Enabling Display Measurement within Augmented & Virtual Reality Headsets

Optical Components Replicate Human Vision for Accurate Display Testing
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Introduction

The application of augmented and virtual reality (AR/VR) devices is growing rapidly in industries as diverse as gaming, military, education, transportation, and medicine. According to the International Data Corporation (IDC), the AR/VR headset market is expected to reach 81.2 million units by 2021, with a compound annual growth rate (CAGR) of 56.1 percent. Every AR/VR device manufacturer takes a unique approach to integrating displays within these headsets, and display technology and hardware environments vary greatly. This market growth fuels an increasing need to measure AR, VR, and MR (mixed reality) displays viewed near to the eye—collectively referred to as near-eye displays (NEDs) (see Fig. 1)—using methods that are adaptable to the geometries of each device and the different display specifications.

![Image of head-mounted NED designs including immersive headsets and transparent augmented reality glasses.](image)

**Figure 1 - Examples of head-mounted NED designs including immersive headsets and transparent augmented reality glasses.**

The increasing importance of AR/VR technology demands control solutions that ensure visual performance. However, achieving a quality, seamless visual experience poses a challenge for device designers and manufacturers due to the limitations of measurement systems. The power of displays viewed as near to the eye as possible—like those in AR/VR devices—is their ability provide immersive visual input. However, as images in these displays are magnified to fill the user’s field of view (FOV), defects in the display are also magnified. These defects not only detract from the user experience, but ultimately can damage a company’s brand image in this increasingly competitive new marketplace. Effective display testing, therefore, is an emerging necessity.

To help manufacturers ensure display quality, Radiant’s AR/VR Lens paired with a ProMetric® Imaging Photometer or Colorimeter provides unique optics engineered for measuring NEDs, such as those integrated into virtual, mixed, and augmented...
real reality headsets. The innovative new geometry of the lens design simulates the size, position, and binocular field of view of the human eye. Unlike traditional lenses where the aperture is located inside the lens, the aperture of the AR/VR Lens is located on the front of the lens to enable the connected imaging system to replicate the location of the human eye in an AR/VR device headset and capture the entire FOV available to the user.

This paper discusses the challenges of NED measurement, introduces Radiant's integrated AR/VR Lens solution, and outlines the solution’s advantages for evaluating the human visual experience in NED applications.

Challenges of Measuring NEDs

Market trends in AR/VR indicate a need to measure more displays that are:

1. Viewed extremely close up
2. Viewed with a wide field of view (immersive)
3. Viewed within head-mounted devices (goggles, glasses, and headsets)

1. Displays Viewed Close Up

Viewed as close as possible to the eye, NED projections are magnified to create the immersive experience (see Fig. 2). This proximity also magnifies potential display defects. For example, light and color uniformity issues, dead pixels, line defects, and inconsistencies from eye to eye become more apparent to the user when viewed close up. The closer a display is to the eye, the more important display testing becomes.

Another characteristic of displays viewed at this proximity is their resolution. To create visual realism of projections across the display, NEDs must have more pixels per eye. However, this poses a challenge for display measurement as high display resolution and pixel density in turn require higher-resolution measurement devices.

2. Displays Viewed with Wide FOV

Depending on the device, images in AR/VR displays are projected across a range of FOVs. With human binocular vision covering approximately a 114-120° horizontal FOV, several leading commercially-available AR/VR NEDs (primarily VR) achieve FOVs ranging between 100-120° (see Fig. 3).

![Figure 3 - FOV comparison of VR headset displays. Source: VRGlassesHeadsets.com.](image)

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3. Radiant Vision Systems, LLC
The wider the FOV of the display, the more challenging it becomes to comprehensively capture all areas of the display using an imaging system for measurement.

3. Displays in Head-Mounted Devices
NEDs are typically integrated within a head-mounted device (HMD), such as a headset or goggles. To measure a display as viewed by a human user wearing such a device, the measurement system must be positioned within the headset hardware at the same position as the human eye (see Fig. 4). The measurement system’s entrance pupil (the optical aperture) must emulate the human pupil position within the headset in order to capture the full FOV of the display through the viewing aperture of the headset.

Additional Unique Measurement Criteria
Display testing in AR/VR applications demands unique image characterization data and analyses. For instance, luminance (brightness of the projection) and color uniformity are critical when combining images from eye to eye, or when images are overlaid on top of the surrounding ambient environment (as in AR).

Image sharpness and clarity are important when displays are viewed near to the eye, and testing for these characteristics is performed using an MTF (modulation transfer function) test method. Characterizing image distortion caused by the viewing goggles or display FOV is key to improving spatial image accuracy and projection alignment. An AR/VR measurement solution should include analysis functions for these common criteria, as well as repeatable, consistent data to ensure device-to-device accuracy.

Measurement Approaches
Emerging AR/VR technologies require an innovative approach to display testing, including new methodology, software algorithms, and—most critical for in-headset measurement—optical geometries. Many technologies exist that attempt to meet the unique testing criteria for AR/VR devices, but have significant limitations when it comes to comprehensively addressing all of the measurable AR/VR display characteristics. Some traditional measurement approaches are outlined below.

Machine Vision Cameras
The key limitation of machine vision is that it is not appropriate for absolute luminance and color measurement (see Fig. 5). Traditional machine vision systems capture relative data only—they do not provide metrological data to measure absolute luminance or color as visualized by the human eye in an illuminated display. To perform a true qualification of AR/VR displays as they are experienced by a human user, the measurement system should provide photometric values. Imaging photometers and colorimeters capture luminance and chromaticity values as they are perceived by the human eye. This is achieved using integrated optical filters that expose specific wavelengths of light to the camera’s image sensor. This process replicates the human photopic response. Photometric imaging systems are commonly used for display testing, as they capture a complete display FOV in a single two-dimensional image to analyze photometric data in a spatial context. This context is critical for evaluations of uniformity, distortion, clarity (MTF), contrast, and image position.
Testing pixel-dense displays like NEDs also requires a measurement system with high resolution and signal-to-noise ratio. Machine vision is typically employed to accomplish extremely fast, repetitive measurement of visual characteristics that are identified based on clearly discernible contrast differences. Many traditional machine vision systems therefore sacrifice resolution for speed, offering low-resolution sensors that capture a high ratio of image noise compared to the signal they receive. Display defects, however, may occur at a level of detail as precise as a single display pixel. If a measurement system cannot discern a defect in a high-resolution display from one pixel to the next, it may miss defects that would appear obvious to a human viewing the NED. Systems with high resolution and signal-to-noise are imperative for measuring displays in near-eye applications with the same precision as the human eye (these systems may include scientific-grade image sensors that are electronically cooled and temperature stabilized to further reduce noise received per sensor pixel).

**Limited-Resolution Cameras**

As discussed, measurement solutions that use low-resolution sensors are a poor fit for testing the high-resolution displays that are used in near-eye viewing applications. The human eye is one of the highest-resolution “imaging” mechanisms there is—estimated to be around 576 megapixels (MP). For this reason, low-resolution imaging systems (even photometry-based systems) will never catch all of the defects that a human user would notice at the proximity of an AR/VR display.

Low-resolution cameras are inadequate for measuring displays used in AR/VR devices. They may miss dots, particles, dead pixels, or other small defects that would be apparent when viewing the display close-up. These systems are also incapable of MTF measurement to evaluate image sharpness.

**Standard Optics**

Standard optical solutions are not designed for measuring within NED environments (headsets, goggles) from the vantage point of a human user. This is a limitation of traditional optical hardware design. For example, a traditional 35 mm lens has an internal aperture. This aperture position causes occlusion of the full FOV of the display due to obstruction by the lens housing and NED device’s entrance aperture (see Fig 6).

![AR/VR device entrance aperture](image)

**Figure 6 - Standard lens with an internal aperture.**
Additionally, standard lenses are typically too large to fit inside NED headsets and goggles at the eye position. The length and width of these lenses prohibits the connected imaging system’s entrance pupil from being positioned where a human user’s eye would be, preventing measurement of displays as they are viewed in use.

Custom Optics
A custom-built optical solution is generally not viable for NED display testing within headsets due to expense, long development time, and minimal scalability to meet future applications. Relying on in-house design also limits product support through the lifetime of the solution.

Custom Software
To accomplish the unique image analysis functions required for AR/VR display testing, some manufacturers may elect to customize a software component in-house. This has similar downsides to customizing the optical hardware component, including increased expense and time to implement, along with minimal scalability for future requirements, limited product support, and inability to apply software for other display test applications.

Replicating the Human Visual Experience
Human visual perception of display quality should provide the standard for optical performance measurement of NEDs. Like the human eye, a NED measurement solution must address the range of display characteristics that can be seen. Measuring a display integrated within an immersive or head-mounted system relies on accessing the display at the appropriate visual position to capture the full FOV that is meant to be viewed by the human user. To replicate human vision for NED measurement, there are several key elements that must be addressed by the display test equipment.

Photometric Measurement
Most essential to the visual quality of any display is the appearance of light and color. Imaging photometers and colorimeters are best suited to evaluate visual display qualities because they are engineered with special tristimulus filters (see Fig. 7) that mimic the response of the human eye to different wavelengths of light (the photopic response curve). A NED measurement system should employ photometric technology using filters to evaluate light values as they are received by the human eye.

Full Field of View
Within the NED headset, the user is meant to have visual access to the entire FOV projected by the display—and therefore may notice defects at any point on the display. Imaging photometers and colorimeters need only one image to capture the display in full. Like the human eye, an imaging system can see all details in a single view at once. Using wide-FOV optics, an imaging system can capture a wide-FOV display even as it is viewed close up—simulating human binocular vision. Photometric imaging systems paired with wide-FOV optics are therefore recommended for the most accurate and comprehensive NED measurement.

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Figure 7 - Imaging photometers and colorimeters capture luminance and chromaticity values as they are perceived by the human eye, using integrated filters to expose each wavelength of light at a different duration to the image sensor to replicate the human photopic response.
High Resolution

AR/VR displays are meant to be viewed extremely close to the eye, which is itself a high-precision imager. Therefore, NEDs are some of the highest-resolution displays, fitting the most pixels in the smallest form factor for a seamless visual experience of images close up. The system used to measure an integrated AR/VR display should have sufficient resolution to capture all details in pixel-dense displays that may be visible to the human eye at close range. Given sufficient resolution of the imaging system’s sensor, each display pixel can be imaged across several sensor pixels, enabling pixel-level defect detection (see Fig. 8).

Aperture

One of the greatest challenges in measuring near-eye displays within headsets is positioning the measurement device in such a way as to view the entire display FOV beyond the goggles. If the measurement system can obtain an image of the full display FOV as the user sees it, tests can be applied to evaluate any defects that may be visible to the user during operation of the device. The challenge is that the human eye is at a very particular position within AR/VR headsets. A display measurement system that replicates the size, position, and FOV of human vision within the headset is necessary for capturing an image of the display for evaluating all qualities that the user may see.

Unique optical parameters that enable imaging systems to capture the full visible FOV include the lens aperture position and geometry. In an optical system, such as the lens on a camera, the aperture or “entrance pupil” is the initial plane where light is received into the lens. A similar point exists in the pupil of the human eye.

Aperture Size

Replicating the human entrance pupil in NED measurement systems by achieving the appropriate aperture size is important for several reasons:

1. An aperture that replicates the size of the human entrance pupil captures equivalent light (equivalent detail) of the display as the human eye.
2. If the measurement system aperture is smaller than the human pupil size, the imaged display appears sharper, with fewer/less severe aberrations than what the human observes. (Display qualification may yield false positives.)
3. If the measurement system aperture is larger than the human pupil size, the imaged display appears to have more aberrations than what the human observes. (Display qualification may yield false negatives.)

Replicating the size of the human entrance pupil enables the imaging system to capture images equivalent in detail and clarity to those viewed by the human eye and make the same determinations of quality.

Aperture Position

Simulating the human eye position within AR/VR headsets is a critical objective for integrated NED measurement. A traditional 35 mm lens has an internal aperture, which cannot capture the full FOV of the display due to obstruction by the lens housing.
and the NED device hardware (the edges of the device’s entrance aperture) (see Fig. 9). Optical components designed with the aperture in front of the lens replicate the intended position of the human eye inside the headset. Combined with wide-FOV optics, an imaging system with aperture at the front of the lens can capture the full display FOV and test for all visible characteristics that will be seen by the human eye.

This effect is like viewing a scene through a knot hole in a fence (see Fig. 10)—when the eye is position at the hole, the full FOV can be seen beyond the fence. As the eye moves away from the hole, the view becomes occluded by the edges of the fence.

Radiant AR/VR Measurement Solution
Radiant developed an AR/VR Lens to address the unique challenges of qualifying integrated NEDs under the same conditions as they are visualized by human users. The AR/VR Lens is designed to be paired with high-resolution imaging photometers and colorimeters, in 16-, 29-, or 43-megapixel models (see Fig. 11). By capturing displays at this detail, the measurement system can evaluate the entire display FOV at once with the precision to capture any defects that might be noticeable to the human eye.

Figure 9 - NED measurement requires a unique optical design that positions the camera aperture at the front of the lens, at the same location as the human eye, enabling visualization of the complete FOV of displays as viewed through headsets or goggles.

Figure 10 - “Knot-hole” example: Top, the entrance pupil is far from the opening (knot hole), providing a limited view of the image. Bottom, the entrance pupil is at the opening providing a fuller view.

Figure 11 - The Radiant AR/VR Display Test Solution includes (left to right): AR/VR Lens, ProMetric® Imaging Colorimeter or Photometer (16, 29, or 43MP options), and TrueTest™ Software with optional TT-ARVR™ module.
**In-Headset Display Measurement**

Radiant’s AR/VR display test solution is specially designed for in-headset display measurement. What separates the AR/VR Lens from other optical components is the lens’s ability to replicate the FOV and entrance pupil of human vision. The AR/VR Lens product specifications include:

1. Aperture (entrance pupil) located at the front of the lens.
2. 3.6 mm aperture size. The average pupil will contract to 1.5 mm in diameter in bright light and dilate to 8 mm in diameter in darkness. Radiant uses 3.6 mm for two reasons: 1) it is in the mid-range of pupil dilation; 2) the 3.6 mm aperture allows a high MTF for the lens.
3. Wide FOV to 120° (±60°) horizontal.

**Importance of Calibration**

Each Radiant AR/VR camera/lens system is factory calibrated to ensure the most accurate images for absolute light and color analysis. Calibration processes include factory distortion calibration to remove lensing effects of the wide-FOV lens, ensuring accurate spatial analysis of the display by the camera software.

When measuring displays using a wide-FOV lens, the image captured by the lens may appear distorted (see Fig. 13). Because the AR/VR solution uses a fisheye lens, an uncalibrated image exhibits barrel distortion. Radiant’s camera/lens solution is calibrated to process out distortion effects before applying display tests. This ensures accuracy of spatial measurements to detect defects where they occur on the display.

**Solution Software**

Radiant TrueTest™ Automated Visual Inspection Software applies analyses to all images captured by Radiant’s AR/VR measurement solution. This platform includes a suite of display tests with standard tests for luminance, chromaticity, contrast, uniformity, and defects like dead pixels and lines. In addition, unique tests for AR/VR projections are available in the pre-configured TT-ARVR™ software module (see Table 1).

<table>
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<td>Chromaticity</td>
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**Table 1** - Display tests in Radiant TT-ARVR™ software module.
Some examples of TT-ARVR software analyses are shown in Figures 14-16 below. These analyses are performed on the AR/VR display to test the manufacturing specifications of the AR/VR device. These specifications can also be published for consumer use (for instance, on an AR/VR headset specification sheet) to help them evaluate the device and compare with competitive products.

Uniformity analysis (see Fig. 14) determines areas of low or high luminance across the display, which may indicate a defect in the display. This analysis can also be used to characterize the uniformity against design specifications.

Analyses performed on the AR/VR display can be used to qualify the display, or may be published (for instance, on an AR/VR headset specification sheet) to help consumers evaluate the device and compare with competitive products.

A checkerboard contrast analysis (see Fig. 15) is performed by projecting a checkerboard pattern on the display within the AR/VR headset. Once the pattern is imaged by the AR/VR test system, the checkerboard contrast test evaluates luminance levels in the image to determine the display system's ability to project distinct light and dark values—a performance parameter that can be indicated on a specification sheet.

A Field of View test (see Fig. 16) measures the actual field of view of the display as imaged within the headset, ensuring that the horizontal, vertical, and diagonal dimensions are correct to design specifications. These measurements can also be reported on a specification sheet for an AR/VR headset.
Conclusion

New display integration environments—like AR/VR and other head-mounted devices—require designers and manufacturers to implement effective methods to test the optical quality of displays that are viewed close-up, from a fixed position, within headset hardware. Standard display measurement equipment lacks the optical specifications to capture displays within headsets to evaluate the complete visible FOV as experienced by the human user.

Radiant’s AR/VR display test solution is the only commercially available measurement system with unique optical components that replicate the human pupil size and position within AR/VR goggles and headsets to capture a display FOV to 120° horizontal. The system offers the high resolution and efficiency AR/VR device makers require, employing a compact camera/lens solution to capture all details visible across the NED in a single image to quickly evaluate the human visual experience.

References


Across industries, the increasing importance of virtual and augmented reality (VR/AR) technology demands control solutions that ensure quality visual experiences. This paper discusses the challenges of measuring near-eye displays as they are viewed by the user of an AR/VR device, and explains the benefits of Radiant’s integrated AR/VR Lens solution for in-headset display testing.

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Radiant maintains direct sales, engineering, and support offices and personnel throughout North America, China, and Korea. Radiant is also sold and supported in other areas of the world by our sister offices in the Konica Minolta Sensing Business.

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