DLP® Technology: Solar loading in augmented reality head-up display systems

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DLP® Technology: Solar loading in augmented reality head-up display systems

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Abstract: Next-generation automotive augmented reality (AR) head-up display (HUD) technology offers many advantages to OEMs, automotive customers, and drivers. However, the optics in a HUD system can magnify and focus sunlight to a portion of the display panel. Careful design and simulation are necessary to mitigate the threat of thermal failure.

Keywords: Head-up display, heads up display, HUD, augmented reality, AR, virtual image, sunlight, solar, temperature, thermal, Texas Instruments, TI, DLP, Kuraray, diffuser

1 Background[1][2][3]

“Augmented reality” has become a ubiquitous phrase in the automotive head-up display industry as recent technological advances enable larger fields of view (FOV) that more fully cover the driver’s forward-looking scene, and longer virtual image distance (VID) to put the HUD graphics closer to relevant real-world objects [1]. These next-generation display systems decrease “eyes-off-road” time by moving information into the driver’s field of view, reduce ocular accommodation time by placing information further away [2], and reduce cognitive loading by contextually attaching information to relevant objects [3].

However, the differences in optical architecture compared to conventional HUDs introduce environmental challenges for the display system. Compared to conventional HUDs on the road today, AR HUD systems have a larger FOV, larger eyebox size, and longer VID. These qualities result in a larger sunlight collection area and higher concentration of that collected energy, causing the potential for high levels of solar irradiance inside the HUD system during every day driving conditions. These concerns warrant additional consideration during the design process that may not have been necessary for conventional HUD systems. Care must be taken to understand what levels of solar irradiance a HUD system might experience during the vehicle's lifetime, and make design choices accordingly. Detailed optical simulation and material testing are necessary to accurately predict the temperature rise of the material onto which the sunlight is incident.

Texas Instruments (TI) has designed and built a prototype AR HUD system based on DLP® technology. This architecture offers benefits in handling focused sunlight. Projection-type HUDs utilize a diffuser screen (pupil expander) which acts as an intermediate image plane. TI and Kuraray have worked together to develop a high efficiency diffuser screen that offers excellent image quality and can handle the high levels of solar irradiance that are possible in these types of AR HUD systems.

This paper offers a thorough exploration of sunlight focus and solar load in an AR HUD prototype, including incoming sunlight assumptions and typical spectral filtering employed by current HUD systems. Simplistic approaches to sunlight modeling involve simulating sunlight along the chief ray of the HUD optics. It will be shown that off-axis sunlight has the potential to cause higher levels of irradiance. Additionally, a variety of mitigation techniques will be discussed as possible options for reducing the solar irradiance to an acceptable level. Real-world testing done by Kuraray on their diffuser screen technology allows us to predict temperature rise of the screen material and ensure that it stays within its thermal limits. Kuraray also tested materials used in emissive display HUD systems and saw a significant temperature rise to the point of visible damage.

2 Optical properties of AR HUD

Geometrical optics describes the relationship between an object, a lens, and the resulting image. Placing an object between a lens and its focal point will create a virtual image that is magnified and appears some distance beyond the object [4]. This method is how HUDs create virtual images. The source object (in this case a diffuser screen or TFT panel) is positioned within the focal length of the HUD mirror optical system. This causes the virtual image to appear projected some distance out in front of the viewer.

The Gaussian imaging equation dictates that in order to increase the virtual image distance we must move the source object closer to the focal point of the optical system, as shown in Figure 1.

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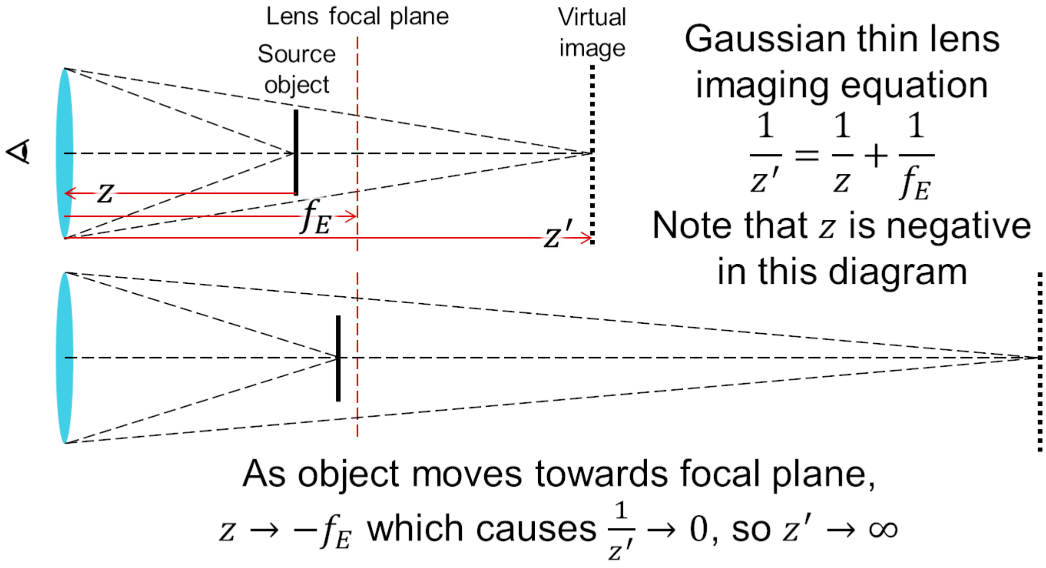

Figure 1. Gaussian optics describes the relationship between object distance (z), image distance (z'), and focal length (f_E) [4]. To achieve a longer virtual image distance the object approaches the focal plane.

When sunlight enters an optical system it tends to focus to the focal point as seen in Figure 2. This concept holds true for HUD optics. HUDs with longer VIDs position the source object closer to the focal point of the HUD optics causing the potential for higher levels of solar concentration on that device. The virtual image distance (VID) of conventional HUDs is around 2.5 m, putting the virtual image close to the vehicle's front bumper. A short VID like this results in little solar concentration because the display panel is not very close to the focal plane. However, the longer VID of AR HUDs requires the display panel to be closer to the focal plane which can cause much more sunlight focus. VID requirements for AR HUD are implementation dependent and open to debate but are typically at least 7 m and often desired to be greater [5].

VID is highly influential on the amount of solar irradiance on the screen. For example, Figure 3 shows solar irradiance in TI's AR HUD prototype configured for two VIDs: 7 m and 15 m. 15-m VID results in higher concentration of solar radiation on the screen because the screen is closer to the focal plane than the 7-m configuration. Careful simulation and analysis are necessary to predict the amount of solar irradiance that is possible and implement mitigation techniques to prevent overheating. The following sections describe one such analysis method and offer a few mitigation techniques that may be applied.

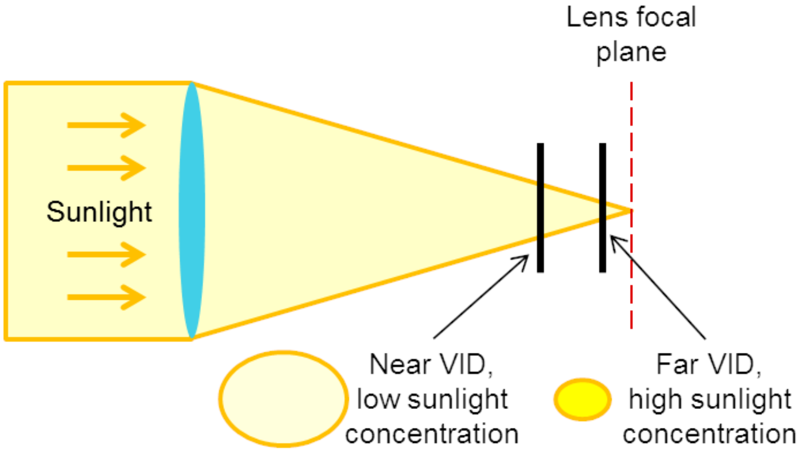

Figure 2. Collimated sunlight will focus towards the focal plane. Objects placed closer to the focal plane will experience higher sunlight concentration (solar irradiance).

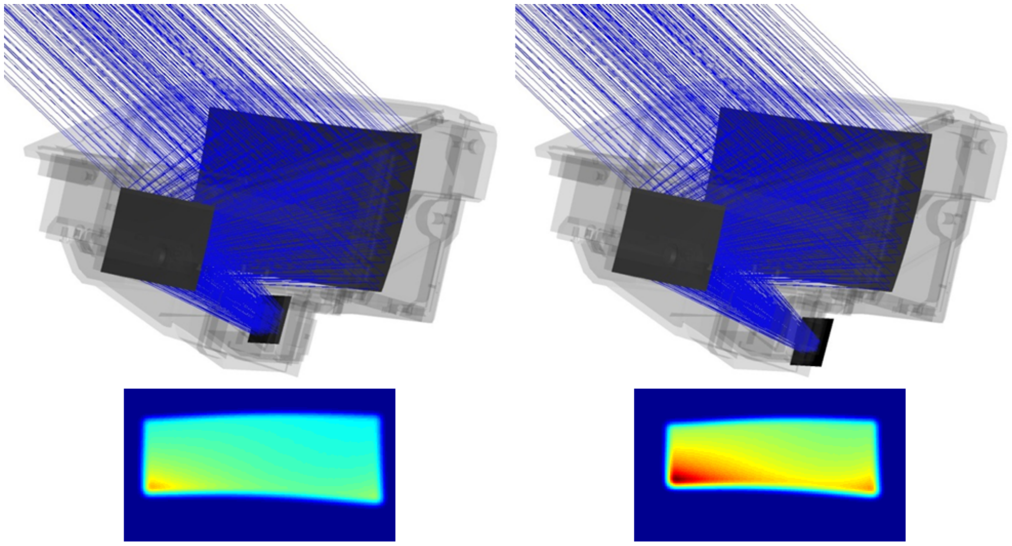

Figure 3. TI AR HUD prototype optimized for 7-m VID (left) and 15-m VID (right). Irradiance distribution on screen shows significantly higher peak irradiance for longer VID configuration.

3 Modeling sunlight in Zemax

Through careful design and simulation it is possible to predict the maximum levels of solar irradiance a HUD system can experience during outdoor driving conditions. Zemax OpticStudio® 17 was used to simulate sunlight propagating through the HUD optical system. The simulation relies on an accurate sunlight source model with proper angular, spectral, and irradiance characteristics. The solar spectrum data used in this analysis (Figure 4) is the ASTM G173-03 Reference Spectrum [6].

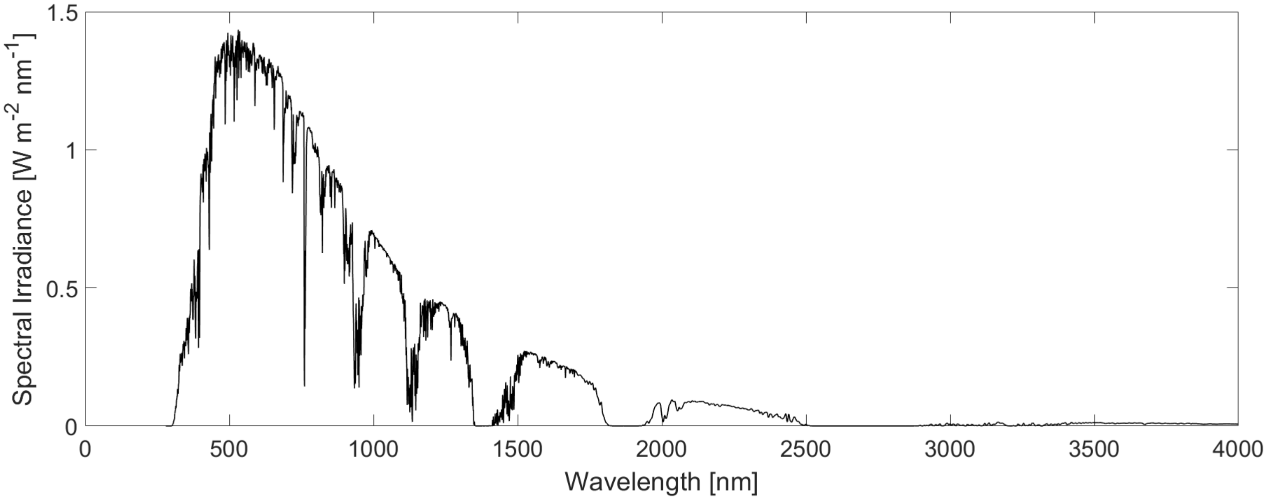

Figure 4. ASTM G173-03 Reference Spectrum (direct + circumsolar) [6]. Total integrated irradiance is 900.14 W/m^2.

This reference spectrum describes the spectral distribution of irradiance at earth's surface, after filtering by the atmosphere. However, this data was captured with the sun at a 37 degree angle and solar irradiance is greater for direct overhead sunlight. Total integrated irradiance from the reference spectrum is 900 W/m^2 but maximum possible direct overhead irradiance on earth's surface is 1050 W/m^2 [7] so the spectral data must be scaled to match this.

Sunlight is attenuated by various optical elements in the car including (but not limited to) the windshield, glare trap, and hot/cold mirrors. The spectral transmission curves of these elements must be taken into consideration for sunlight modeling. Since there is significant design flexibility in these HUD systems, the following simulations will make some assumptions and simplifications that result in a conservative estimate of maximum possible irradiance. First, we assume complete attenuation of invisible radiation (UV and IR). Current HUD architectures employ spectral filtering with the windshield, glare trap, and hot/cold mirrors to reduce this invisible radiation but exact spectral curves of these elements vary between designs. It is expected that future HUD designs will employ more aggressive spectral filtering around the emission wavelengths of the HUD light source. For example, newer windshields may offer additional IR/UV filtering [8] resulting in less invisible sunlight energy entering the HUD system. In this analysis the filter is assumed to eliminate wavelengths around the measured spectral output of TI's AR HUD prototype system. Figure 5 shows the measured HUD spectral emission and the portion of sunlight that could be filtered out without affecting the HUD virtual image.

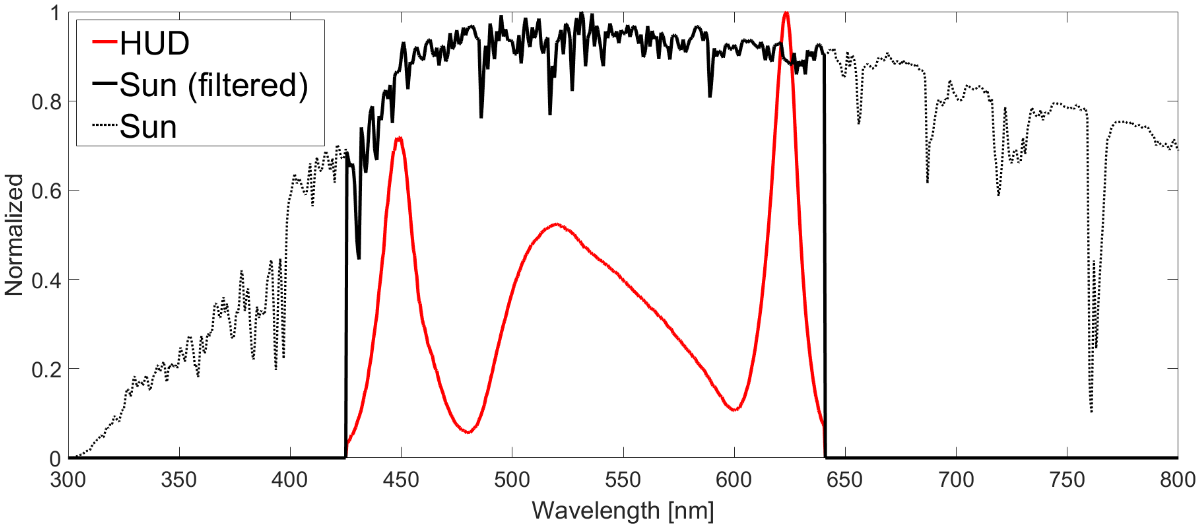

Figure 5. Spectral filtering can reduce sunlight energy entering the HUD system. HUD energy is contained between 420 nm and 640 nm. Filtering lower and higher wavelengths can reduce sunlight energy with minimal effect on HUD light. Full spectrum irradiance of 1050 W/m^2 is reduced to 325 W/m^2 after spectral filtering.

The relative transmission of various elements is also estimated to reduce the overall sunlight loading by an additional 25%. These losses are summarized in Table 1. Based on these assumptions, the resulting maximum possible solar irradiance entering the HUD system is approximately 244 W/m^2.

Table 1. Assumed efficiencies of optical elements that attenuate sunlight entering HUD system.[1]

Optical Element	Efficiency
Windshield	83%
Glare Trap	95%
Mirror	95%
Total	**75%**

(1) Windshield efficiency estimated based on Fresnel equations for 2 surfaces, n = 1.5, AOI = 60° [9]. Glare trap and mirror efficiencies are conservative estimates based on measurements and common specs. These values vary system to system and must be characterized in more detail for individual system analysis.

A more accurate (but more computationally intensive) approach is to characterize the spectral transmission curves of each optical component in the sunlight path. It is possible to load this transmission data in Zemax for a more physically accurate ray trace, but for these simulations the energy loss was approximated to speed up raytracing.

Modeling sunlight geometry in Zemax can be accomplished with a “Source Radial” object with radial intensity values set based on circumsolar measurement data from Grether, Nelson, & Wahlig, 1975 [10]. The resulting angular intensity plot in Figure 6 shows that the sun emits light in a ~0.5 degree circle. Alternatively, the “Source Two Angle” object can be used with the X and Y half angle set to 0.25 degrees. While this does not incorporate the angular intensity variation across the disc of the sun, it is sufficiently accurate for this kind of simulation.

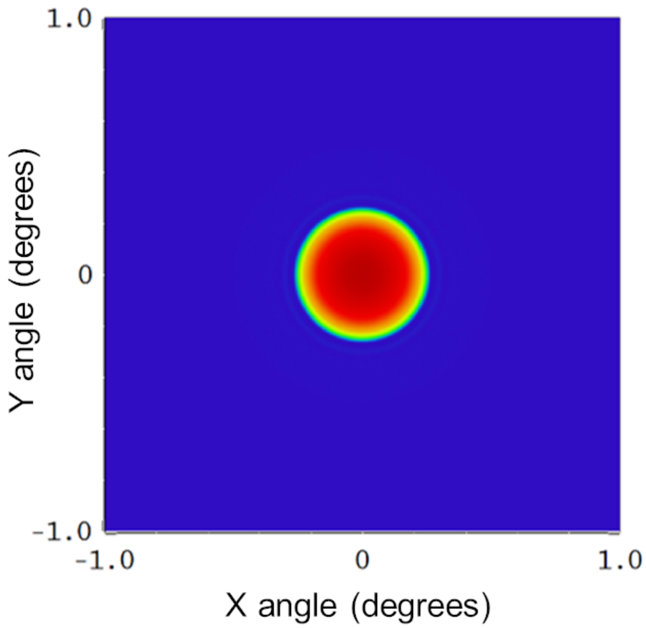

Figure 6. Angular intensity of “Source Radial” sunlight source used in simulations.

In Zemax the sunlight spectrum can be modeled as a subset of the blackbody spectrum contained between two wavelengths [11]. For this analysis a 5800K blackbody source was defined between 400 and 700 nm with 100 discrete spectral lines. The source power in W must be calculated based on the source area to achieve a desired level of irradiance. It’s possible to specify the source area as a 1-m × 1-m square so that the source power is equal to the source irradiance, but this is computationally inefficient as many source rays miss the HUD altogether. It is more efficient to closely match the source area to the entrance aperture of the HUD system. In this simulation the source was defined as a 0.34-m × 0.2-m rectangle to more closely match the HUD optics, requiring a source power of 16.6 W to achieve 244 W/m^2.

During every day driving, vehicles can experience a wide range of input sunlight angles as the car turns and tilts up and down on hills. Therefore it is important to scan the incoming sunlight across an appropriate range of angles. For example, if the target vehicle is a convertible there are more opportunities for sunlight to enter the HUD system than in other vehicles. This simulation started by aligning the sunlight source with the HUD chief ray propagating out through the windshield, but it was found that significantly higher levels of irradiance were possible for off-axis sunlight. To find which input angle would result in the highest level of irradiance a script was used to scan the sunlight source around a range of angles centered on the entrance aperture. This can be accomplished with a Zemax macro, or using one of the various API options built into Zemax. This analysis used the MATLAB API, but the same technique can be done with C#, C++, or Python. Figure 7 shows the sunlight source layout and the rotation axes.

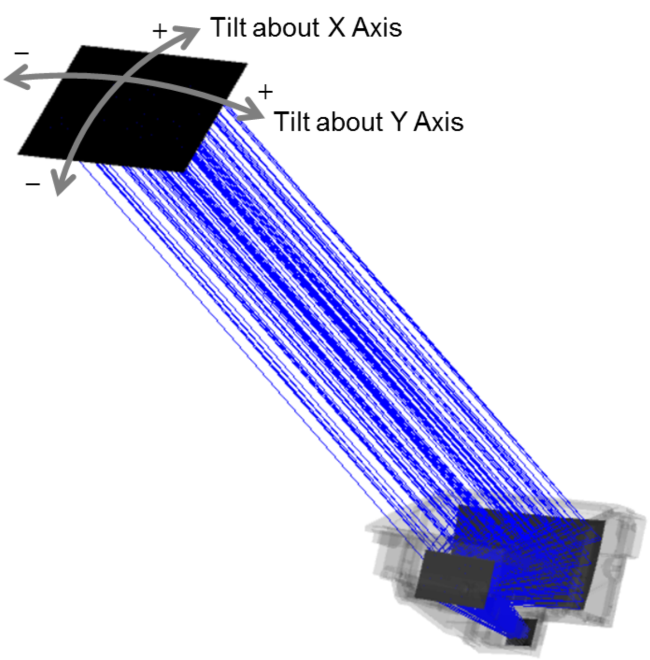

Figure 7. Real-world driving conditions are wide-ranging so it is important to scan the simulated sunlight source across a range of input angles. On-axis rays are shown here.

The script varied the X and Y tilts at 1 degree intervals. At each X and Y tilt the peak irradiance at the screen surface was recorded. These values were used to generate the plot in Figure 8, showing us that the worst case irradiance on screen is not on-axis (0, 0), but rather sunlight entering the system at a (3, 7) degree angular deviation from the optical axis. Comparing on- and off-axis irradiance distributions on the screen in Figure 9 we can see that the sunlight is concentrated into a smaller area resulting in a higher localized irradiance spot, even though the total flux may be less than the on-axis case. In the case of the TI AR HUD prototype, the peak solar irradiance simulated on screen was 40 kW/m^2 for the 7-m VID configuration and 57 kW/m^2 for the 15-m VID configuration.

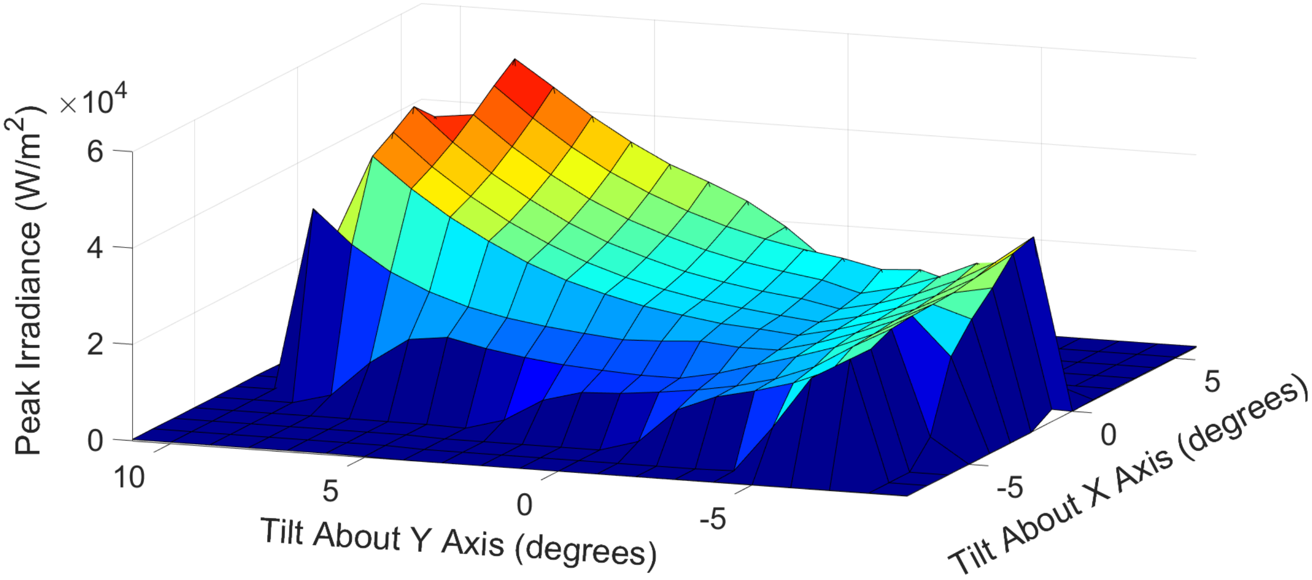

Figure 8. Peak irradiance on screen as a function of input sunlight angle. Peak irradiance can be much higher for off-axis sunlight. Worst case peak irradiance for TI AR HUD prototype was found to be at 3 and 7 degree tilt about the X and Y axes, respectively.

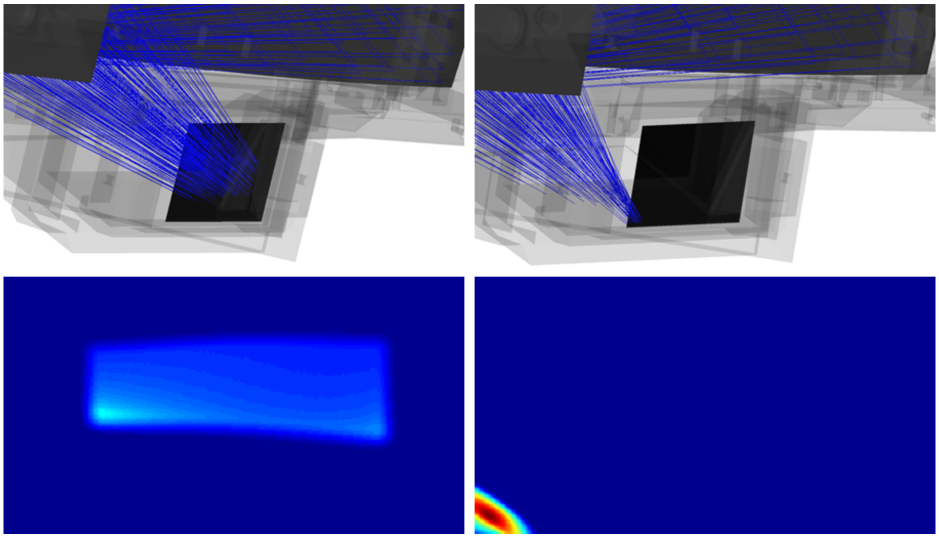

Figure 9. On-axis (left) and worst case off-axis (right) solar irradiance simulated in TI's AR HUD prototype system. In this case, worst case off-axis peak irradiance was 2.7x on-axis peak irradiance.

It is important to note that these simulations only recorded irradiance incident on the screen area. It is possible that higher irradiance may occur off-screen so care must be taken to simulate and understand this and choose suitable mechanical enclosure materials.

4 Thermal effects of solar irradiance

Simulating peak solar irradiance is only the first step in predicting and avoiding thermal failure. Solar energy is converted to heat based on the spectral absorption of the material onto which it is incident.

The micro lens array (MLA) screen used in the DLP HUD is molded with UV curable resin on 0.3-mm thick polycarbonate film. The absorption of the MLA screen is shown in Figure 10. From the spectral radiation of sunlight (AM 1.5 G) and the absorption of the MLA screen, the solar radiation absorbed by the MLA screen is shown in Figure 11. It is necessary to take preventative measures such that absorption in the vicinity of 350 nm, around 1680 nm, and longer than 2000 nm is greatly reduced in order to prevent thermal failure.

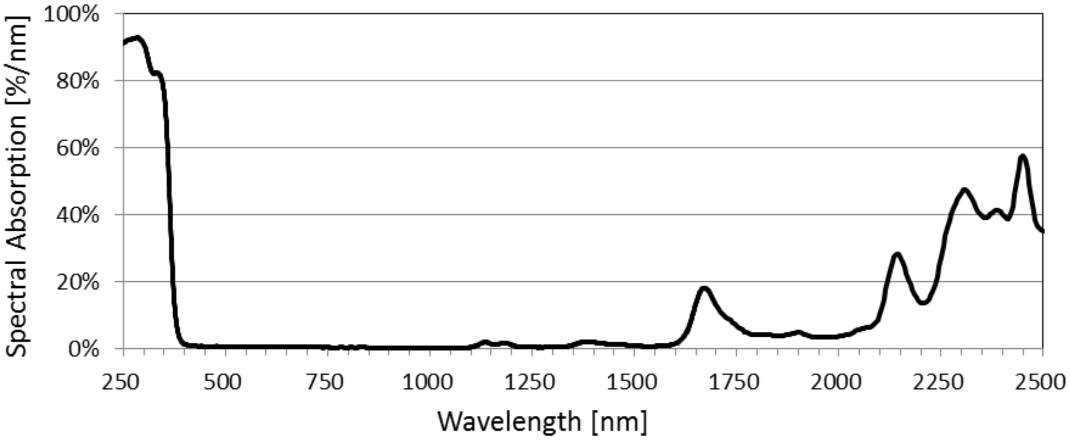

Figure 10. Spectral absorption of MLA screen.

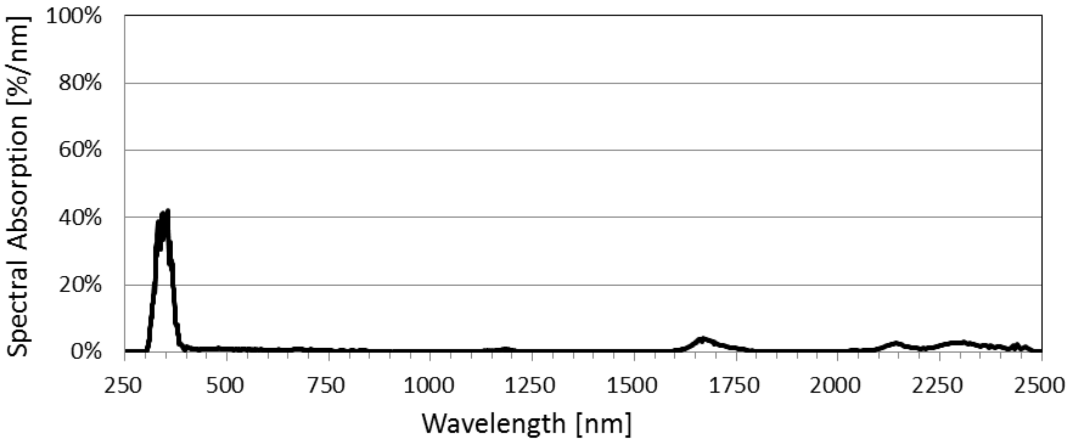

Figure 11. Spectral absorption of MLA screen multiplied by reference solar spectrum (AM 1.5 G).

5 Real-world testing

Real-world testing was performed on a MLA screen and a TFT panel exposed to various levels of solar irradiance. The MLA screen was made by Kuraray and the TFT panel (Figure 12) was removed from a HUD module from a 2016 BMW F30.

Figure 12. TFT panel used for sunlight testing. Part number E06030K16.

Sunlight was focused on the MLA screen with a Fresnel lens (Figure 13). The relationship between the distance from the Fresnel lens to the MLA screen and the solar irradiance was measured with an optical power meter, and the distance from the Fresnel lens to MLA screen was adjusted so as to obtain the desired solar irradiance. The temperature of the MLA screen was measured with a thermal camera. The emissivity for measuring the temperature with the thermal camera was 0.902 obtained from the absorption spectrum.

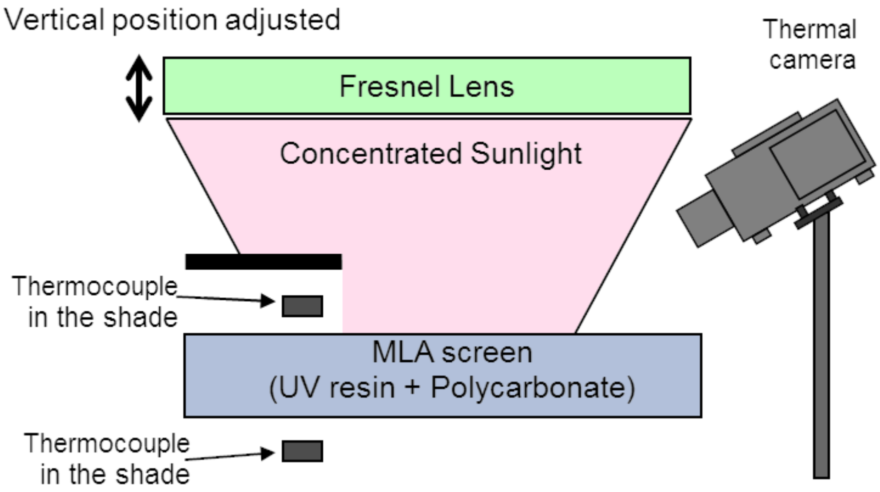

Figure 13. Test setup for measuring temperature as a function of solar irradiance.

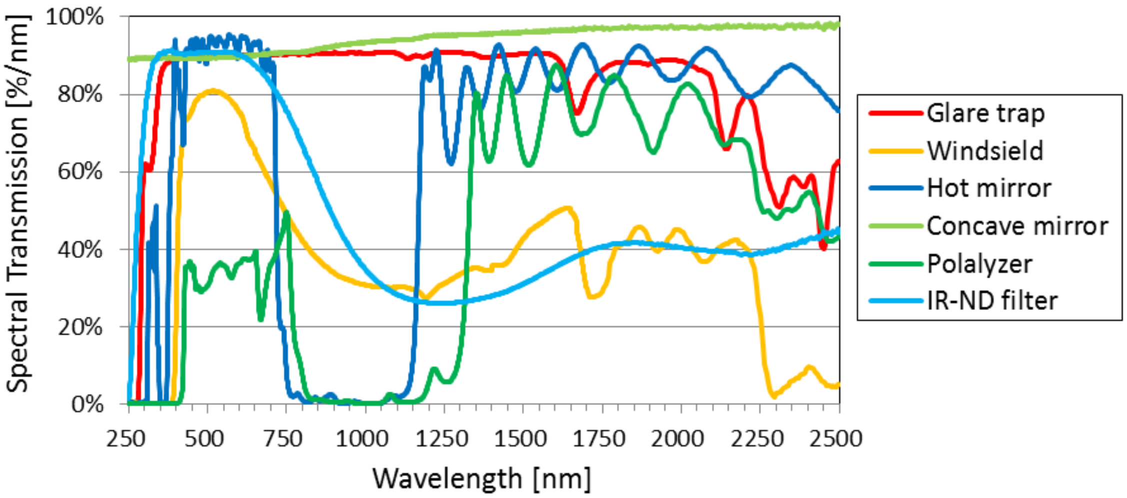

Figure 14. Spectral transmittance curves for various optical elements that are commonly found in automotive HUD systems as measured by a spectrophotometer (Hitachi U-4100).

Table 2. Three test conditions for determining relationship between solar irradiance and temperature rise.

Test Condition	Optical element stack
A	Windshield, glare trap, concave mirror, MLA screen
B	Windshield, glare trap, concave mirror, hot mirror, IR-ND filter, MLA screen
C(1)	Windshield, glare trap, concave mirror, polarizer, TFT panel

(1) Note condition C is testing a TFT panel.

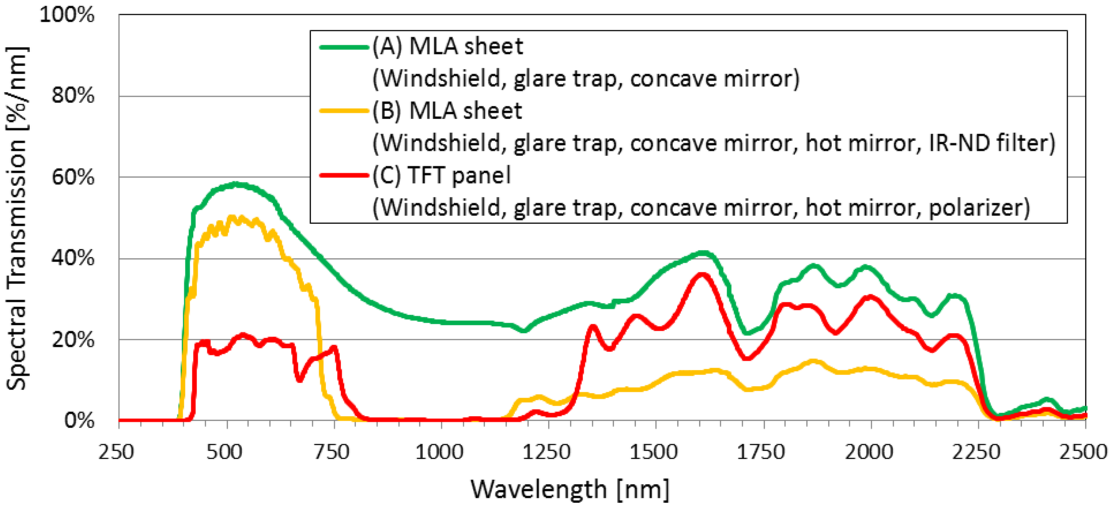

Figure 15. Spectral transmission of optical stack for three test conditions described in Table 2.

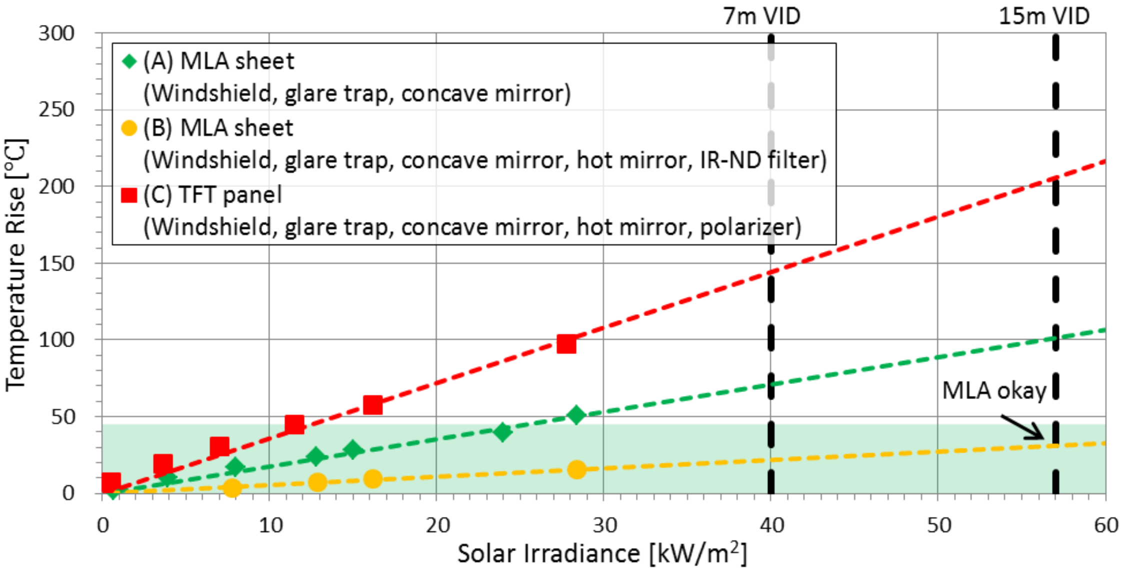

Figure 16. Temperature rise vs solar irradiance. Vertical lines are shown for the predicted solar irradiance in the TI AR HUD prototype configured for 7-m and 15-m VID. TFT temperature was seen to increase 6x faster than MLA under similar solar irradiance. The green shaded region indicates temperature rise less than 45°C.

In the experiment, the MLA screen and TFT panel were exposed to concentrated sunlight passing through various optical components described by three conditions in Table 2. The spectral transmission of each optical element is shown in Figure 14 and the combined spectral transmission of each condition from Table 2 is shown in Figure 15. It can be seen in Figure 16 that the TFT panel temperature (condition C) rises significantly faster than the other 2 test conditions even though that condition rejects the most visible sunlight due to the polarizer.

Assuming a maximum ambient inner-dashboard temperature of 105°C, the maximum temperature rise due to solar loading must be less than 45°C to maintain a screen temperature below its maximum operating temperature of 150°C. In the case of condition (A), 26 kW/m^2 solar irradiance caused a temperature rise of 45°C. If the maximum HUD solar irradiance is less than 26 kW/m^2 the temperature of the MLA screen will be less than 150°C, so thermal failure can be avoided. In the case of condition (B) 82 kW/m^2 is predicted to cause a temperature rise of 45°C. In condition (C) just 12 kW/m^2 is predicted to cause a temperature rise of 45°C. Based on this data it can be seen that HUD architectures based on DLP projection technology and Kuraray MLA screen technology are well suited for the increased solar loading of next-generation AR HUD systems.

The potential for temperature rise due to solar irradiance grows significantly with increasing VID. Conventional HUDs on the roads today don't experience this amount of irradiance due to the smaller collection area and shorter VID of around 2.5 m. AR HUDs demand longer VID and larger optics causing the potential for much higher levels of solar irradiance and therefore much higher temperature rise on the display panel. TFT panels are highly absorptive and are therefore more susceptible to damage from solar irradiance than transmissive MLA screens.

6 Techniques for sunlight mitigation

In certain cases the predicted levels of solar irradiance may be higher than the materials can tolerate. In these cases the designer may wish to incorporate one of the following strategies to reduce the level of solar irradiance. Projection-type HUD architectures such as those using DLP technology enable the flexibility of changing the intermediate image size, which in turn changes the magnification between the intermediate and virtual images. Lower magnification will result in lower solar irradiance on the screen. There are, however, other tradeoffs associated with decreasing system magnification (such as overall HUD package size) so this may not always be the best solution.

Tinting and polarization can also reduce the amount of sunlight incident on the screen. Tint can be applied to various elements in the optical path with similar effects. However, no matter where the tinting is applied it will also reduce HUD brightness by an equal percentage, which can make it difficult to achieve the desired 17,000 cd/m^2 virtual image brightness [1] [2]. Polarization-based sunlight filtering schemes require light from the HUD to be polarized as well. This severely impacts HUD image visibility while wearing polarizing sunglasses, which is a critical performance requirement for next-generation AR HUD systems [1]. However, from the data in Figure 15 and Figure 16 it can be seen that even with polarization removing nearly 50% of the visible sunlight energy (condition C), the TFT panel still reached critical temperatures under relatively low solar irradiance.

The increasing availability of laser light sources suitable for automotive applications [12] opens up the opportunity for narrow-band tri-pass spectral filtering to reject sunlight. In the case of direct laser illumination (as opposed to laser-phosphor or LED sources), the HUD light energy will exist within narrow bands corresponding to the laser emission wavelengths. A spectral filter designed to transmit just these three bands can reflect up to 92% of sunlight energy, assuming a 20-nm notch width as shown in Figure 17.

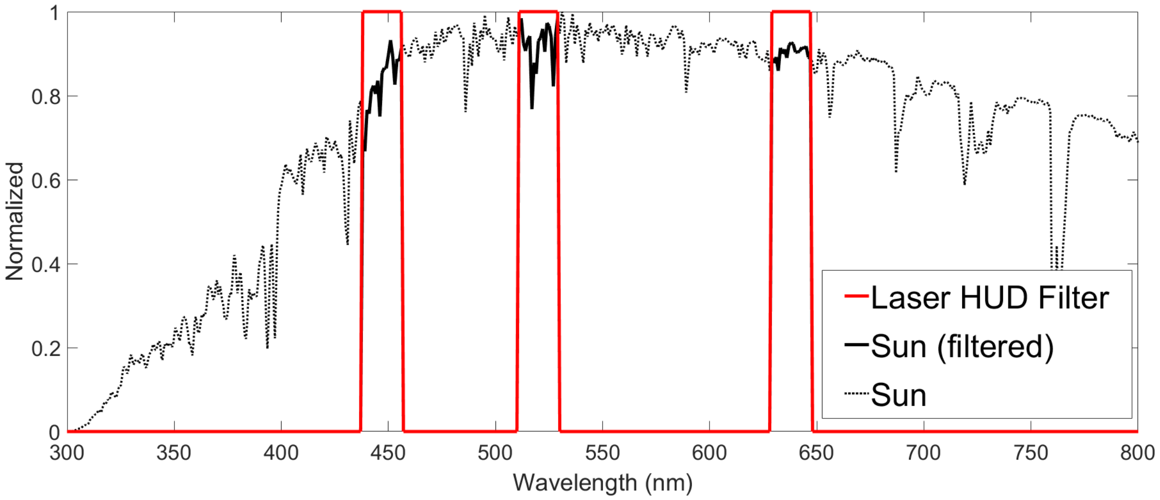

Figure 17. Tri-pass 20-nm notch filter designed around direct laser wavelengths could dramatically reduce sunlight entering HUD system.

There are various challenges with direct laser sources in automotive applications, such as temperature stability and lifetime. As the technology matures system-level benefits of using narrow-band light sources will become possible. HUDs based on DLP technology are illumination source-agnostic, meaning they can be designed to utilize LED or laser light sources efficiently. DLP technology is able to make use of the benefits of laser light sources for improved sunlight rejection and other system performance improvements such as color saturation, size reduction, contrast improvement, and power efficiency [12].

7 Conclusion

Next-generation AR HUD systems must be carefully designed with environmental conditions in mind throughout the design process. Sunlight poses a considerable challenge due to higher levels of magnification and larger sunlight collection area in AR HUDs than has been seen in conventional HUD designs. Care must be taken to understand the potential sunlight focus in AR HUD designs, and make design choices or employ mitigation techniques to bring the solar irradiance to an acceptable level. The amount of acceptable solar irradiance is highly dependent on materials located at the HUD image source. In the case of projection-type HUDs, such as HUDs based on DLP technology, the diffuser screen takes the brunt of this solar irradiance and therefore must be able to withstand the amount of solar energy loading expected.

MLA diffuser screen technology made by Kuraray has been designed to withstand these environmental conditions. The transmissive nature of the screen results in minimal energy absorption and therefore causes very little temperature rise. With proper design techniques, the predicted temperature rise of these screens under the most demanding conditions is still below the operating temperature capability of the diffuser screen materials. This ensures the system will withstand the potentially damaging levels of solar irradiance while maintaining a bright, high-resolution, vibrant image that has become standard in the automotive HUD industry.

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