# Testing the Next Generation of AR/VR Displays: An Innovative Solution

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## Abstract

Across industries, the increasing importance of augmented and virtual reality (AR/VR) technology demands control solutions that ensure technology performance. Achieving a quality and seamless visual experience continues to be a challenge for device designers and manufacturers due to limitations of measurement systems. The power of displays viewed as near to the eye as possible — such as those in AR/VR devices — is their ability create an immersive experience. 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 optics engineered for measuring near-eye displays (NEDs), such as those integrated into virtual, mixed (MR), and augmented reality headsets. The innovative new geometry of the lens design simulates the size, position, and 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 imaging system to replicate the location of the human eye in an AR/VR device headset.

This paper discusses the challenges of NED (near-eye display) measurement, introduces Radiant's integrated AR/VR lens solution, and outlines the solution's advantages for evaluating the human visual experience in NED applications.


## 1 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[1].

Fig. 1 Three examples of head-mounted NED designs.

This market growth fuels an increasing need to measure AR, VR, and MR displays viewed near to the eye — together referred to as near-eye displays (NEDs) (Fig. 1) — using methods that are adaptable to the geometries of each device and the specifications of displays that create immersive visual environments.

## 2 Challenges of Measuring NEDs

Market trends in AR/VR indicate a need to measure a growing number of displays that are:

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

### 2. 1 Displays Viewed Close Up

Viewed as close as possible to the eye, NED projections are magnified to create the immersive experience. This proximity, however, also magnifies potential


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display defects. For example, 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 this resolution and pixel density requires higher-resolution measurement devices.

### 2.2 Displays Viewed with Wide FOV

Depending on the device, NEDs can display images across a range of FOVs. With human binocular vision covering approximately 114-120° horizontal FOV, several leading commercially-available AR/VR NEDs (primarily VR) achieve FOVs ranging between 100-120° (Fig. 2).

Fig. 2 With the display in a fixed position within AR/VR devices, horizontal FOV is leveraged for an immersive experience.

The wider the FOV of the display, the more challenging it becomes to comprehensively capture all areas of the display for measurement.

### 2.3 Displays in Head-Mounted Devices

NEDs are typically integrated within a head-mounted device, such as a headset or goggles. In order 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. The measurement system's entrance pupil (the optical aperture) must emulate the human eye position within headsets in order to capture the full FOV of the display through the viewing aperture of the headset.

### 2.4 Unique Measurement Criteria

Display testing in AR/VR applications demands unique image characterization 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 the ambient environment (as in AR).

Image sharpness and clarity is important when displays are viewed near to the eye, and testing for this is commonly 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.

## 3 Replicating Human Visual Experience

Human visual perception of display quality should provide the standard for performance measurement of NEDs. Like the human eye, a NED measurement solution should address the range of display characteristics that can be seen. Measuring a display integrated within an immersive or head-mounted system is about accessing it at the right position to capture the full FOV that is meant to be visible to the human user. To replicate human vision for NED measurement, there are several key elements that must be addressed.

### 3.1 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, as they are calibrated to match the visual perception of the human eye based on how wavelengths of light stimulate the cones in the eye (the photopic response curve). A NED measurement system should employ photometric measurement technology to evaluate these values as they are received by the human eye.

### 3.2 Full Field of View

Within the NED headset, the user is meant to have visual access to the entire projected FOV at once—and therefore can notice defects at any point on the display. Using wide-FOV optics, an imaging system can capture the full FOV of displays viewed close up, just like the human eye. CCD-based imaging photometers and colorimeters need only one image to capture the display in full. Like the human eye, an imaging system can see all important criteria in the image at once. Photometric imaging systems paired with wide-FOV optics are therefore recommended for the most accurate and comprehensive NED measurement.

### 3.3 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.

The system used to measure an integrated AR/VR display should have sufficient resolution to capture the amount of details that may be visible to the human eye at close range. Given sufficient resolution, each display pixel can be imaged across multiple CCD pixels, enabling pixel- and subpixel-level defect detection (Fig. 3).

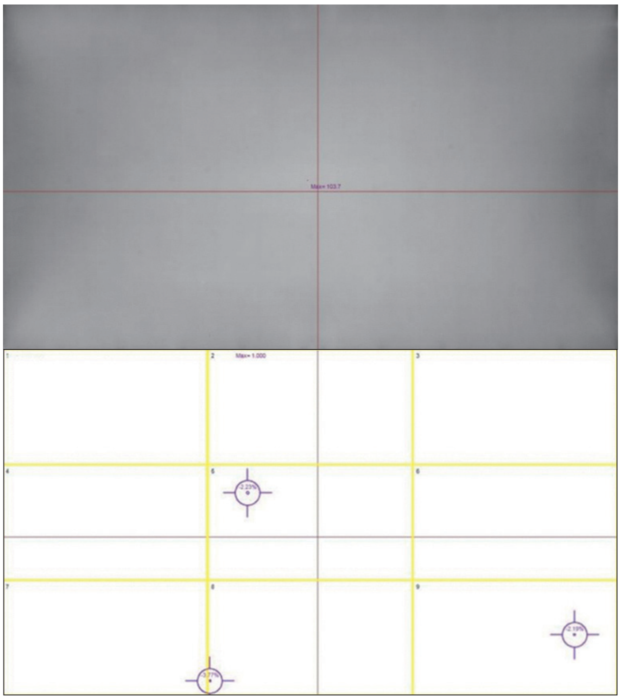


Fig. 3 The top image shows the raw image captured by a high-resolution photometric imager. On the bottom, an analysis has been applied to detect tiny pixel-level defects. Close-up viewing in the AR/VR headset may make such defects apparent to the human eye.

### 3.4 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 display FOV in full. 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.

There are unique optical parameters that enable imaging systems to capture the full visible FOV, including 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 aperture. A similar point exists in the pupil of the human eye.

#### 3.4.1 Aperture Size

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

a. An aperture that replicates the size of the human entrance pupil captures equivalent light (equivalent detail) from the AR/VR display as the human eye.
b. 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.
c. 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.

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

#### 3.4.2 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) (Fig. 4). 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 field-of-view 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 can be compared to viewing a scene through a knot hole in a fence (Fig. 5)—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.

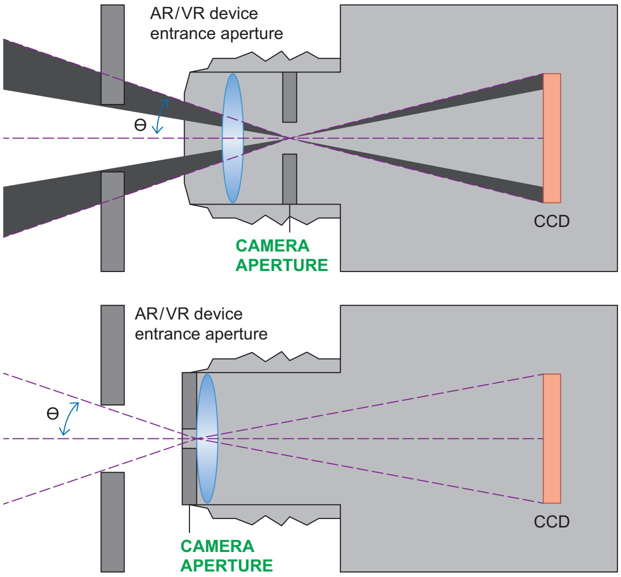



Fig. 4 NED measurement requires a unique optical design that positions the camera aperture at the front of the lens, at the same location as a human viewer's eye, enabling visualization of the complete FOV of displays as viewed through headsets or goggles.

Fig. 5 "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.

## 4 Radiant AR/VR Measurement Solution

Radiant developed its 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 either 16- or 29-megapixel models (Fig. 6). By capturing displays at this detail, the complete 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.


Fig. 6 The Radiant AR/VR Display Test Solution includes (from left to right): AR/VR Lens, ProMetric® Imaging Colorimeter or Photometer (16- or 29-megapixel options), and TrueTest™ software with the optional TT-ARVR™ module.

### 4. 1 In-Headset Display Measurement

Radiant's AR/VR measurement solution offers the only optical component designed for in-headset display measurement. What separates this lens from other optical components the lens's ability to replication the FOV and entrance pupil of human vision (Fig. 4). The AR/VR lens product specifications include:

1) Aperture (entrance pupil) located at the front of the lens.
2) 3.6 mm aperture size. A standard 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.

### 4. 2 Importance of Calibration

Each Radiant AR/VR camera/lens system is factory calibrated to ensure that it captures the most accurate images for absolute light & 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 (Fig. 7). Because the AR/VR solution uses a fisheye lens, the uncalibrated image appears with barrel distortion. Radiant's camera/lens solution is calibrated to acquire undistorted images before applying display tests (Fig. 7). This ensures accuracy of spatial measurements to detect defects where they occur on the display.

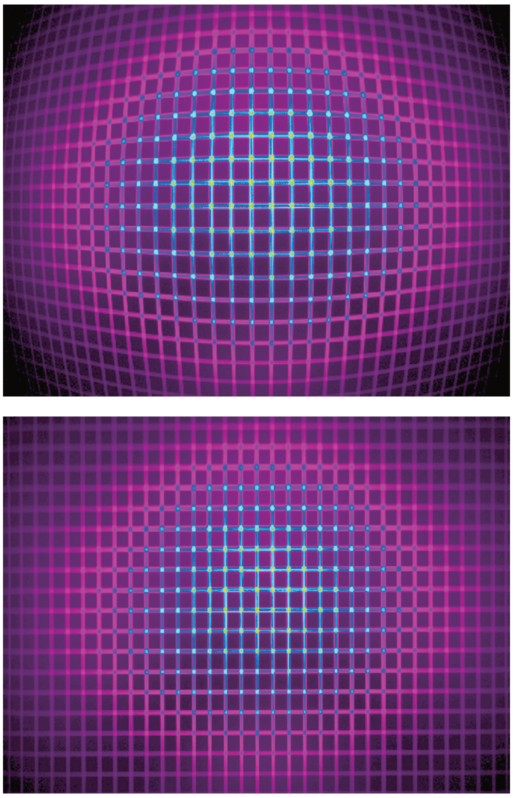


Fig. 7 Top, an image captured by an uncalibrated wide-FOV system; bottom, image captured by a system with distortion calibration applied.

## 4. 3 Solution Software

Software used to apply analyses in Radiant's AR/VR measurement solution is the Radiant TrueTest™ Automated Visual Inspection Software. This platform includes a suite of display tests, including 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 (Table 1).

Table 1 Display tests in Radiant TrueTest™ TT-ARVR™ software module.

| TT-ARVR™ Software Module Tests | |
|---|---|
| • Uniformity | • Points of Interest |
| • Line Defects | • MTF Slant Edge |
| • Particle Defects | • MTF Line Pair |
| • Pixel Defects | • Distortion |
| • ANSI Brightness | • Focus Uniformity |
| • Sequential Contrast | • Pattern Mura |
| • Checkerboard Contrast | • Field of View (Device FOV) |
| • Chromaticity | |

Some examples of the software analysis are shown in the Figures 8-10. These analyses are performed on the AR/VR display to test the manufacturing specifications of the AR/VR device. These can be published for the consumer (for instance, on an AR/VR headset specification sheet) to help them evaluate the device and compare with competitive products.

Uniformity analysis (Fig. 8) determines areas of low or high luminance across the display, which may indicate a defect in the display, or can be used to characterize the uniformity against design specifications.

A checkerboard contrast analysis (Fig. 9) is performed by displaying a checkerboard pattern on the display within the AR/VR headset. This test evaluates 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 (Fig. 10) measures the actual field of view of the display as imaged within the headset, ensuring that the measured 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.

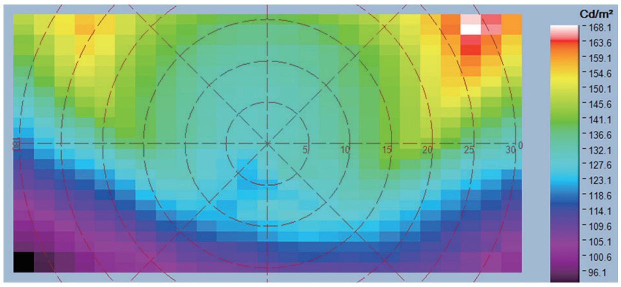



Fig. 8 Uniformity analysis (shown in false color).

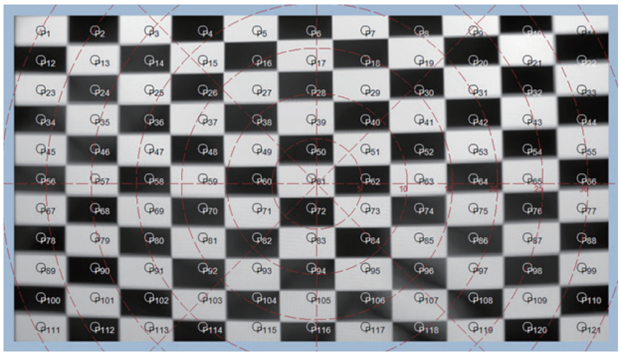
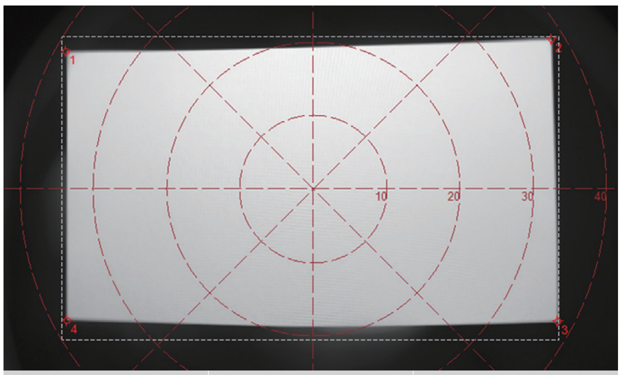


Fig. 9 Checkerboard contrast analysis.



| Result | Value | Unit |
|---|---|---|
| Horizontal FOV | 66.504 | Degrees |
| Vertical FOV | 37.488 | Degrees |
| Diagnol FOV | 76.342 | Degrees |

Fig. 10 Field of view analysis.

## 5 Conclusion

New display integration environments—like AR/VR and other head-mounted devices—require designers and manufacturers to implement effective methods to test 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 full display 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 the full display FOV to 120° horizontal. The system offers the high resolution and efficiency AR/VR makers require, capturing and evaluating a complete immersive display FOV in a single image to quickly evaluate the human visual experience.

### References

1) International Data Corporation (IDC).
(2017, March). *IDC's Worldwide AR/VR Headset Tracker Taxonomy, 2017*.
https://www.idc.com/tracker/showproductinfo.jsp?prod_id=1501