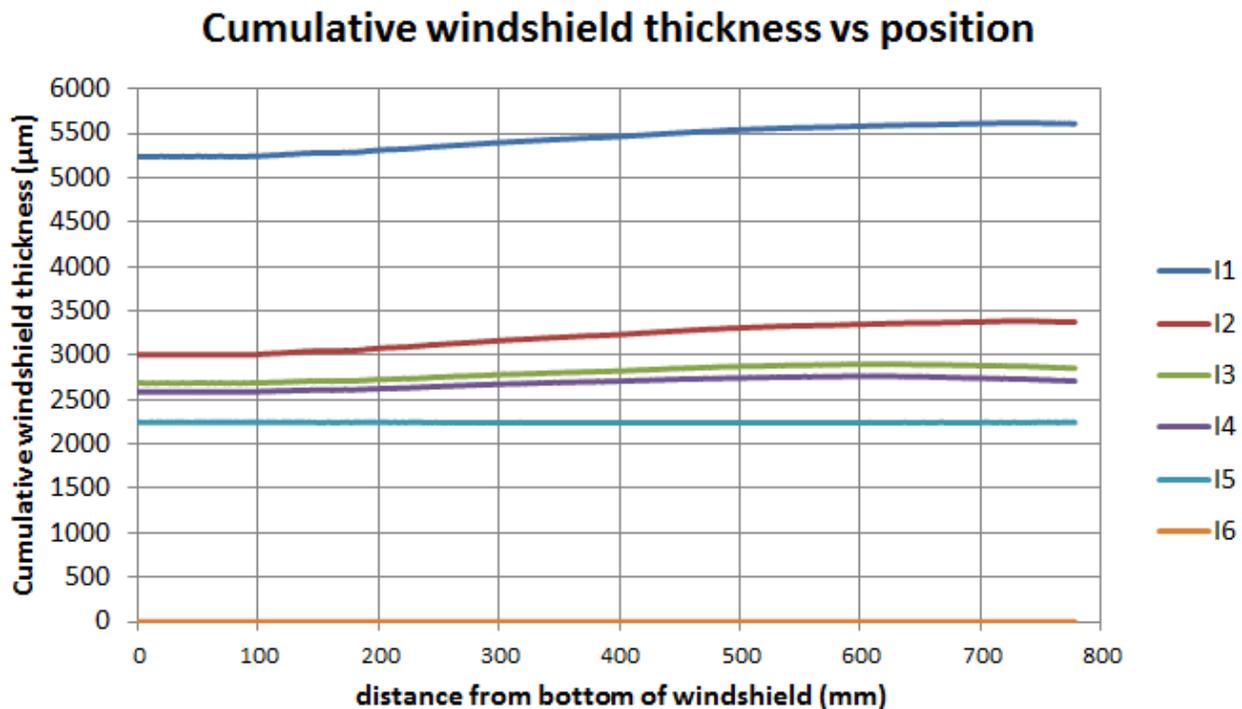


Figure 9. Cumulative thickness map of a hand-held probe scan line from bottom to top of a 5-layer windshield.

Figure 10 shows thickness scans of the individual layers in the same 5-layer windshield shown in Figure 9 as a function of distance from the bottom of the windshield. Note that the figure uses two different vertical scales. The scale on the left is used for the thicknesses of the top and bottom glass layers. The scale to the right is used for the thicknesses of the top and bottom PVB layers, the acoustic interlayer and the sum of the PVB +acoustic layers.

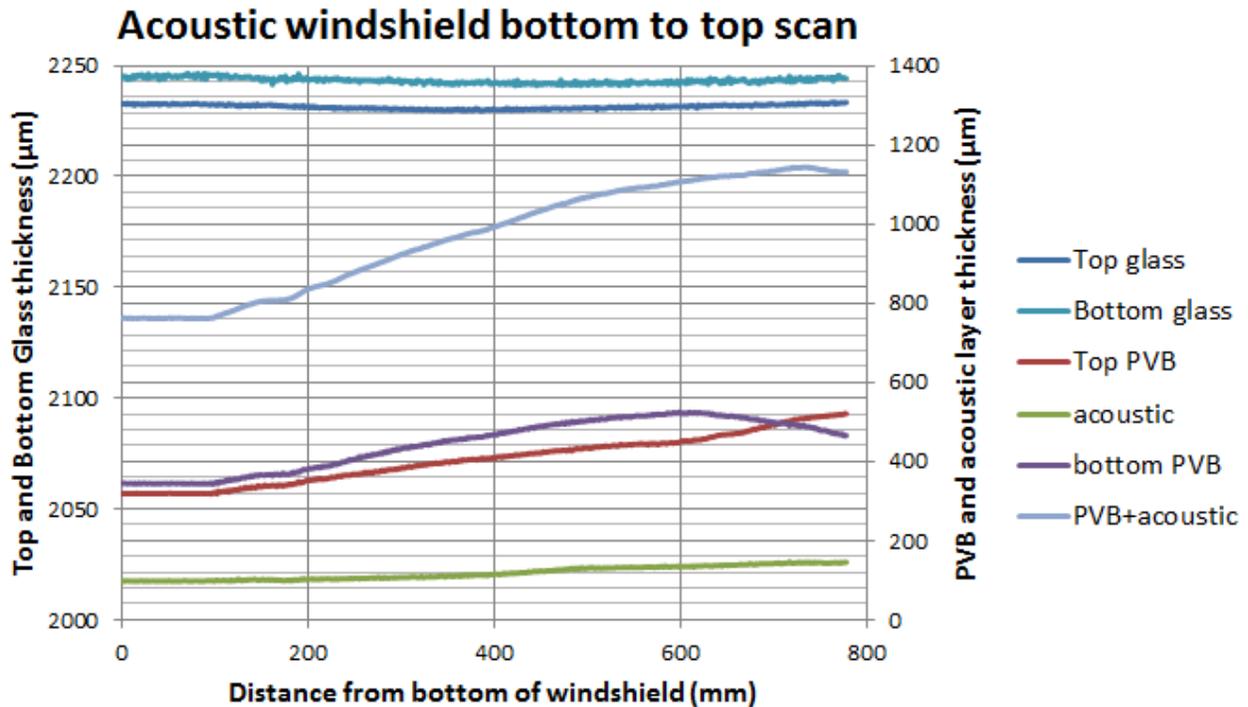


Figure 10. Layer thicknesses for the acoustic windshield shown in Figure 9.

Figure 11 shows layer thickness distribution of the same 5-layer windshield, but over a smaller portion of the windshield, located between 225 and 525 mm from the bottom edge, where thickness changes in the inner PVB and acoustic layers change linearly. This region of the windshield encompasses the viewing location of the HUD image for the nominal driver. During measurement the probe fixture was moved at a rate of 5 mm/s, resulting in 0.1mm spacing between successive data points.

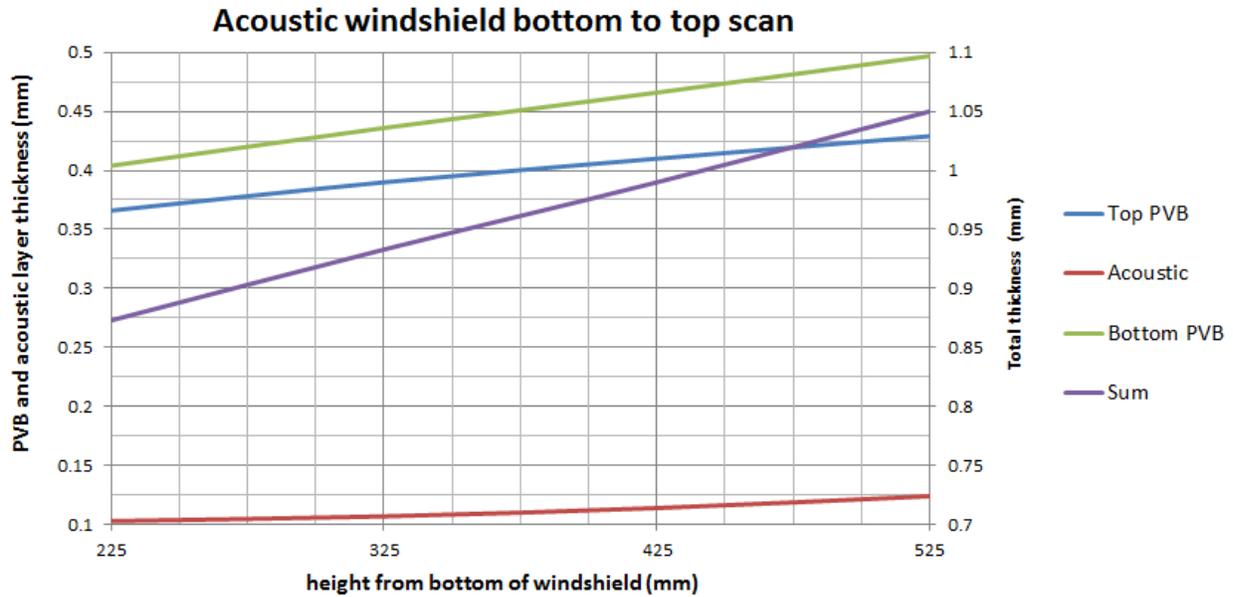


Figure 11. Acoustic windshield quantitative partial scan of wedged layers and their total thickness as a function of height from the bottom of the windshield.

Table 3 shows the statistics for the top and bottom glass layers and the calculated wedge angle for the acoustic windshield described above over the scan region from 225 to 525 mm from the bottom of the windshield. Notice that the glass layers in windshields used for HUD displays have extremely tight tolerances on thickness uniformity. The wedge angle of the combined acoustic and PVB layer is  $0.588 \pm 0.011 \text{ mrad}$  (or  $0.0337^\circ \pm 0.0006^\circ$ ) for this windshield. The wedge angle was calculated from the best fit slope to the line from all of the data points, and the standard deviation was found from the local slopes using sets of five adjacent measurement points.

Table 3. Glass layer thickness and wedge angle statistics for the 225 – 525 mm region from the bottom of the 5- layer acoustic windshield described above.

units	Top glass thickness	Bottom glass thickness	Wedge angle	
	( $\mu\text{m}$ )	( $\mu\text{m}$ )	(mrad)	(deg)
mean	2230.468	2242.465	0.588	0.0337
stdev	0.371	0.751	0.011	0.0006
max	2231.450	2244.480	0.600	0.0344
min	2229.66	2241.01	0.570	0.0327
range	1.79	3.47	0.030	0.0017

Figure 12 shows the measured thicknesses of all of the individual layers along the scan line as a function of a scan distance for a wedged section piece of another acoustic windshield. The wedge sample is a ~160 mm square piece of a HUD windshield which encompasses the nominal viewing region. The data was obtained with a spacing of 1 mm between adjacent data points along the scan direction.

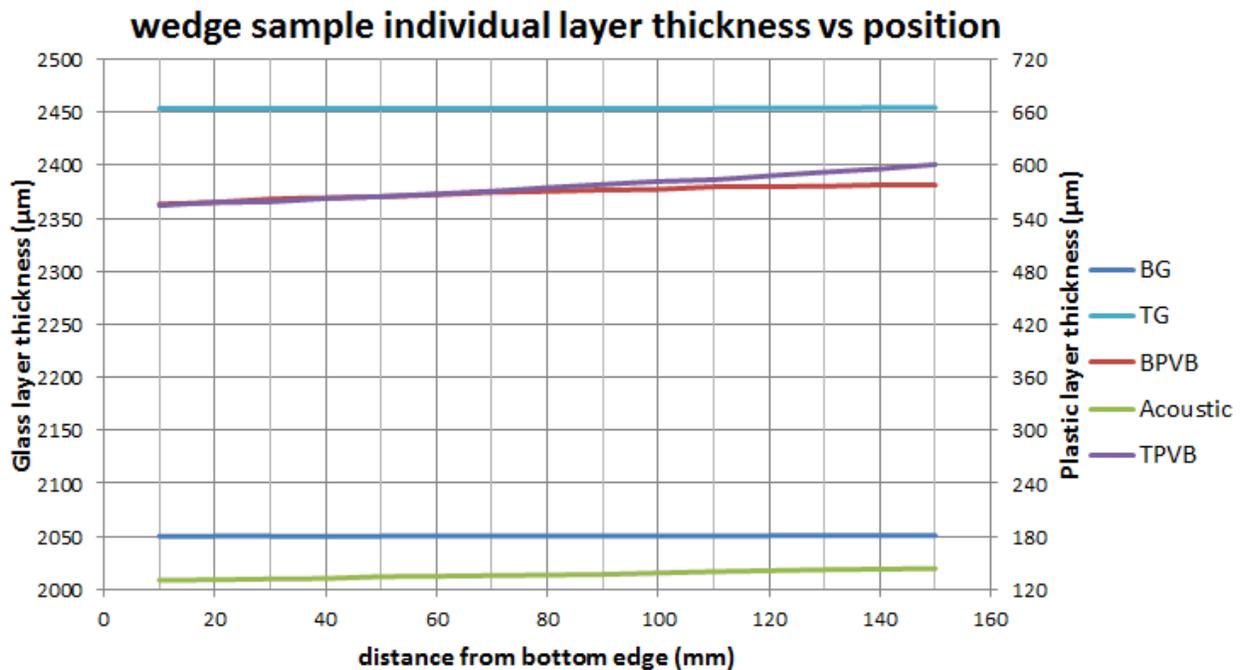


Figure 12. Layer thickness scan line for a wedge section from a second 5-layer acoustic windshield.

Figure 13 shows the measured total thicknesses of this windshield wedge, as well as the combined thickness of the plastic layers.

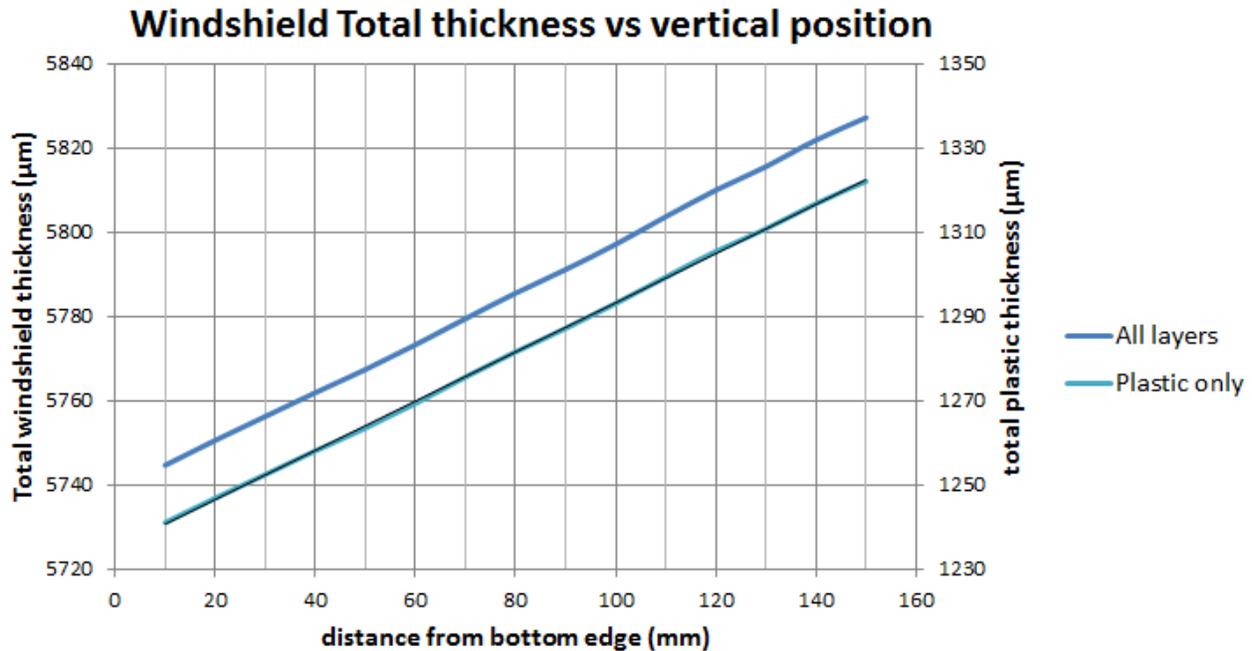


Figure 13. Total thickness and total plastic layer thickness for the wedge section thickness scan shown in Figure 12.

Table 4 shows the calculated wedge angle for this sample, and the corresponding statistical data. Table 4 shows statistical data for the thickness of the top and bottom glass layers of the sample in Figure 13. Notice that the thickness tolerances for the glass layers in this sample are much tighter than for the 5-layer windshield data shown in Table 3.

Table 4. Statistics for the wedge angle and the glass layer thicknesses for the 160-mm windshield wedge sample shown in Figure 11C

	Bottom Glass thickness	Top Glass thickness	Wedge Angle plastic only		Wedge Angle Total	
units	(µm)	(µm)	(mrad)	(deg)	(mrad)	(deg)
mean	2050.304	2453.862	0.584	0.0335	0.594	0.0340
stdev	0.227	0.266	0.022	0.0013	0.024	0.0014
max	2050.72	2454.39	0.62	0.0353	0.64	0.0369
min	2050.02	2453.58	0.55	0.0316	0.56	0.0319
range	0.70	0.81	0.06	0.0037	0.09	0.0050

## Summary

Windshields that are optimized for HUD displays have very tight tolerances for thickness uniformity of the glass layers and for wedge angles on the laminated PVB layers. Each model car has different wedge angle and thickness requirements, and as a result,

precision metrology and quality control is becoming highly important. We have demonstrated, that the time-domain low-coherence technology used in the commercially available Optigauge® II provides the needed capability for measuring the thickness and angle profiles of individual layers in a windshield.

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