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Precision Measurement Solutions

AUTOMOTIVE WINDSHIELD METROLOGY AND QUALITY CONTROL USING OPTICAL TECHNOLOGIES

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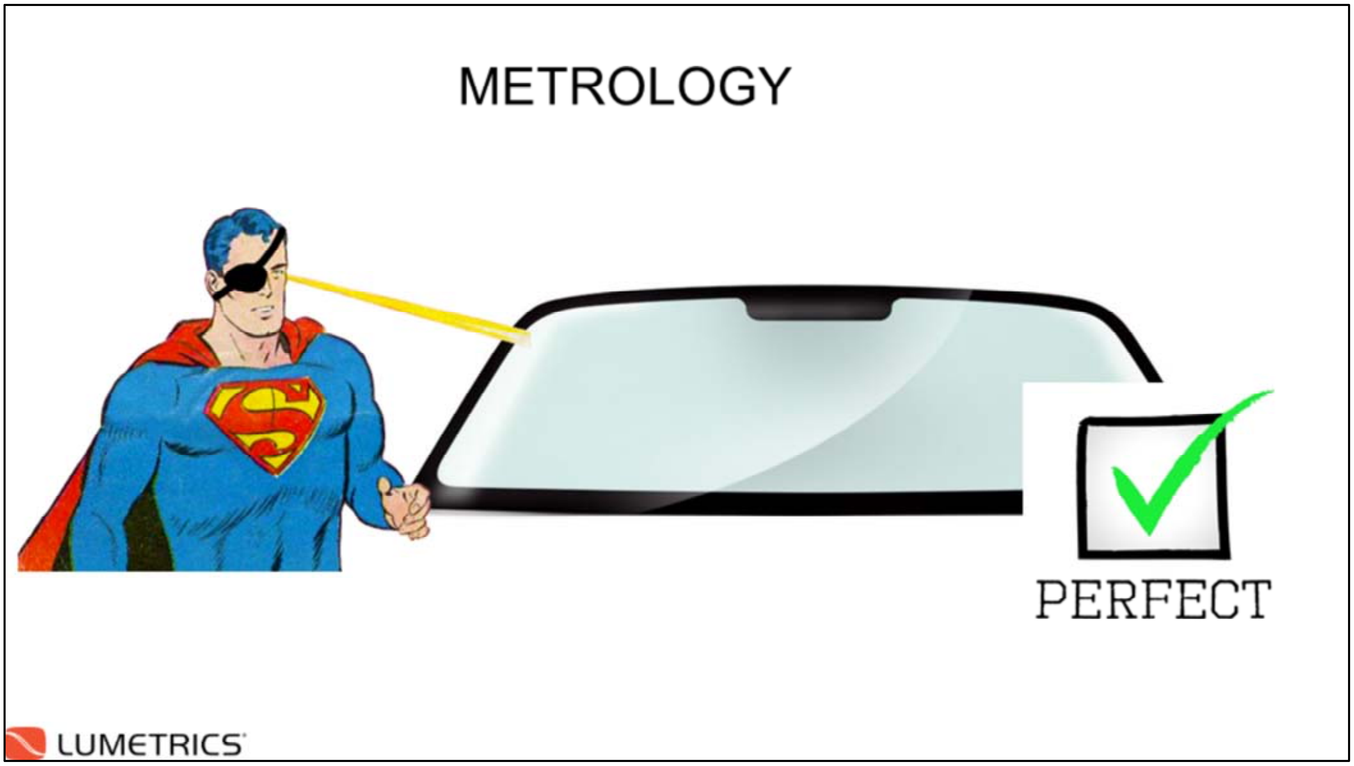
Welcome to this presentation. These notes will aid you in reviewing the slides. You may contact the author directly at fignatovich@lumetrics.com with questions. I have been involved in the field of optical metrology for over a decade. The range of the applications for optical metrology tools is vast – from glass manufacturing, to medical devices, to food packaging and more. My goal for this talk is to provide a technical overview of the optical measurement technologies that are available for windshield manufacturers for the purposes of quality control, prototyping and production. Some might be familiar, while others may be new.



Wouldn’t it be great if we had some kind of tool, a “supertool”, which with a single touch of a button could tell us: “yes, this windshield is manufactured perfectly”, or “no, this windshield is not perfect due to A, B, and C” so that we can then go and fix any issues on the manufacturing line.

MEASURED WINDSHIELD PARAMETERS

Optical performance:

- **Impurities/defects**
- **Tint**
- **Distortion**
- **HUD projection quality**

Mechanical properties:

- **Break strength**
- **Bond strength**
- **Stress (tempered and regular glass)**

Physical dimensions:

- **Outer dimensions**
- **Front and back curvature**
- **Thickness and thickness distribution**
- **PVB HUD wedge angle**
- **Glass pane gap control**
- **PVB thickness uniformity**
- **Acoustic layer thickness**

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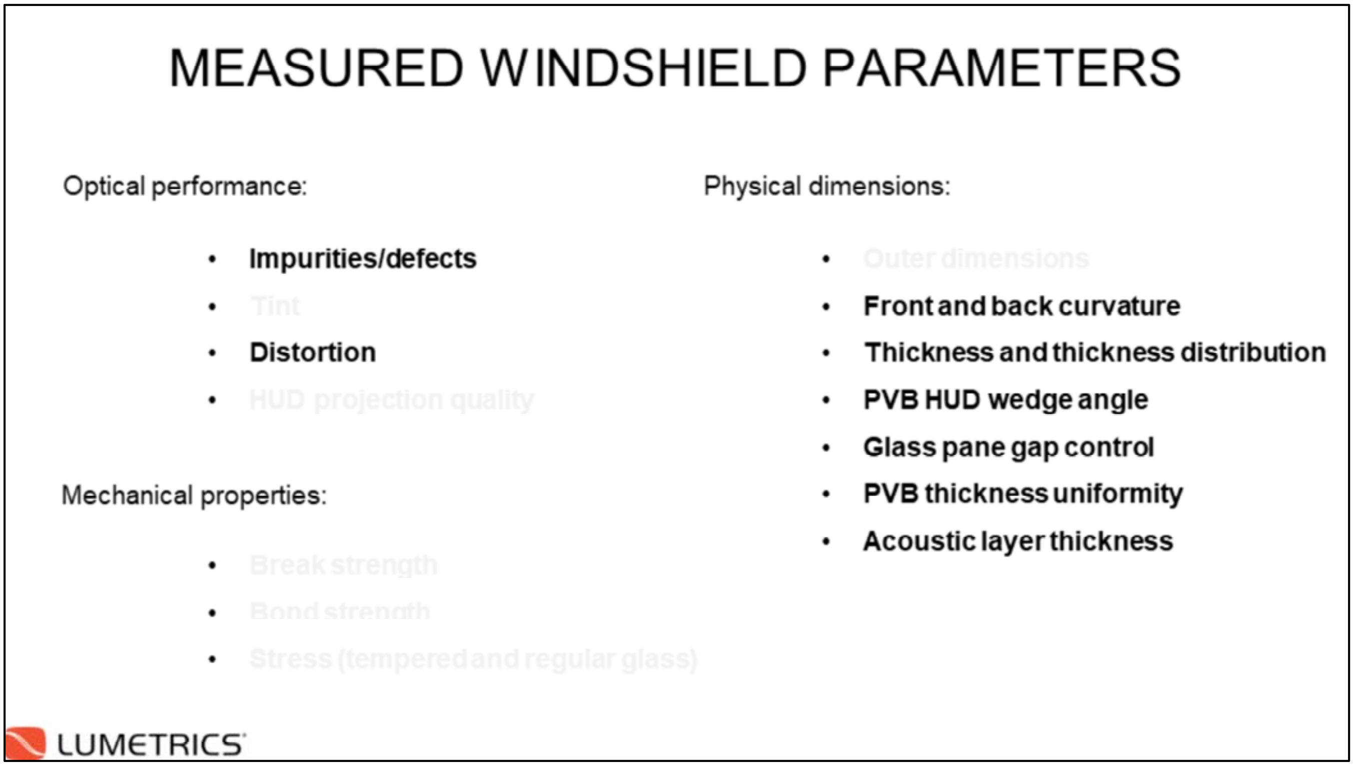
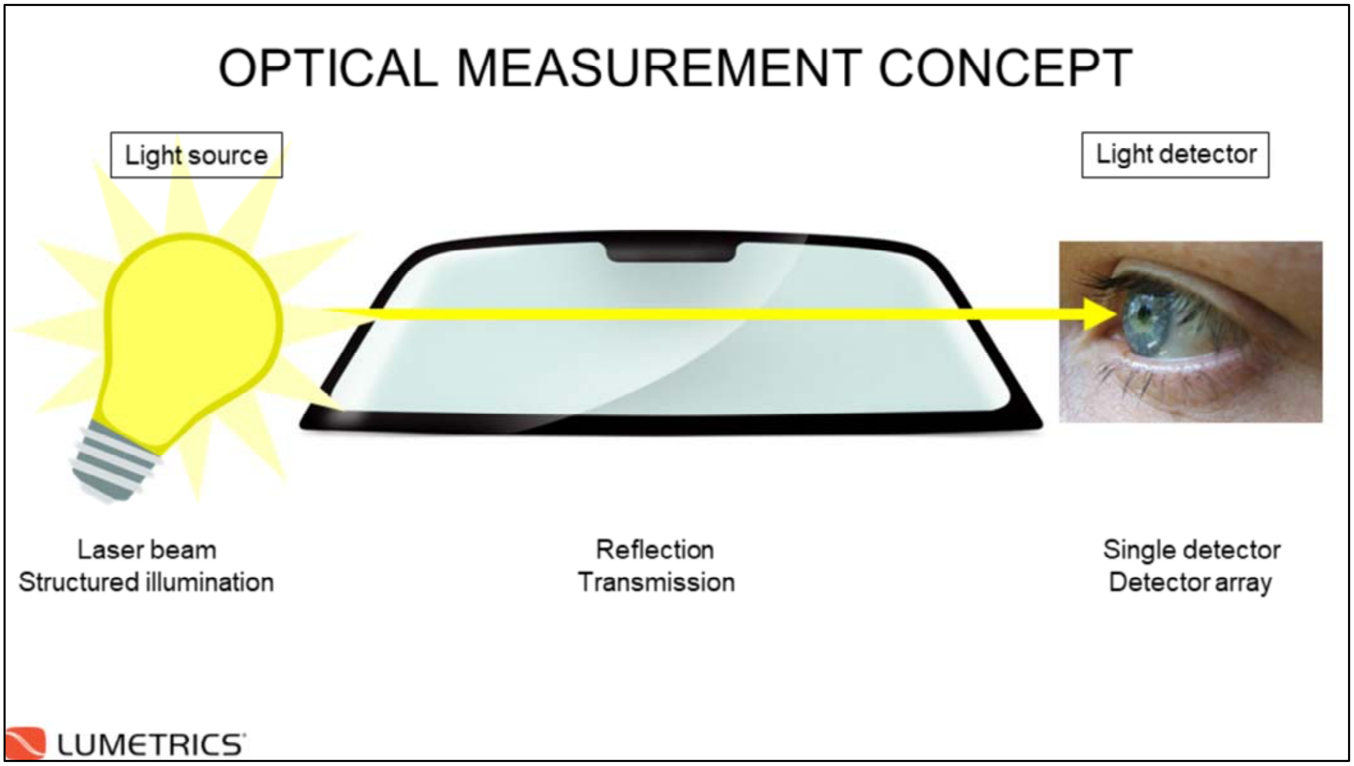
In real life you have a set of parameters that are available for measurements. Those include dimensional parameters, optical performance parameters and physical parameters (mechanical properties). Some are measured directly, and some are measured indirectly. There are optical techniques and tools available to assess each one of these parameters.



I will focus mostly on the techniques related to these most common parameters.



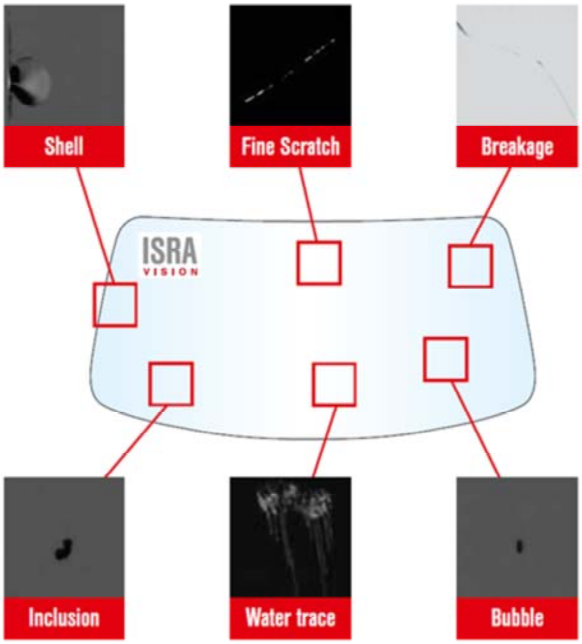
Optical measurements are surprisingly simple and intuitive. You have a source of light; the light then interacts with the windshield; and then a detector analyzes the light after the interaction.

There are only two types of interactions with the windshield – light passing through (transmission) and light reflecting from the windshield.

There are also two kinds of the light source – a narrow laser beam, which is also sometimes called a point source; and then pretty much everything else, which is called an extended source or a structured light source. A light bulb is an example of extended light source, a uniformly lit TV screen is another example, the room lights, the LEDs and so on.

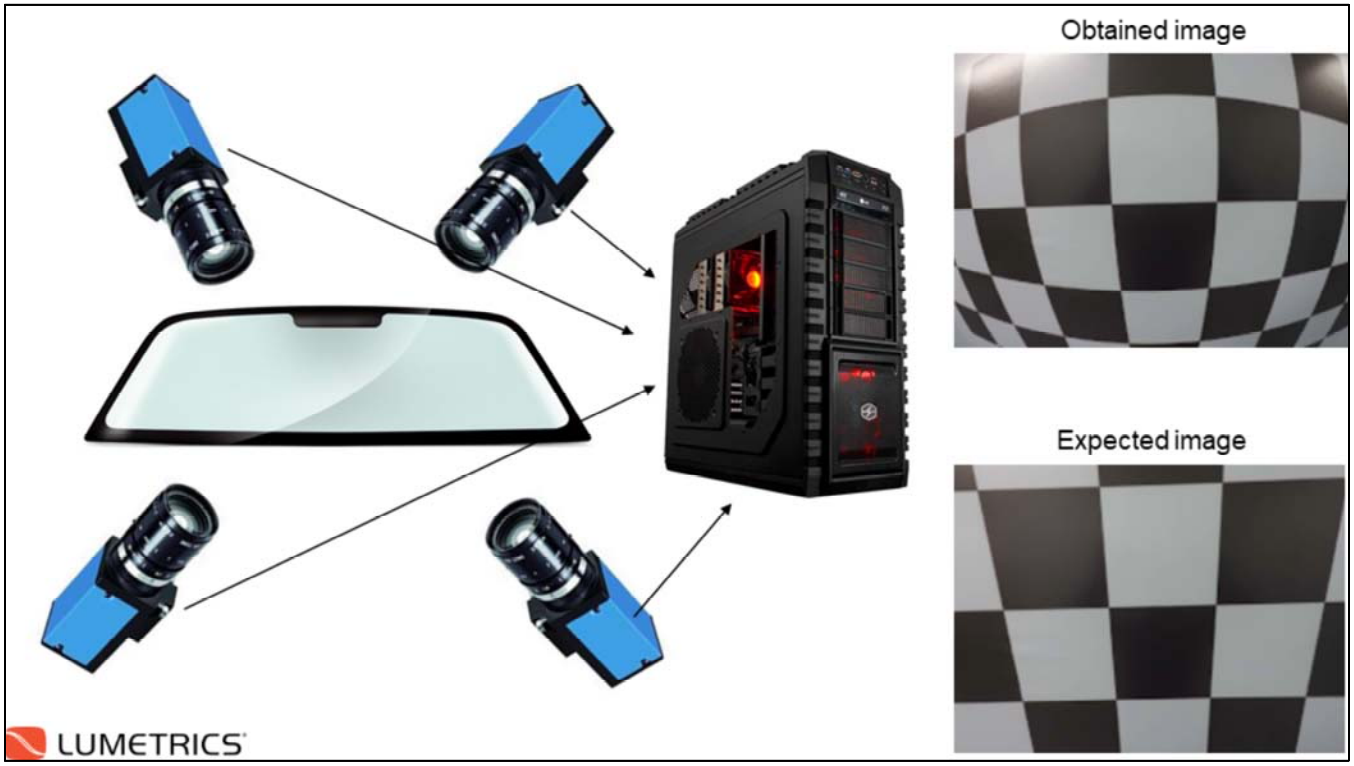
On the detection side you again have two options. One option is a single detector, a "dumb detector, which only tells you the brightness of the light it receives. And another option is an an array of the detectors. A most common array of detectors is just a regular CCD camera, which you have for example in your smart phone. In addition to the brightness of the light ray, the detector array can also tell you the location or the direction of the light beam depending on how you configure it.

DEFECTS AND DISTORTION

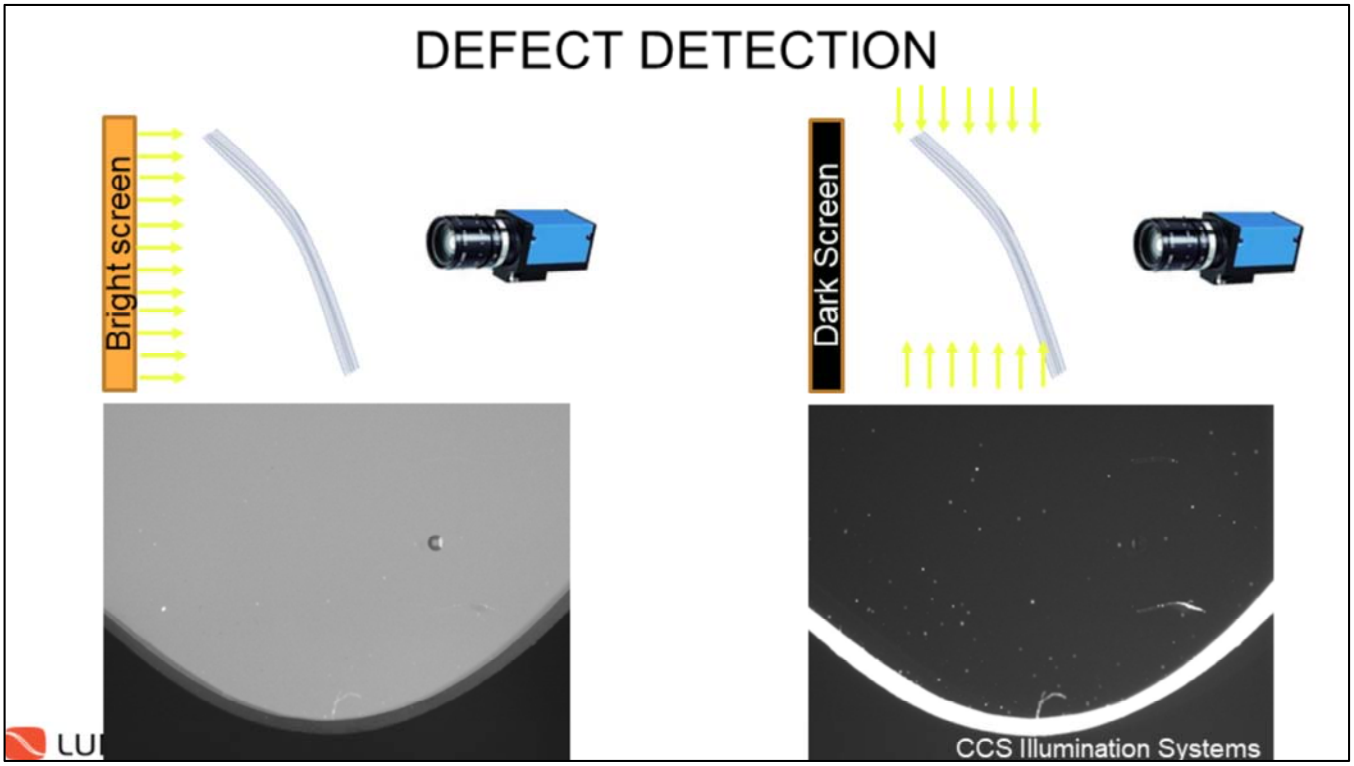


Vision systems are designed to visually assess the quality of the windshield. Any deviations from the expected image indicate an issue. When looking through the windshield, you expect to see the surroundings that are free of any artifacts. Presence of artifacts in your visual field indicates presence of defects in the windshield.

The image on the right is another example. We are looking at the reflected image of a building, which has straight lines, so we don’t expect to see waves/ripples. Presence of the wavy lines indicate some issues with the shape of the windshield.

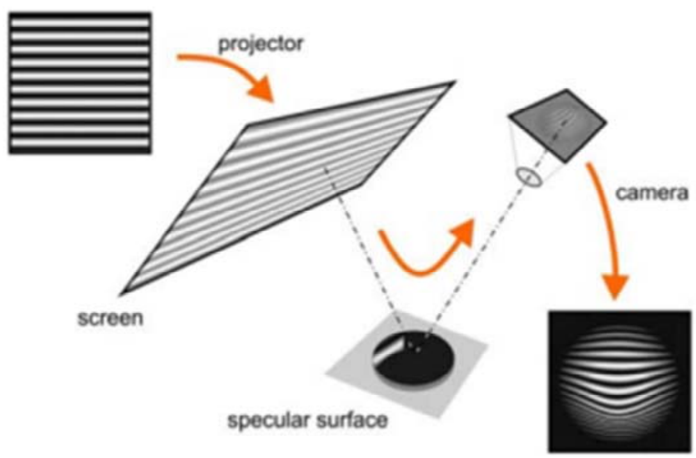


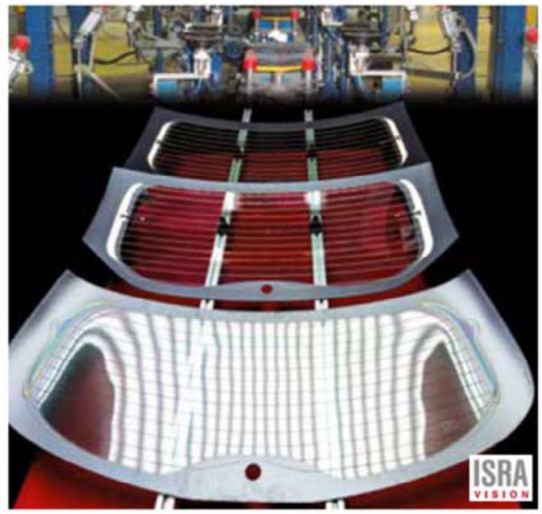
Vision-based systems are modeled exactly in that way. You have one or several cameras looking at the windshield, they acquire images that are sent for processing to a computer. The computer then compares the images it receives with the images it expects, and then conduct intensive number crunching in quantifying these deviations. Most of the complexity of these systems is in the image processing software, not the hardware.



There are two types of defect detection approaches – the bright field and the dark field. For the bright field you position the windshield in front of a uniformly lit screen. The expected images is therefore just a uniform background. Another approach is to place the windshield in front of a dark background and illuminate the screen from the sides. The reason why there are two different types of configuration, is that each configurations will detect certain defects better than others. So you need both approached to reliably detect all defects.

DISTORTION via DEFLECTOMETRY





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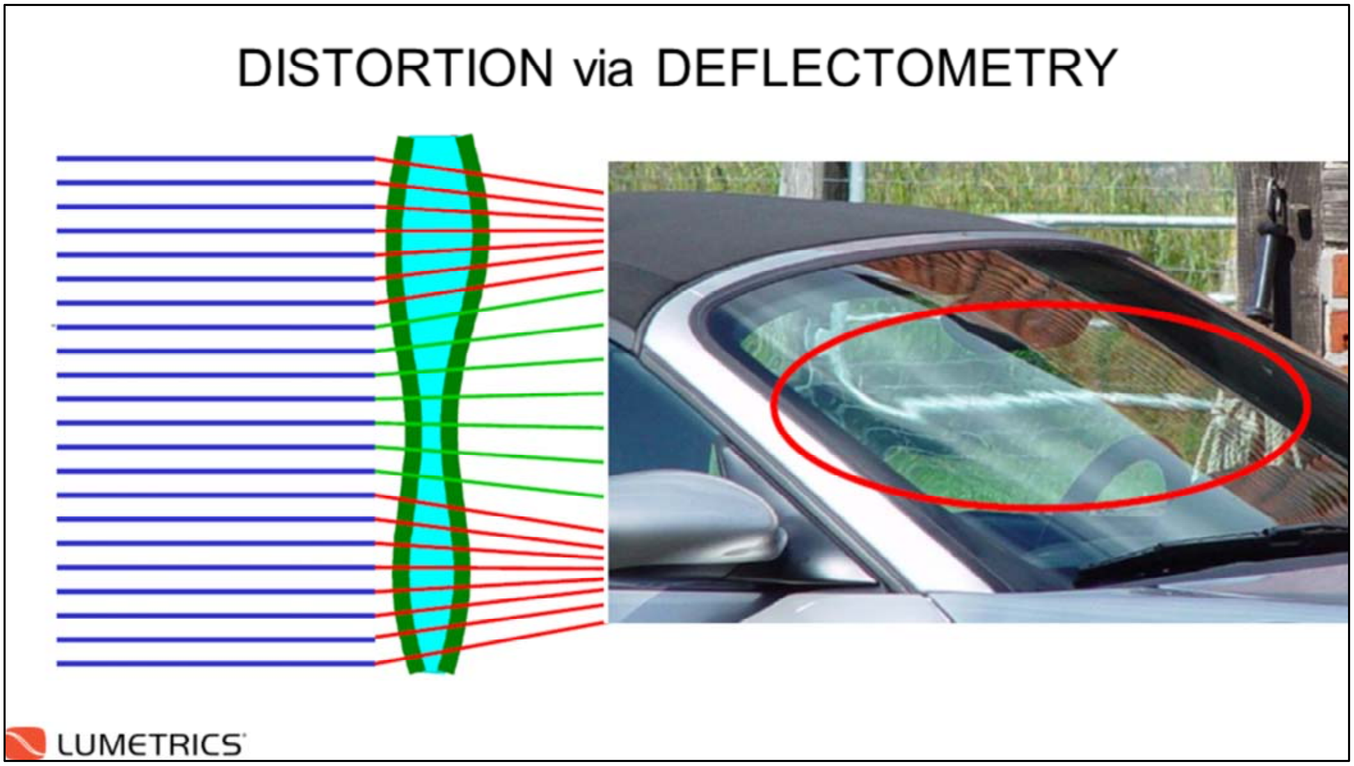
For distortion measurements instead of a uniform screen the instrument makers use what's called a structured illumination. Typically it contains rows of straight parallel lines. Then you have two options again: 1) you can look at these lines through the windshield, or 2) image these lines via reflection from a windshield. In each case, changes in straightness of the lines is a measure of the windshield quality.

The image on the right is a good illustration. The waviness of the straight lines is a measure of the waviness in the shape of the windshield. This is actually a very powerful tool, as very tiny variations become visible even for the naked eye. You can also notice change in the color (toward the edges of the windshield), which can indicate presence of contaminant film, or delamination, or stress. Also, by following the exact shape of the lines you can assess the general shape of the windshield, although not very accurately.



Same approach works in transmission as well. In transmission, any variations in thickness, or in the material homogeneity (change in the physical or optical density) will make the portions of the windshield act as a lens, a very weak one, and therefore change the direction of the propagating rays. The image on the right illustrates that very well. Here we are looking at the straight beams of a gate, that do not appear straight due to the mediocre quality of the windshield.

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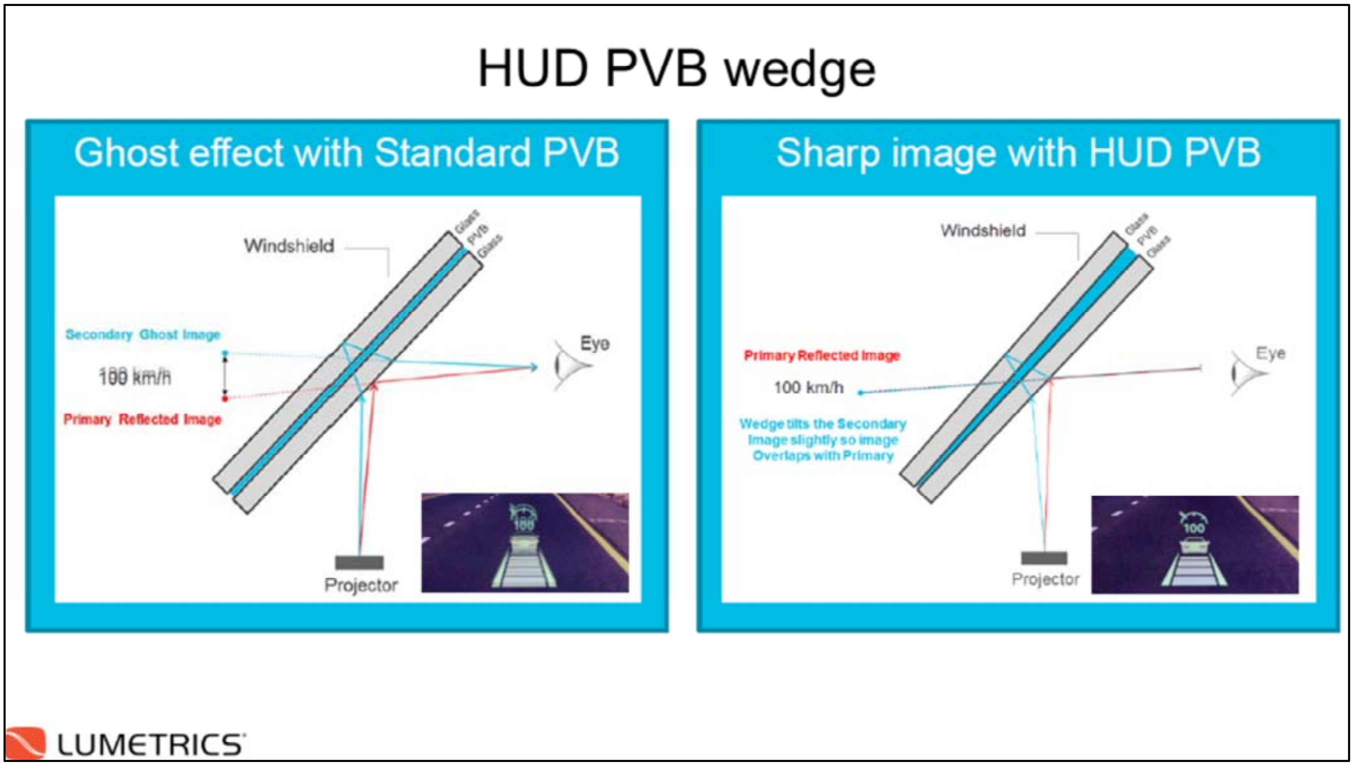
These images illustrate the improvements in the optical quality of windshields over the last 20 years. Anyone in optical manufacturing will have a huge appreciation of the degree of improvement and will also have a huge appreciation to the amount of effort it took to bring the quality of the windshield to this level. The quality of the windshields are now approaching that of optical components. Optical components have much tighter tolerance requirements than any precision mechanical components.

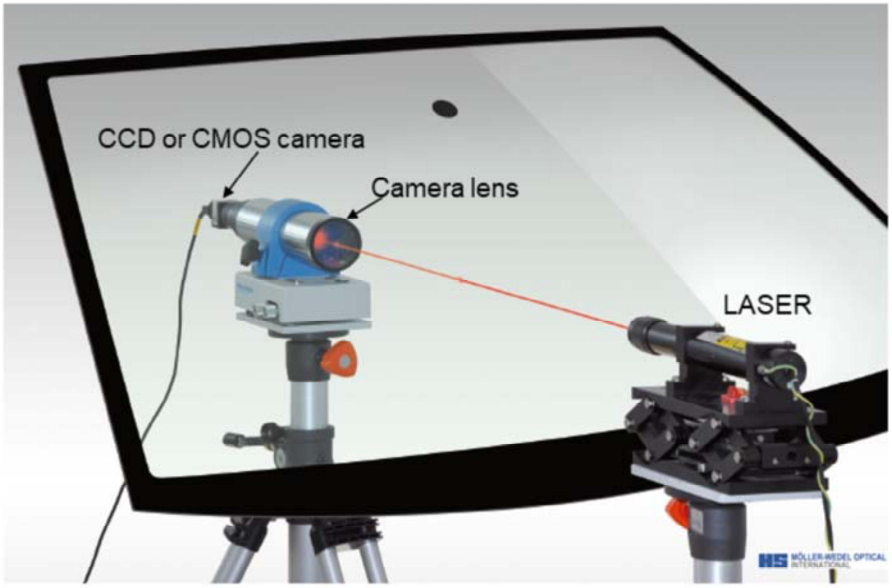
With the advent of self-driving and assisted driving capabilities, the windshield is starting to play a role as part of the optical trains (optical system) needed to property operate the sensors that enable these enhanced riving capabilities. And this is just the tip of the iceberg. The bottom line is that the requirements for windshield will soon be matching those for optics, and therefore require next generation metrology tools.



The most prevalent example where the windshield plays a role in the optical system is the heads-up display (HUD) functionality. This is a very good example where the windshield must have certain optical properties. The windshield is used to reflect the light from a projector, so it plays the role of optical element that's placed into the path of the light from the projector. The main problem here is that the image is formed by two different reflections – one reflection is off the surface facing the driver, and the other reflection is from the opposite surface of the windshield. In a typical windshield that has uniform thickness, these two reflections are shifted in space with respect to each other, resulting in a blurry image. Therefore, in order to combine these two reflected images into a single image, the windshield must have a slight wedge. And the angle of the wedge must be very tightly controlled.

There are few ways you can measure the wedge angle.

SECONDARY IMAGE ANGLE MEASUREMENT



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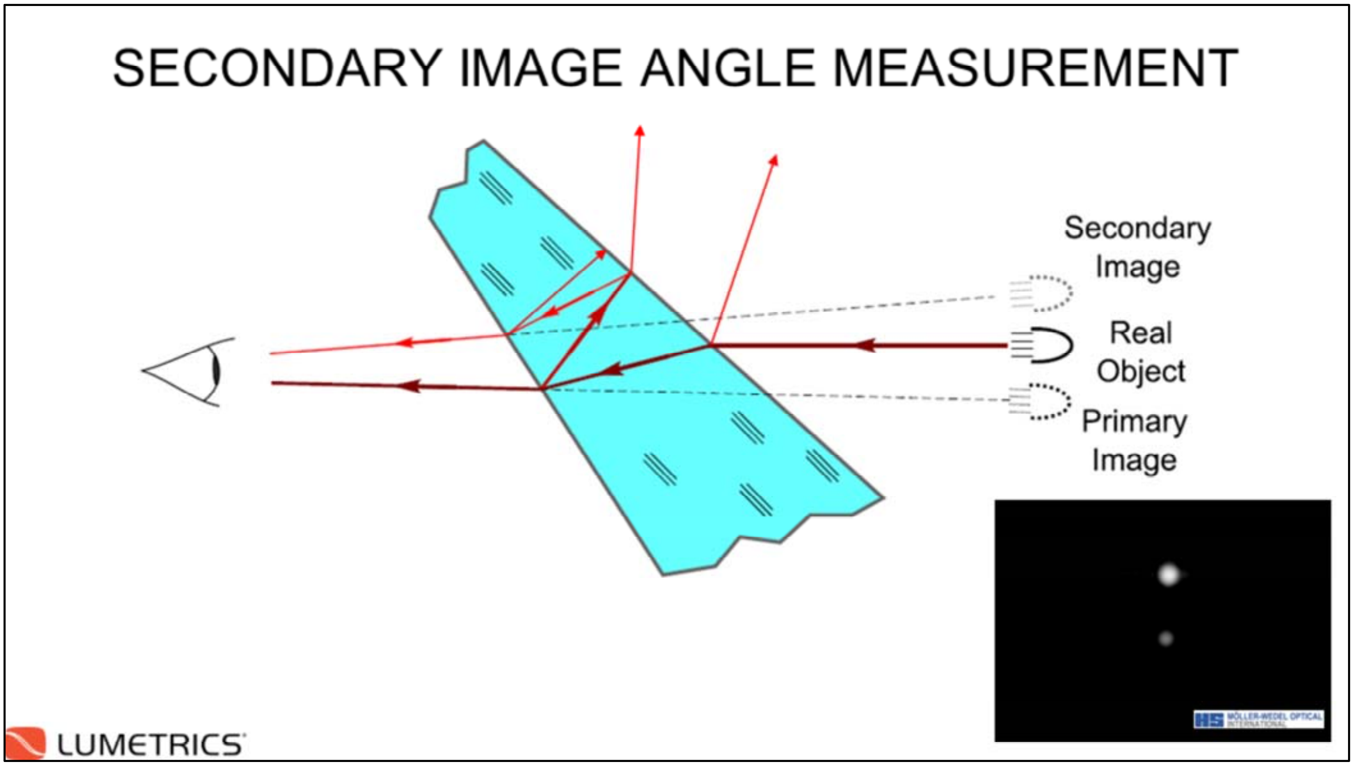
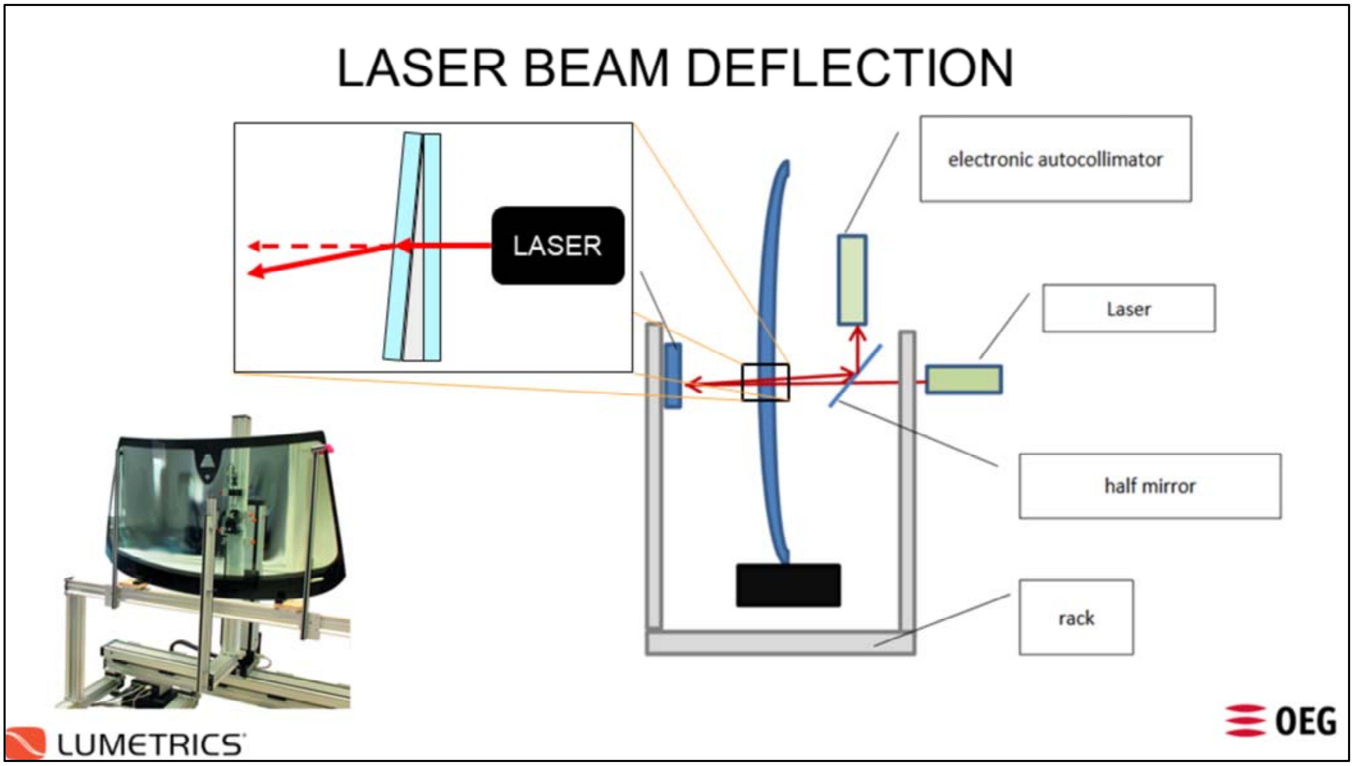
This method you are probably most familiar with. This is an indirect measurement of the wedge. Again, as I explained in the beginning of the lecture, we see three main components – the light source (a laser) the detector array (the CCD camera with an objective), and the light traveling through the windshield.



Here's what happens when the laser beam travels through the windshield. Most of the beam travels through the windshield. At the interfaces it experiences changes in the direction due to the optical phenomenon called refraction. After it refracts on the first surface it then travels to the next surface. Here, most of the beam is transmitted, but a small portion of the beam is reflected by the second surface back into the glass window. It then travels to the first surface, and a small portion of that beam is again reflected into the windshield. Finally, this twice-reflected beam exits the windshield. So at that side of the windshield we end up with two transmitted beams. The second beam is much weaker sincedue to the two reflections. What's important is that the second beam travels at an angle with respect to the main beam. And that angle corresponds (but not exactly equal) to the wedge angle.

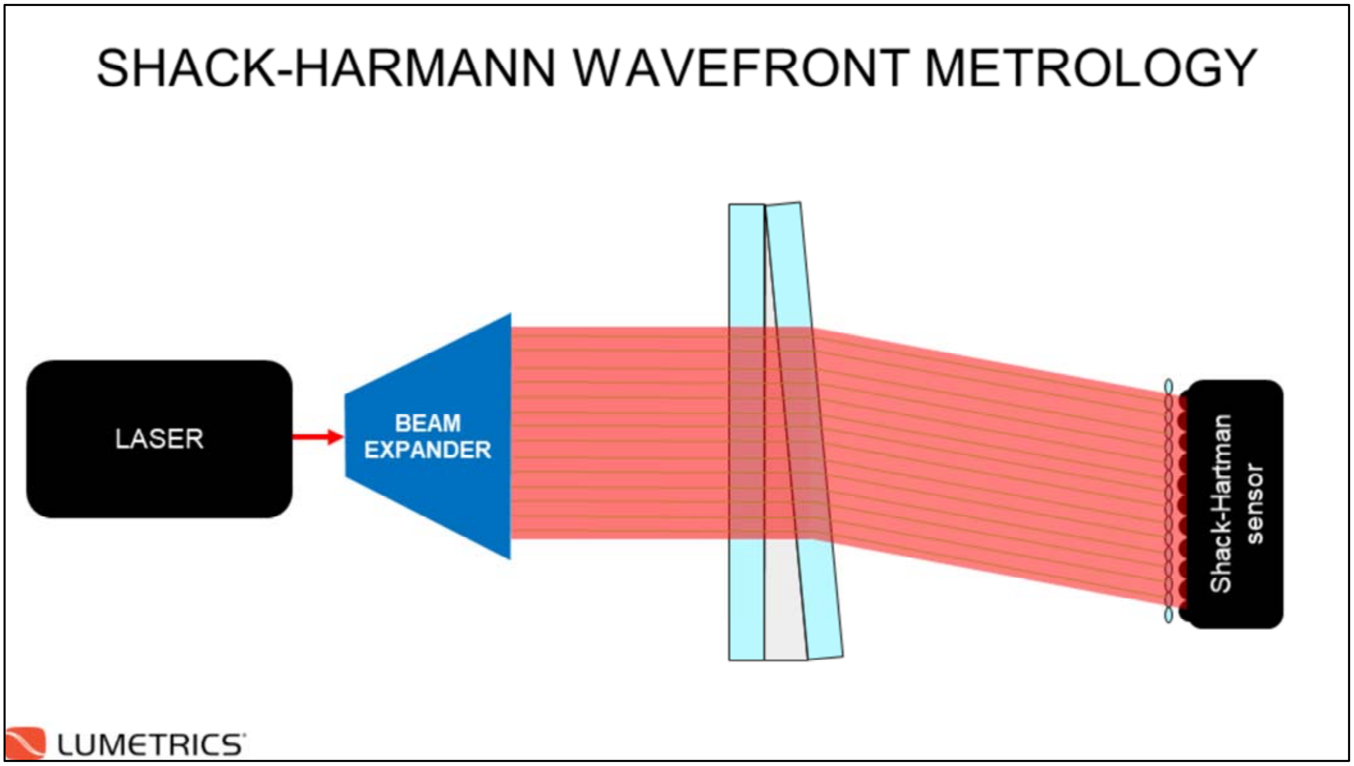
The camera sees these two beams as two spots, and the distance between the two spots is proportional to the angle between the two beams. And so the distance between the two spots is proportional to the wedge angle.

This technique of having laser beam interact with an object is generally called as laser deflection metrology.



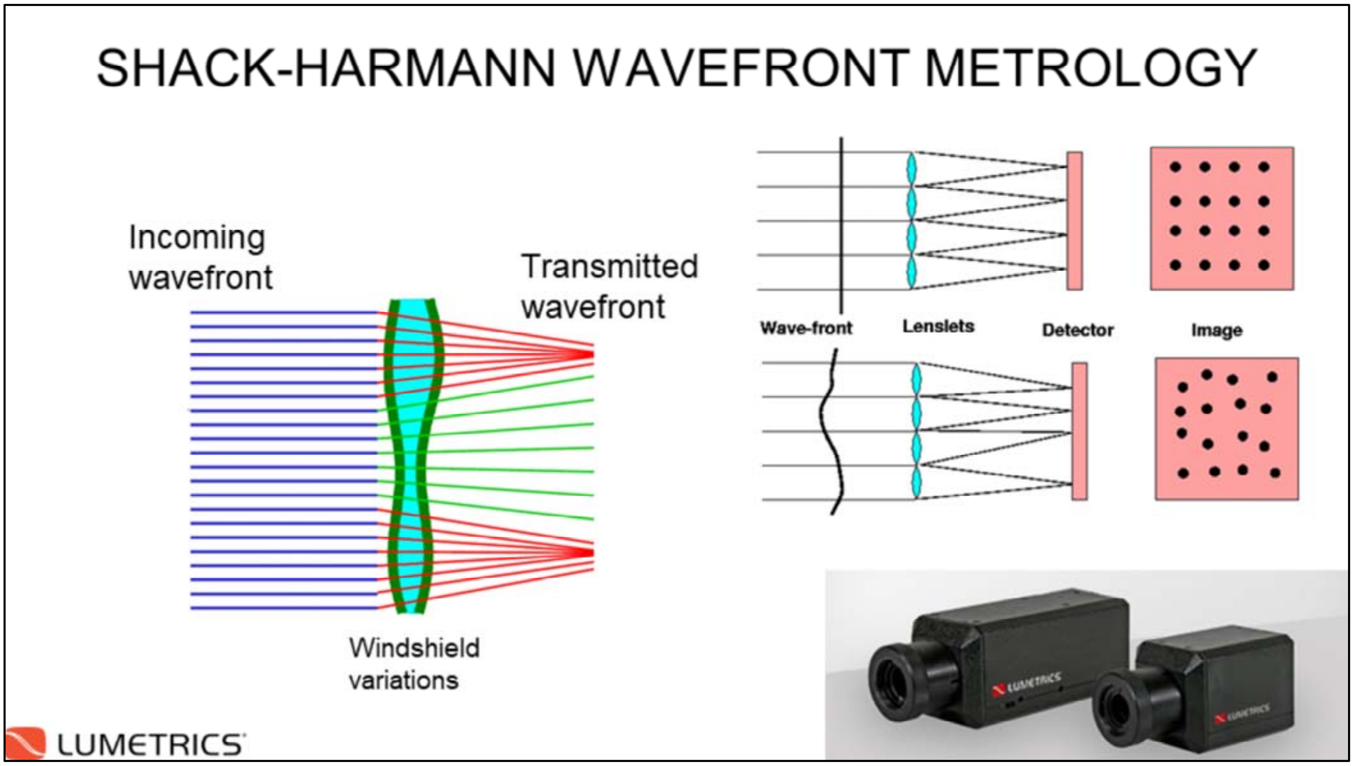
In another approach, you don't even need to have the second twice-reflected beam to measure the wedge angle. This technique looks at the change in the direction of the propagation of the transmitted beam with respect to its original direction. In this particular implementation of that technique, the beam is reflected by a mirror and travels through the windshield again, to amplify the effect. Again, the camera looks at the displacement of the laser beam dot with respect to the original location.

Both techniques I described in this and the previous slides, produce point measurements of the wedge angle. In order to measure the wedge angle throughout the HUD region, the beam should be scanned across the windshield. However, it is a challenging task. In order to retain the accurate measurements, the relative position of all parts of this measurement system must maintain their relative position with high degree of accuracy. It is not an obvious task when you must move things mounted on a large u-shaped fixture.



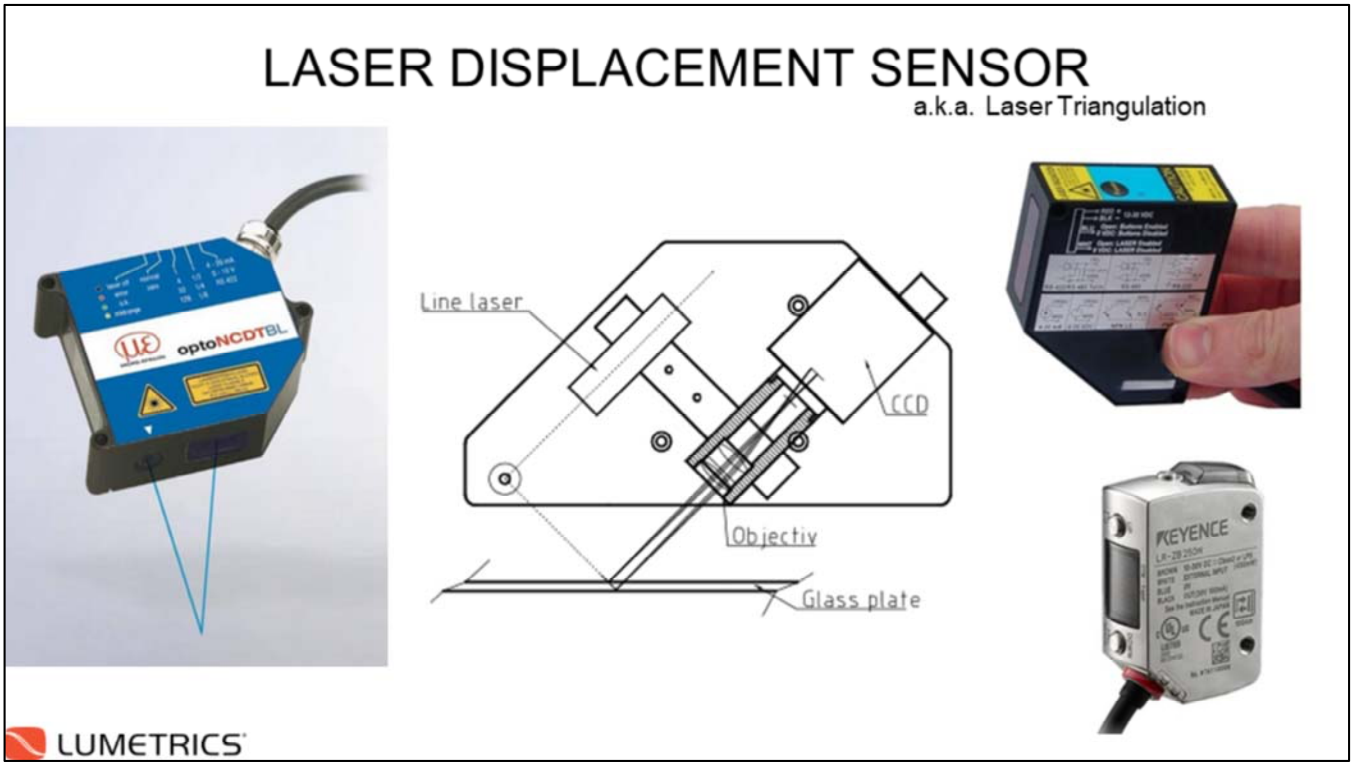
There is technology that does not require mechanical scanning, but it operates under the similar principle. Shack-Hartman wavefront measurement technique is a very known technique in the field of optics and mirrors testing, but it has not yet found its way into the windshield market. Lumetrics specializes in these measurements.

Here, again, you start with a narrow beam of light, but then you increase it size in the beam expander. Then this large beam travels through the windshield, where it changes direction based on the wedge angle. The beam is then analyzed by a special detector array, the wavefront sensor. This sensor consists of a CCD array with an array of tiny lenses in front of it. This lenslet array effectively breaks the large beam into an array of independent rays (or beamlets). Similar to the technique described in the previous slide, this configuration looks at the change in the direction of each of the beamlet, and therefore assesses the wedge angle at each location of the windshield area that’s illuminated by the expanded beam.

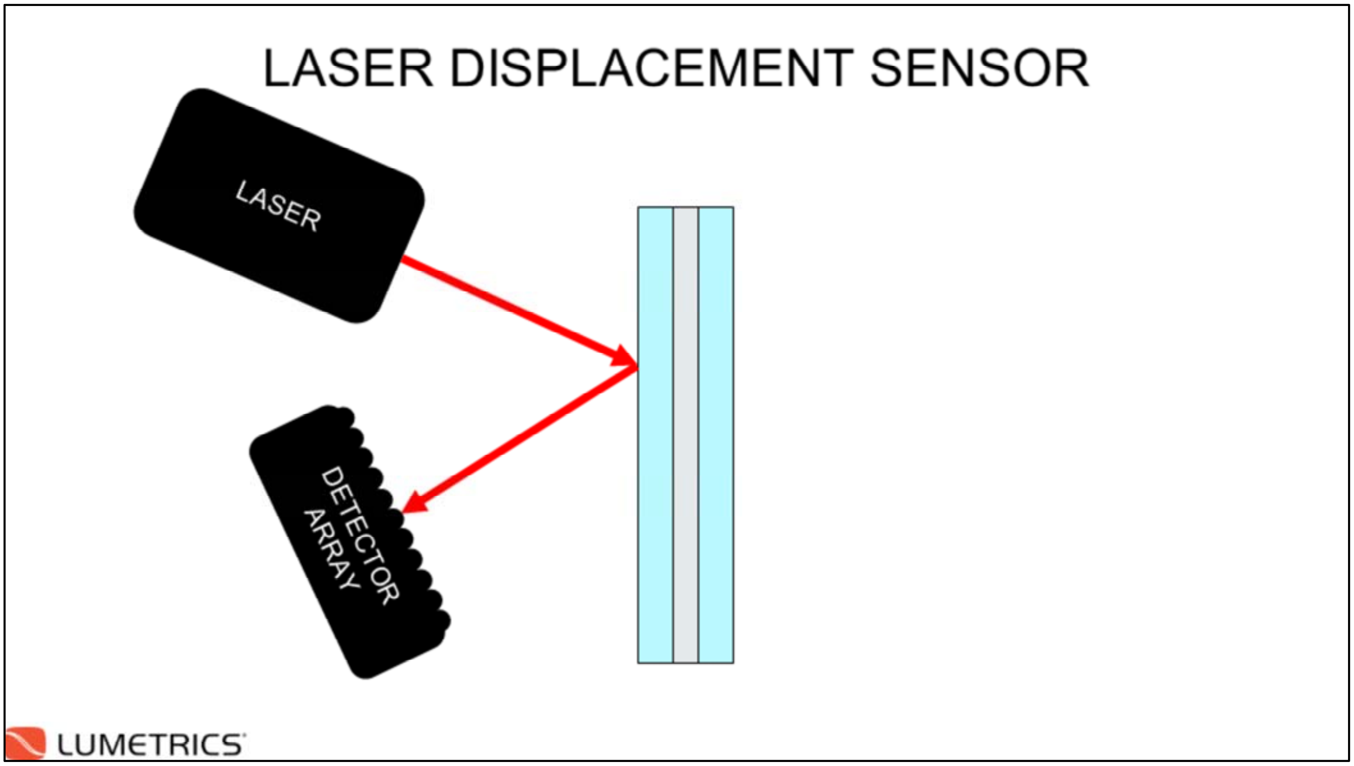


In addition to the wedge angle, this technique also allows you the measure the windshield distortion. When the windshield acts as the lens, it changes the directions of the beamlets. The lenslet array of the Shack-Hartman sensor results in the bright spots in the CCD image, and the location of each spot corresponds to the propagation direction of each beamlet. If the beam is not distorted, you just have an equally spaced array of dots (see the upper right image). However, any changes in the direction of propagation of the beamlets result in the shift of the corresponding dots (next image below the upper right image). By measuring the magnitude of the deviations you can measure the distortion in the windshield.

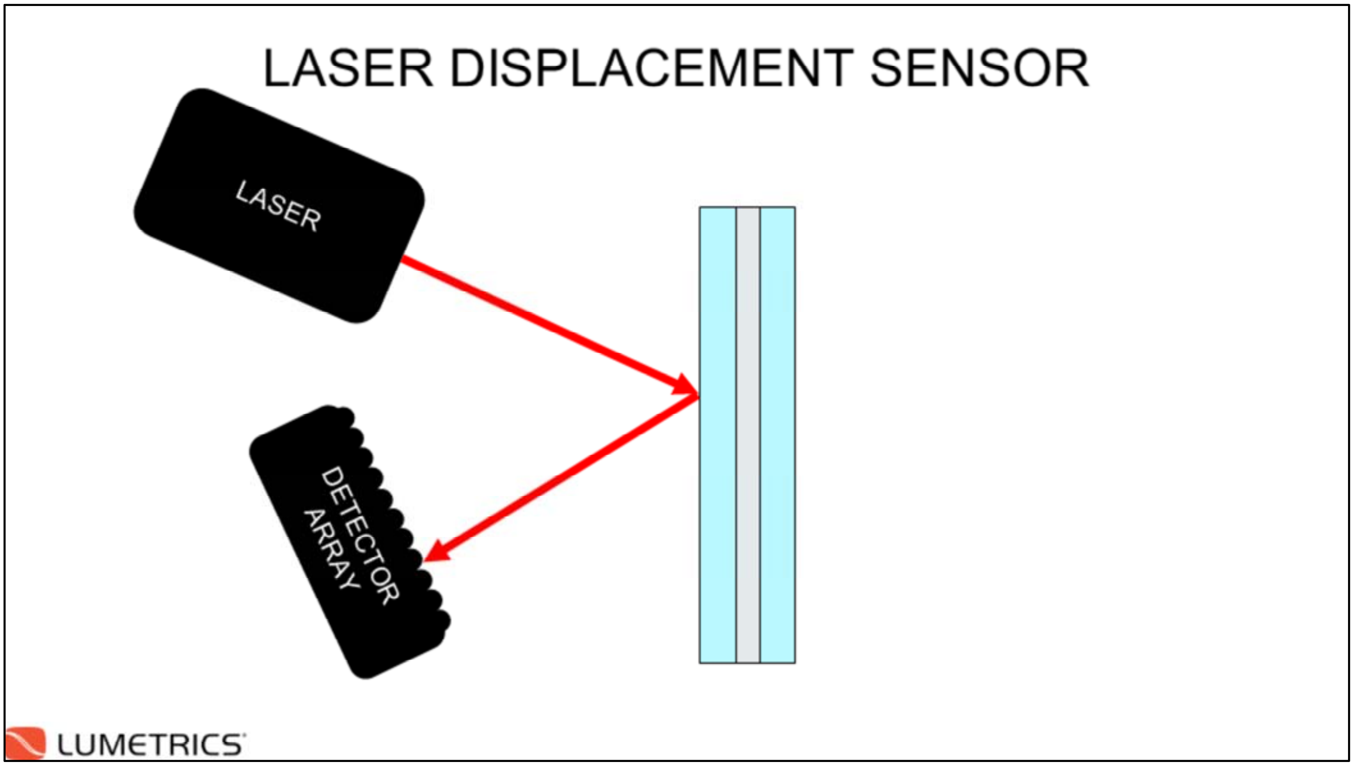
The bottom right image shows pictures of the wavefrton sensors – these devices consists of a CCD camera with a special attachment in the front.



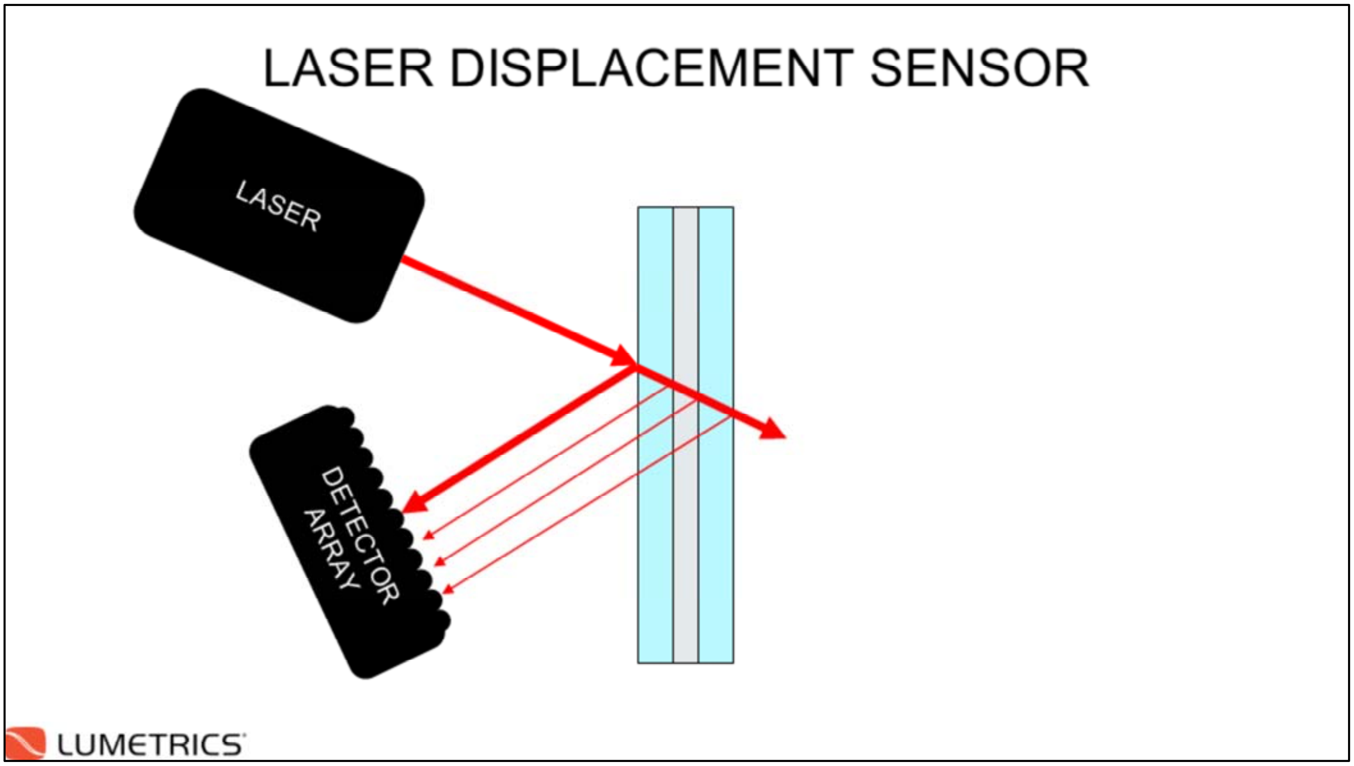
Here is one of the probably most ubiquitous tools – the laser displacement sensor. It is a very common tool that can be found virtually in any production line. They are also sometimes referred to as laser triangulation sensors. The primary purpose is to measure the distance between the sensor and a surface. However, it is also can be used for thickness measurements, although with some significant limitations.



The way it works, you take a laser and send it into the surface of interest at an angle. And then you place a detector array in the path of the reflected beam. The detector array tells the location of the beam spot on its surface.

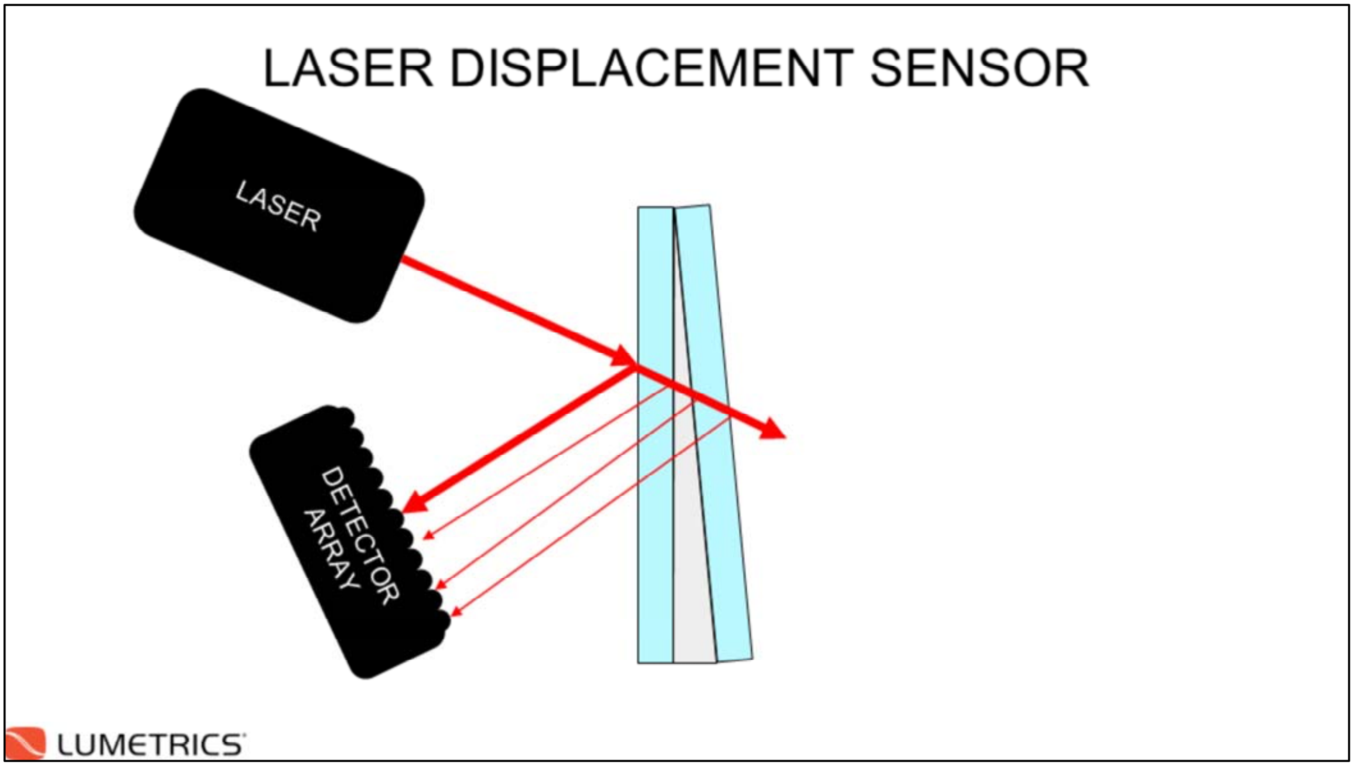


As we move the windshield away from the sensor, the position of the reflected beam changes on the detector array. By measuring the magnitude of the shift in the beam location, we can calculate the shift in the position of the reflecting surfaces.



In case of a transparent object, like windshield, the incoming laser beam is not only reflected by the front surface. The beam travels through the windshield, and then gets reflected from each of the interfaces – the first arrow here is reflection from the air-to-glass interface, then glass to PVB, then PVB to glass, then again glass to air. The detector array then receives four reflections, and measures how much these reflections are shifted with respect to each other. This information, in turn, is used to calculate thicknesses of each of the layers.

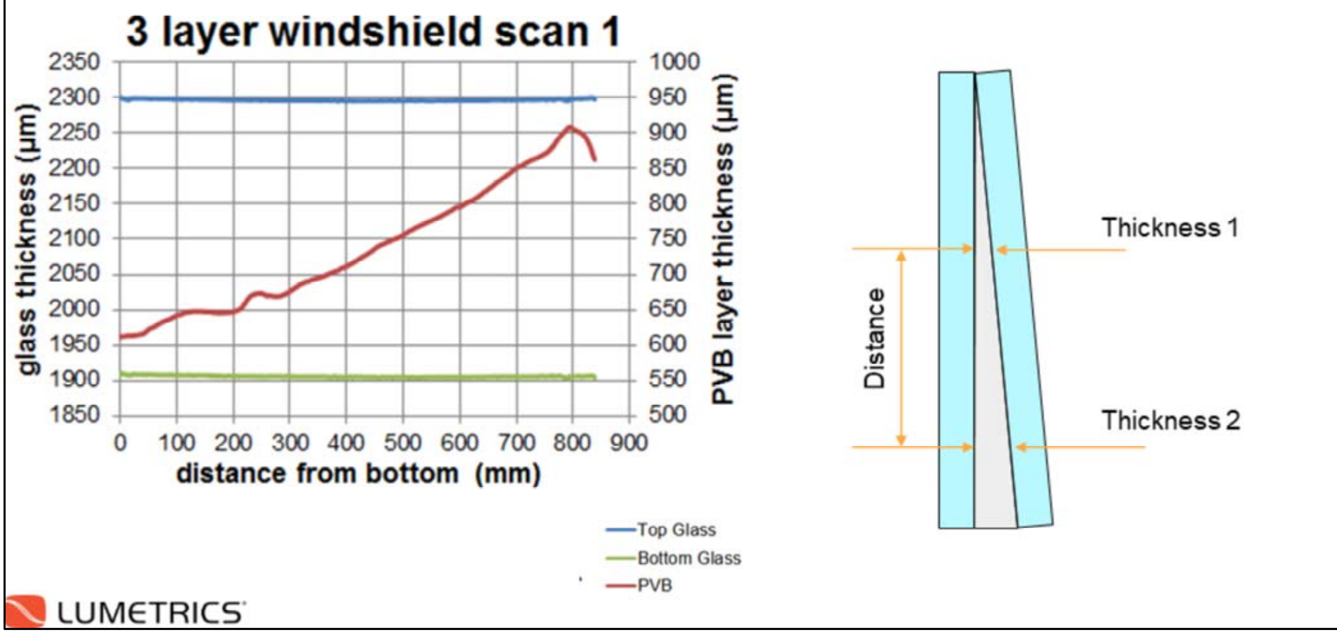
There is a wide variety of these laser triangulation sensors on the market You can vary the number of pixels in the detector array, the size of the beam and do other things to improve the measurement accuracy. These sensors are compact and light weight. But be careful – these sensors work best when used either for distance measurement or for thickness measurements of plane-parallel materials. Measurement accuracy is affected for multiple layers, and for curved glass. The measurement accuracy further deteriorates when the windshield has a wedged PVB.



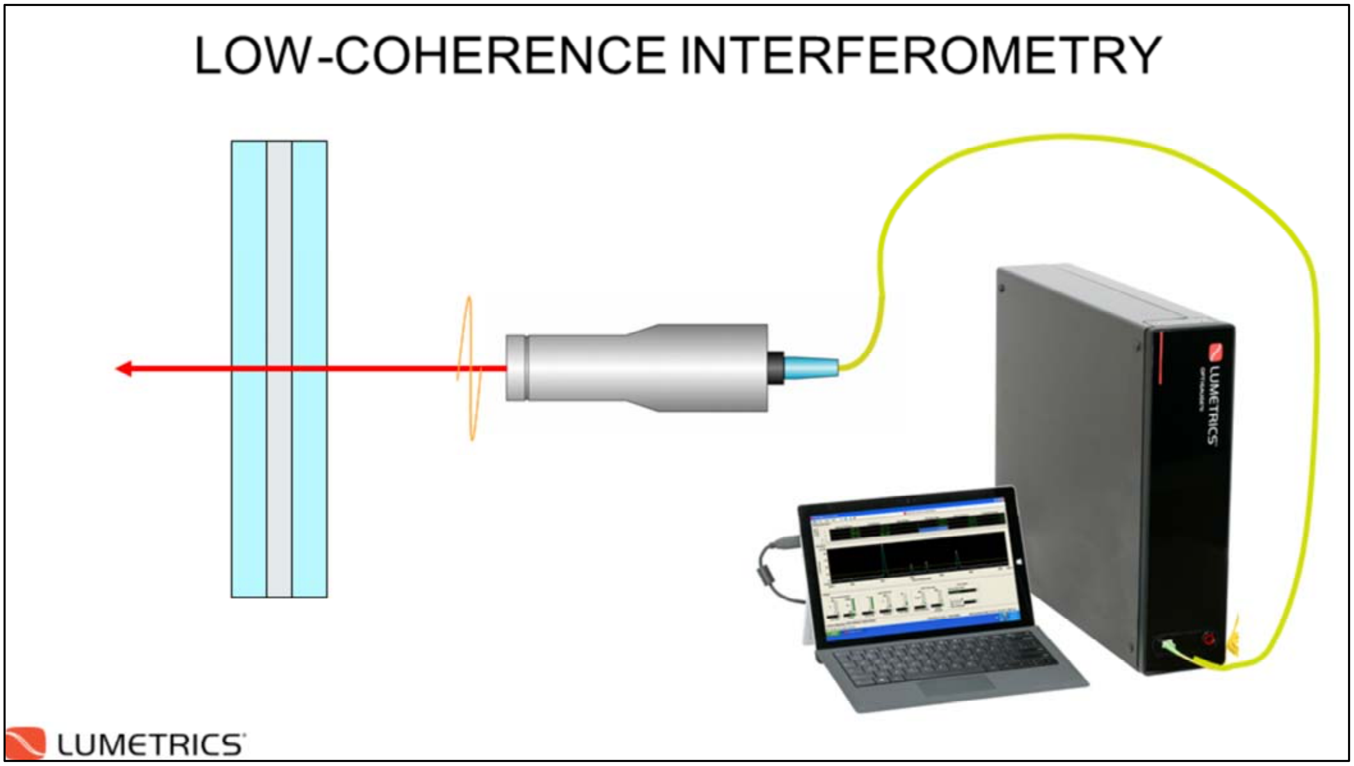
Here's the explanation of what happens in presence of the wedge. The wedge angle affects the angle of the reflected light, and the distance between the spots in the detector array now contains information about two parameters – the thickness of the PVB layer and the angle. The instrument still sees the spots and is calculating the thickness numbers based on these spots, but the numbers are fatally flawed.

We have seen many attempts to use this type of sensor as thickness measurement. Most people don't realize that this sensor only works well for a perfect plane-parallel sample, where you have perfectly flat layers of material stack on each other. The moment you have curvature or thickness variations, it fails.

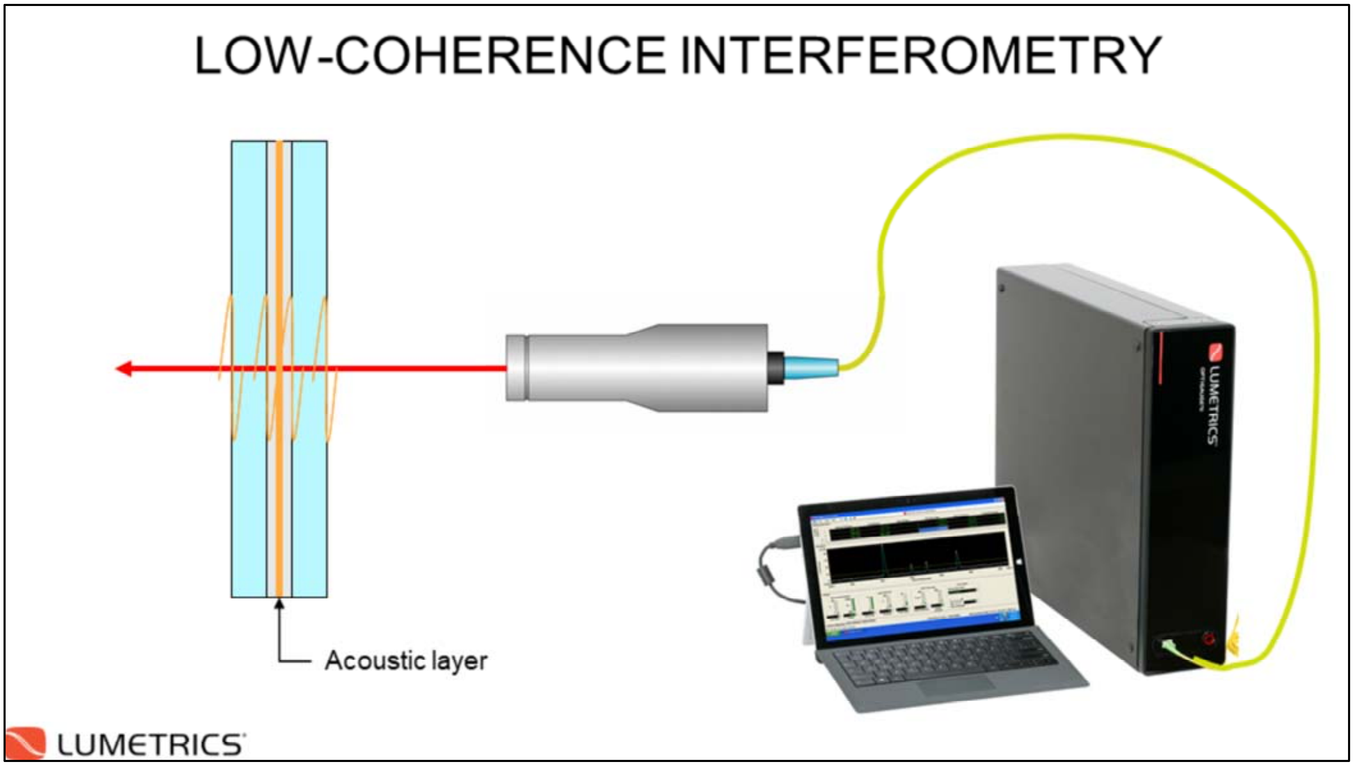
$$\text{WEDGE angle} = \tan^{-1}\left(\frac{\text{Thickness 2} - \text{Thickness 1}}{\text{Distance}}\right)$$



Measuring thickness is a more direct way in evaluating the wedge angle. You just need to measure the change in the thickness of PVB layer over some distance and calculate the wedge angle. You can also map out the change in thickness of PVB layer and see if it deviates from a linear progression at any point along the HUD portion of the windshield. The red line on the graph shows changed in the PVB layer across the HUD region. We have obtained this graph at Lumetrics using low-coherence interferometry.



Low coherence interferometry is another powerful Lumetrics technology. A single optical probe acts as both the light source and a detector. It emits the light beam, collects the reflected light, and sends it to a processing box via optical fiber. The probe itself is very simple instrument, light weight, robust, and resistant to harsh environments.
To explain this technology in simple terms, I like to draw a parallel to a sonar. In a sonar you emit a pulse of sound and then listen for the echo – the reflection of that pulse from an object. By measuring the time delay of the echo with respect to the emitted pulse of sound, you can calculate the distance to the object. Low-coherence interferometry technique has a similar concept, but it uses light instead of sound.
Several automotive glass manufacturers use this technology for prototyping, to confirm optical quality, and for troubleshooting lamination issues.

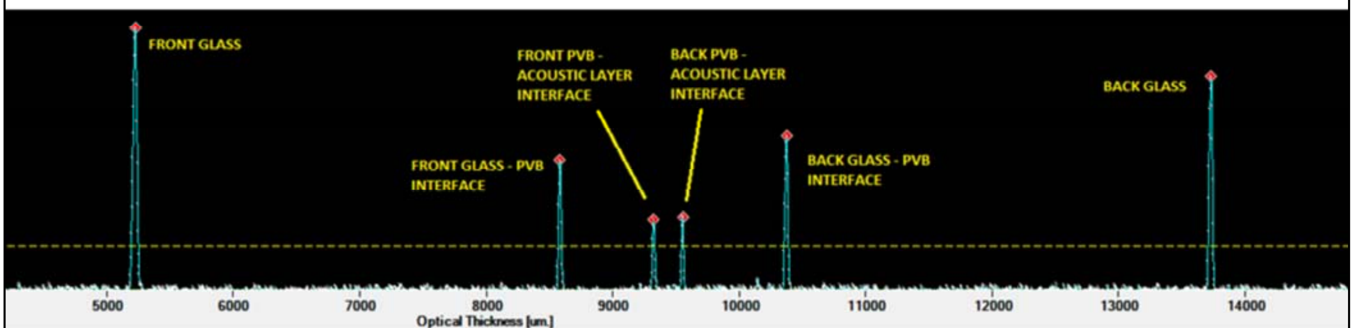


The probe emits the pulse of light, the pulse travels through the windshield, and then each interface within the windshield reflects the pulse back. The 4 pulses in this example then travel back to the probe, and then through the optical fiber into the box, which finds the time delay between the pulses. The time delay between the pulses then corresponds to the distances between the reflecting surfaces (i.e. to the thicknesses of the layers). Again, this is a very simplified description to enable the listener to develop understanding - the mechanism of operation is somewhat different in the actual implementation.

Because the probe acts as the emitter and receiver, there are no triangulation-related errors. The only requirement is to keep the probe oriented approximately perpendicular to the glass interface, so it can collect the reflected light. This technology is very good a detecting small reflections, so it can measure the thickness of the acoustic PVB layer as well.

LOW-COHERENCE INTERFEROMETRY

Windshield component	Measured thickness, mm
Exterior glass pane	2.213
PVB layer	1.207
Acoustic PVB layer	0.156
Interior glass pane	2.210



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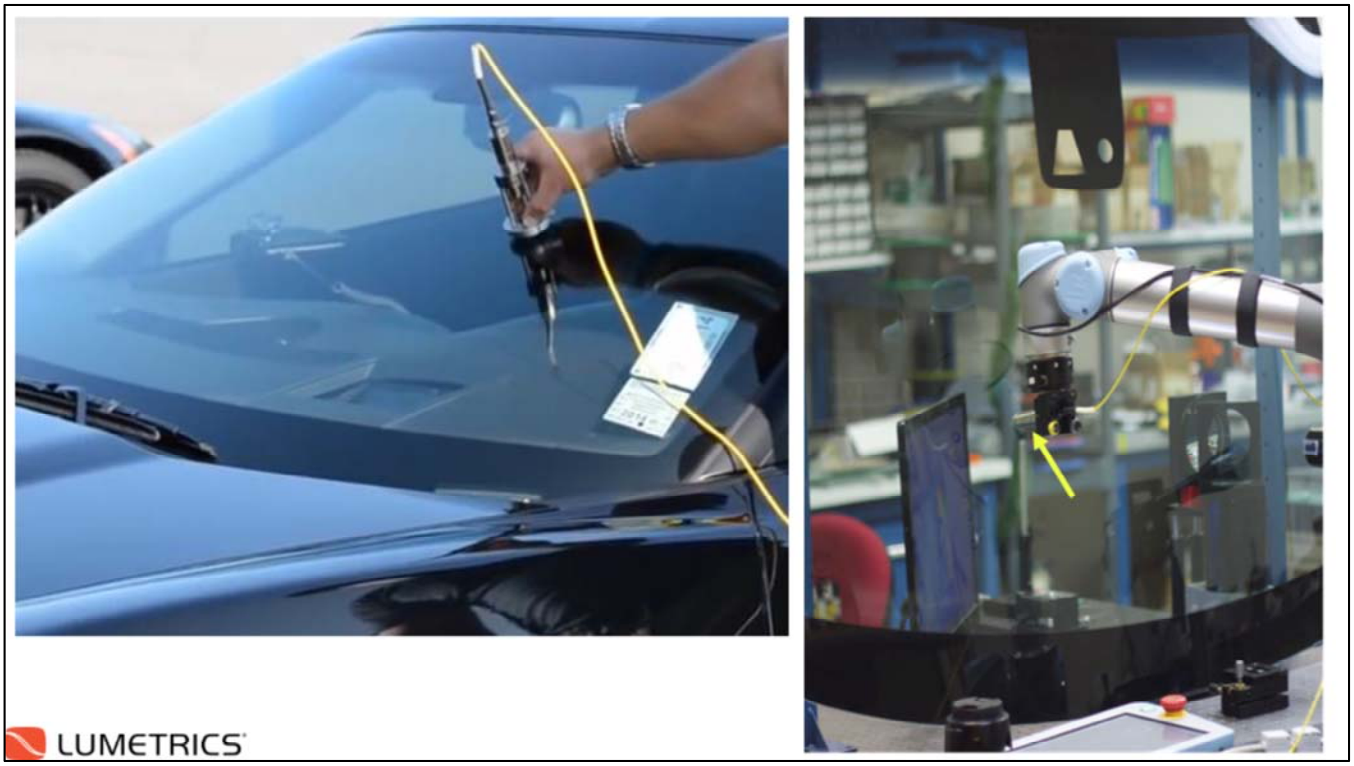
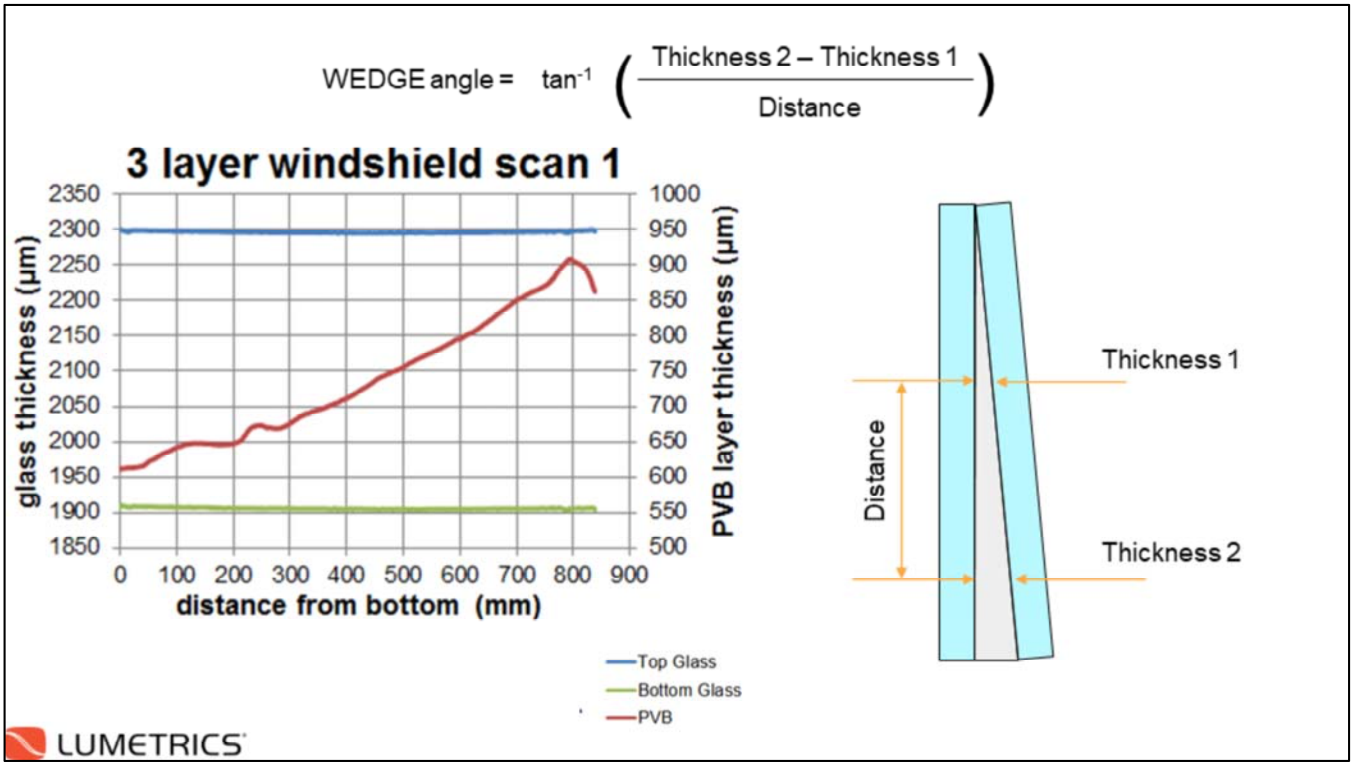
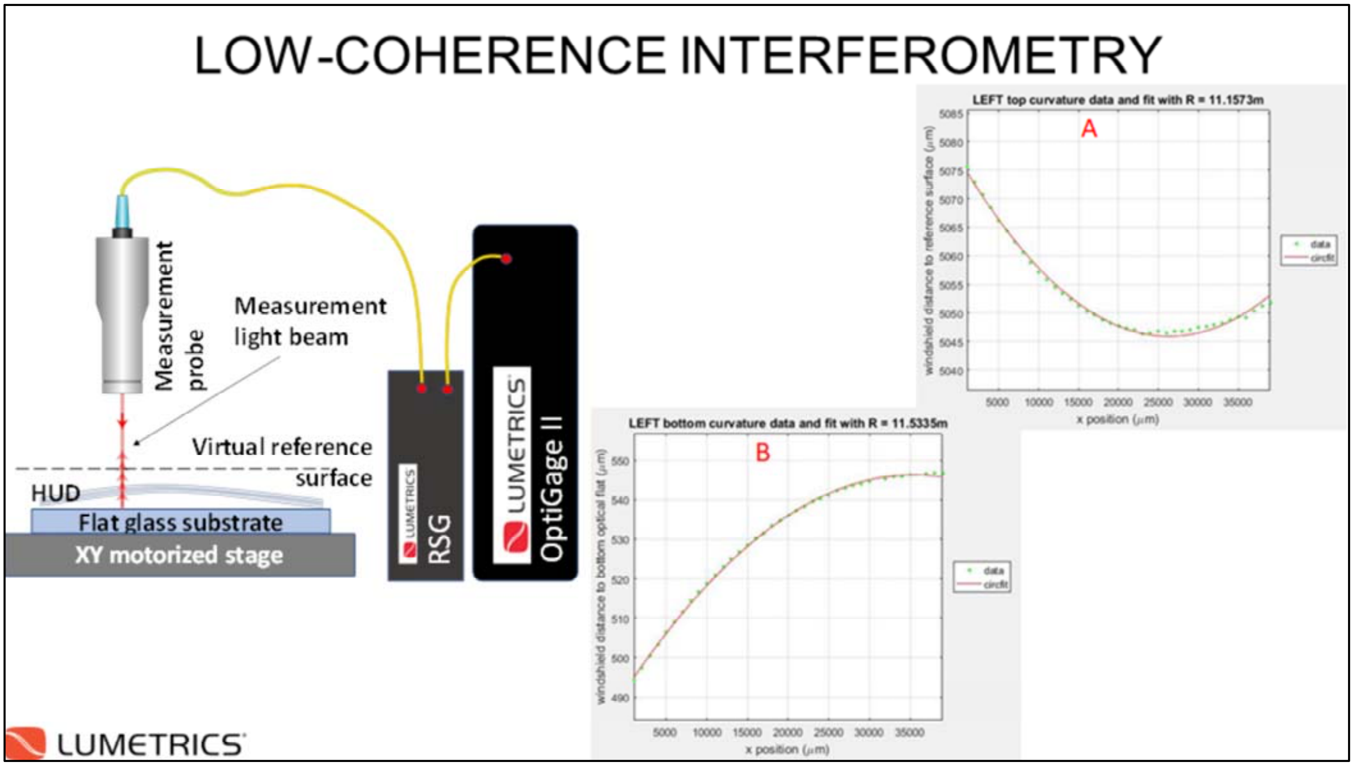
Here is an example of the signal we see from a windshield. View the graph peaks as the pulses reflected from all the interfaces within the windshield. These pulses are spread in time, but in this graph the time has already been converted to coordinates in free space. The thickness of each windshield layer is then obtained by dividing the distances between the corresponding pulses by the refractive index (a parameter inherent for each type of material). For glass, the refractive index is equal to 1.518, for PVB it is 1.485, and for acoustic layer it is 1.476.



The optical probe is a simple, robust and lightweight device. Therefore, it can be held by hand during the measurements. Or, the measurements can be automated by integrating the probe into an XY scanning stage or by mounting it on a robotic arm. When combining the probe with the robotic arm, it can also be used to measure the shape (radii of curvatures) of the windshield.



We used the probe mounted onto a scanner to assess thickness changes in the PVB, as well as in glass panes, in the HUD region. The red line in the graph shows the thickness of the PVB layer as a function of the distance. The graph immediately shows the inconsistencies in the PVB layer. The blue and green lines are the thickness of the two glass panes around the PVB layer.



This slide demonstrate measurements of the shape of the top and bottom surfaces of the windshield in the HUD area.

On the left is out flagship thickness measurement product. It uses 1310nm infrared light for measurements. For windshields with the IR coatings we have developed another instrument (on the right) that uses red light for measurements.

	Defects	Distortion	Shape	R of curvtr	Thkness	Wedge angle
Bright/dark field machine vision	Green	Yellow	Gray	Gray	Gray	Gray
Deflectometry in transmission	Yellow	Green	Yellow	Gray	Gray	Gray
Deflectometry in reflection	Yellow	Green	Green	Yellow	Gray	Gray
Secondary angle / laser deflection	Gray	Gray	Gray	Gray	Gray	Yellow / Green
Laser beam displacement	Gray	Gray	Yellow	Yellow	Yellow	Red
Shack Hartman wavefront sensor	Yellow	Green	Green	Green	Gray	Green
Low-coherence interferometry	Gray	Gray	Green	Green	Green	Green

- Green: Can be used with good accuracy
- Yellow: Can be used depending on requirements
- Red: Not recommended / insufficient accuracy
- Gray: Not applicable

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This slide summarizes the applicability of the optical technologies covered in this presentation. The green boxes mean that the technology is applicable and accurate. The yellow boxes mean that while you can use this technology for the corresponding application, be mindful of the measurement requirements and tolerances. Based on these requirements, the technology may not be the best suited. Red box means that the technology is not recommended for that application. The split cell for the Wedge angle measurement application using Laser deflection means that the technology works well in case of a single point measurement, but loses its accuracy if scanning is required.