# Holographic AR HUD with Large FOV and Aberration Correction

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## Abstract
Holographic AR (Augmented Reality) HUDs (Head-Up Displays) enable a large virtual image to be overlaid in the drivers FOV (Field of View) at a far distance. The optical function of the HUD is encoded in a holographic film which can be laminated into the windscreen of the vehicle. The volume of the optical engine under the dashboard is significantly reduced compared to a traditional HUD. The single element hologram includes aberration correction.

## Author Keywords
Hologram; Holographic; Augmented reality; AR; Head-up Display; Automotive HUD; AR-HUD.

## 1. Objective and background
The automotive industry would like to progress to the next generation of AR HUDs, where the virtual image could overlay 3 lanes of the road. To achieve the large FOV required, there would likely be a hologram laminated into the windscreen of the vehicle.

The hologram must not affect the see-through of the real world, therefore large continuous holograms are required. The virtual image should be perceived at a far distance (3-20 metres) so the driver can focus on the real world and virtual image at the same time.

Conventional HUDs rely on specular reflection from the windscreen which limits image brightness and requires wedged windscreens to minimise double images. This also limits the possible replay geometry. The volume required under the dashboard scales with FOV, as a collimating optic is required. This limits the maximum FOV.

A holographic AR HUD allows for off-axis (non-specular) replay geometry with high brightness, large FOV and a large eyebox.

A single element off-axis holographic system normally has aberrations, reducing the image quality. The aim of the project is to record large area holograms with aberration correction to generate high quality, large FOV images.

The AR HUD improves driver safety as information such as speed, directions and any warnings are displayed in the drivers eyeline. The driver does not need to look away from the road to obtain this information. Also, as the AR HUD virtual image appears at a far distance, the driver does not need to refocus at a close distance to obtain the information, as is normally necessary when information is on the dashboard/ instrument cluster.

## 2. Results
A large holographic optical element (HOE) of 400x300 mm has been recorded. The resulting FOV from the typical driver viewing position is at least 20x15 degrees (HxV) with a large eyebox (at least 150x100 mm). The hologram is currently monochrome red but will be manufactured in full colour RGB in future.

The hologram is recorded with a novel phase profile, such that the aberrations are field-invariant. Zemax models have been created to show the optical performance. The virtual image distance is > 5 metres.

The hologram is a volume phase reflection hologram (VPH) which minimises the effects of unwanted diffraction orders. The hologram is wavelength and angle selective which helps maintain real world see through performance.

The HOE is continuous, having been recorded with large optical elements and a single continuous wavefront. Therefore, the hologram is free from artifacts, compared to a hologram created by pixel by pixel recording methods (discontinuous wavefronts) which may show edge artifacts in the far-field. The hologram material is proprietary silver halide, but could be copied into photopolymer e.g. Covestro Bayfol.

Automotive manufacturers have very strict requirements on transparency, haze and any artifacts (e.g. rainbowing around sunlight/car lights), therefore we believe a large continuous wavefront analogue master hologram is potentially preferred over a large area pixelated master which may introduce haze or artifacts into the copied photopolymer. However, to record the large sizes of hologram required for a large FOV AR HUD, large optical elements and highly sensitive material is needed, such as silver halide.

The silver halide material is manufactured in-house and therefore certain parameters can be optimised (emulsion thickness, coating dimensions, bandwidth, wavelength sensitivity (RGB can be recorded), dosage requirement). Typically, the intensity and dosage to expose silver halide holograms is at least 30 times less than for photopolymer which allows for larger area holograms to be exposed with uniform intensity. Shorter recording times allows for greater vibration stability and higher hologram efficiency. The silver halide master can be copied into photopolymer with a high intensity copy beam for mass manufacturing. Trulife Optics has equipment and expertise in reel to reel copying.

Photopolymer typically has higher transparency than silver halide and is more suited for mass manufacturing due to the dry processing requirements. Trulife Optics has developed a proprietary technique for processing silver halide such that higher transparency is achieved and there is no print-out (silver halide normally darkens over time with exposure to light – a process known as print-out). This process is called Silver Halide Sensitised Gelatin (SHSG) and potentially allows silver halide to be used as the final holographic material.

The recording setup consists of a high power (500 mW) 640 nm laser which is expanded and collimated by a large lens/mirror (15 inch diameter) to record a hologram of 400x300 mm (with some beam clipping in the corners, larger sizes are possible in future). The hologram is tilted relative to the collimated reference beam at about 56 degrees to the normal (to mimic a car windscreen rake angle) The object beam is a diverging beam from about 400 mm to cover the hologram area (a typical image source to windscreen distance). The object beam is at approximately normal incidence to the hologram plane. See figure 1.

Unwanted artifacts (e.g. transmission artifacts generated during recording due to Fresnel reflections from the glass/emulsion


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surfaces) can be recorded into the hologram, which could result in artifacts visible during use of the HUD. This is mitigated by using single sided AR (Anti-Reflection) glass during recording to reduce reflections from the object beam, and polarized laser light (P polarized) at Brewster's angle (approximately 56 degrees) to minimize reflections from the reference beam.

This is a standard holographic HUD setup. This leads to perfect image quality at the centre of the FOV, but due to the extended image source size there are normally field dependent aberrations towards the edge of the FOV. This can result in 'image swim' where the virtual image appears to move as the viewer moves around the eyebox.

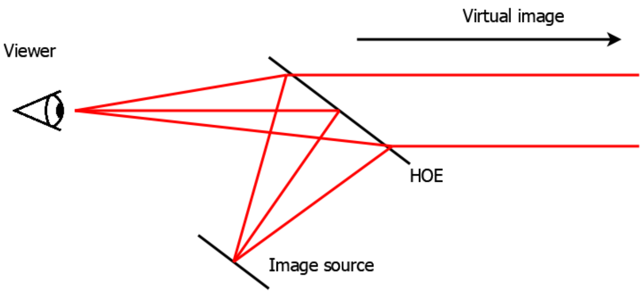


**Figure 1.** Typical holographic HUD replay geometry (HOE in windscreen)

The novel part of our design is to modify the object beam to a proprietary phase profile. This results in field-invariant aberrations across the FOV, reducing image swim. The aberrations are effectively averaged out across the FOV, slightly reducing the centre field resolution but providing a better image quality as the viewer moves around the eyebox. (see Figure 2.)

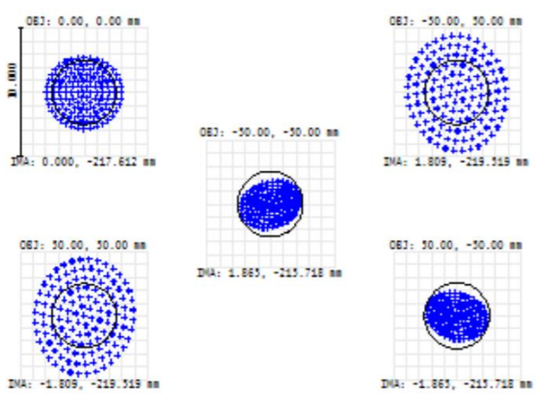

**Figure 2.** Image simulation of spot size (as seen by the eye) at 5 field points. The eye is in the centre of the eyebox in this simulation.

It has been shown that two element freeform holographic HUDs can also show field-invariant aberrations (5); however this requires an extra hologram, which would take up more volume under the dashboard, which is not desired. Our single element hologram solution provides adequate image quality with the simplest and most compact method.

The hologram is recorded and replayed on a flat substrate. The recording can be adjusted to account for the hologram curvature that would occur once laminated into a curved windscreen.

An advantage of a holographic HUD over a conventional HUD is that the complexity and size of the collimating optics (used to set the far virtual image distance) can be optimized during holographic recording. The hologram then adds the optical power needed in the HUD. For example, we have used a large diameter f/10 achromatic doublet for optimal collimation quality. It would be difficult to achieve this optical quality with lens/mirrors in the volume under a dashboard, especially as the desired FOV for AR HUDs increases. This also reduces the cost, weight and volume under the dashboard considerably. There are also less alignment/tolerance issues with a simple holographic HUD.

The off-axis geometry (non-specular) achievable with a holographic HUD laminated in a windscreen would allow vehicles with flat/low rake windscreens to have HUD capability – e.g. tractors, trucks, fork lifts, airplanes. There is also more flexibility in system design when the HUD is not limited to specular angles.

A typical HUD normally uses a wedged windscreen to mitigate the double image caused by Fresnel reflections from both windscreen surfaces, which can be expensive to make. This is not necessary with an off-axis holographic HUD, although it is still necessary to laminate the hologram inside the windscreen which can be challenging.

Drivers often wear polarizing sunglasses for glare mitigation (typically blocking horizontally polarized light), but some HUD designs use P polarized light, which means the display image is not visible while wearing polarized sunglasses. A holographic HUD can use any polarization of light, so polarizing sunglasses can be used.

Artifacts can be generated when replaying the hologram (when the hologram is in the windscreen). For example, Fresnel reflections of the sun from the inner surface of the windscreen can go back into the hologram and generate an image of the sun directed towards the drivers eyebox. High quality AR coating on the inner surface of the windscreen can reduce this effect. A thick polymer coating (e.g. 70 microns) will reduce the spectral bandwidth of the hologram and reduce the brightness of the artifact. There can also be artifacts diffracted towards the world side due to Fresnel reflections and conjugate diffraction (a hologram is reciprocal and can diffract light which enters from the opposite direction to the recording geometry).

The thickness of the polymer will also increase the DE (diffraction efficiency) of the hologram. This can be up to 100% efficient, which is significantly higher than the specular reflectivity from the windscreen normally used in HUDs (approximately 5-10% depending on geometry and polarization). Therefore, less brightness is needed from the display unit to make the image visible over the real-world background, which means a more efficient system. There would be less need for e.g. thermal cooling of the display unit.

The bandwidth of the hologram is also an important choice in terms of the real world photopic visibility – if the hologram is too broadband and efficient, then too much real-world light could be diffracted away from the driver.

The virtual image distance and image magnification is typically fixed, and determined by the distance between the display and the hologram.

The Picture Generation Unit (PGU) for a single element off-axis holographic HUD typically uses a monochromatic light source (laser) to mitigate the effects of chromatic dispersion – this dispersion would reduce the resolution. A broadband source (LED) would result in reduced resolution. The image generator can be any standard source (LCOS/DLP/MEMS) with laser illumination, focused onto a diffuser at the object plane. However, for a large object size sufficient to achieve the desired FOV of approx. 20 x 15 degrees, the extended source size is approx. 150 mm x 100 mm, which would require a relatively large, long throw projector underneath the dashboard. We have shown an alternative, compact solution which is a standard LCD panel with the LED backlight replaced by edge lit laser backlighting.

Chromatic dispersion can be managed with a multi-element holographic system, but this increases volume and complexity. A thick hologram with a relatively short virtual image distance (e.g. 2 metres) and suitably designed off-axis geometry may allow for minimal resolution loss with LED illumination. However, laser illumination typically provides sharper images and more efficient light utilization. As the PGU uses a diffuser, the negative effect of speckle is largely eliminated.

The display panel is aligned normal to the hologram (i.e. no tilt) which allows for optimal image quality. There are no lenses/mirrors in between the display / hologram. It is possible to change the alignment of the hologram/display but this may require additional optics in recording or replay to correct for aberrations and distortion.

One option that is opened up by this flat panel, edge lit design (matched to a hologram) is that the PGU does not need the typical large volume, and could be placed elsewhere in the vehicle – for example mounted in the roof. Although this would be more complicated in terms of aberration control, it could allow easier mitigation of artifacts.

Another issue with HUDs is that sunlight can hit the PGU and wash out the image, or potentially damage the display if the sunlight is focused via the collimating optics onto the display. This often necessitates complicated glare traps. The flexibility of positioning a single flat panel display in our design can allow for easier mitigation of sunlight glare issues.

The automotive industry would ideally like a multi focal plane virtual image, however this is difficult to achieve. Multi depth phase SLMs (spatial light modulator) have small active areas which result in small FOV and small eyebox (low etendue). The use of a diffuser in the system to expand the FOV destroys the depth information generated from phase SLMs. We have shown that a PGU comprising a lenticular LCD screen with laser backlighting can achieve stereoscopic variable virtual image depth (with a reduction in resolution). As the HUD is large enough that both eyes can comfortably see the image at the same time, good depth perception is achieved. An alternative may be electronic switchable diffusers (displays) which can be diffuse or transparent, and located at different depths from the windscreen. Movable diffusers can also be used to generate different depth planes.

An alternative to far-field HUDs are holographic diffusers in the windscreen. Here, the image appears in the plane of the windscreen and care needs to be taken when making the hologram not to introduce unwanted haze/lack of transparency. The holographic diffusers are less prone to generating any artifacts from sunlight/headlights etc. Potentially both holographic diffusers and holographic AR HUDs could be used in the same vehicle.

## 3. Conclusion

A large area holographic HUD has been demonstrated which can be laminated into a windscreen to enable the next generation of large FOV automotive AR HUDs.

## 4. Impact of Research

Previous work (Ceres, Zeiss, Bosch) has utilised pixelated digital holographic masters which are copied into photopolymer. This may result in see-through artifacts due to far-field diffraction from the edge of the pixels and/or haze. The pixelated master does have the benefit that a field varying wavefront can be created across the hologram area, and a large size master can be created. Other traditional, analogue HUD holograms recorded directly into photopolymer (Luminit) have limits on the HOE size achievable and field-dependent aberrations reduce image quality. This work shows the combination of a large continuous wavefront HUD HOE with a high-quality image across the eye-box. A simple PGU is also demonstrated.

## 5. References


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