Metrology challenges in near to eye display characterization for human factors correlation

Richard L. Austin[1], Bruce S. Denning[1], John Penczek[2]
[1]Gamma Scientific, San Diego, USA, [2]University of Colorado, Boulder, USA
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Abstract
We present metrology challenges and solutions to measure Near Eye Displays performance parameters that can produce visual discomfort and headaches. Accurate measurement data correlates to what the eye perceives when the entrance pupil of the Light Measurement Device (LMD) matches the location and pointing direction of the display user's eye.

Introduction
The ability to predict Head Up Display (HUD) and Augmented Reality and Virtual Reality (AR/VR) Near Eye Display (NED) user experience relies on optical, geometric, photometric, color and temporal measurements. Each of these measurements requires sufficient resolution and repeatability relative to the ability of the human eye to discern difference to be useful in predicting user satisfaction with a particular display system. Other display systems factors such as weight, head or face mounting comfort are also important parameters but are not addressed in this paper. The measurement of the display characteristics a human observer would see as the foveal region of the eye is scanned to different pointing directions within the virtual image field of view is the primary purpose of this paper. These measurements are only meaningful in predicting user acceptance if they can be reported in absolute photometric and colorimetric units in a repeatable, reproducible manner and traceable to international standards. Only with this absolute metrology basis can reliable limits to these measurement parameters be set. The performance limits being set need to account for the wide variety of user eye to head geometry as well as the focus accommodation range of the individual users eyes to guarantee a positive user experience and assure the acceptance to a broad array of potential commercial users.
The important optical radiation performance parameters include luminance, color, resolution and virtual image distance both in the center of the measurement field and the uniformity across the whole image area. Recent work has reported that the entrance pupil size of the Light Measurement Device (LMD) must be $\leq$ 5 mm diameter to assure repeatable and reproducible photometric and colorimetric measurement results [1, 2, 3, 4].
We also give a method of measuring the Michelson contrast and derive resolution of the display applying the methods prescribed in the Information Display Measurement Standard (IDMS) for direct view display technologies. The results, Michelson contrast measurements covering the complete FOV, are given for an Epson Moverio BT-300 Smart Glasses AR display with two different vantage points for motion of the LMD entrance pupil through the Qualified Viewing Space (QVS). One measurement vantage point is the plane of the entrance pupil or Pupil Rotation Point (PRP). The other vantage point for the Michelson contrast mapping is the an and Eye Rotation Point (ERP). We also present a process/method to determine the parallax based on the author's experience with parallax measurements on Head Up Displays and other bi-ocular displays similar to other methods [5, 6].
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NED measurement geometry
The IEC Technical Committee 110, Working Group 12 (TC110 WG12) is working to create a standard test method for NEDs. The geometric coordinates for describing the eye pointing direction while viewing the NED is a rotation about a vertical axis and a horizontal axis of rotation on top of the rotation. This creates the familiar Azimuth (AZ) and Elevation (ELEV) angular coordinate system. The AZ lines through the coordinate space trace longitudinal great circle lines all passing through on two points along the Y vertical axis. From the center of the coordinate system the AZ angle are positive signed for angle to the right of the Z optical axis when viewed from the center. The ELEV pointing direction

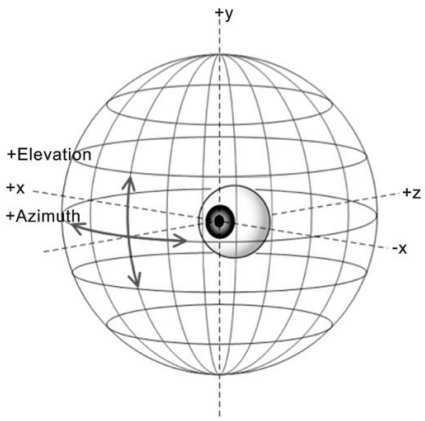

Figure 1. Spherical coordinate system to specify the angular pointing directions to different measurement locations within the within the virtual image measurement field.

angles are positive in the positive Y axis direction and define planes parallel to the X Z plane slicing through the spherical volume. This is illustrated in Figure 1. Viewed from the center of the coordinate system, the zero-degree pointing direction along the Z axis corresponds to the optical axis of the NED Device Under Test.

An additional consideration of the geometry for measurement is the vantage point or center of the spherical coordinate system. One of the choices being considered as the standard vantage point is the PRP and

the other is the ERP. The difference between the two vantage points is shown in Figure 2. Shown in the figure is a view down the Y axis at a horizontal sectional view in the X Z plane. The section is through the center an AR users eye-plane. The left eye illustrates the change in pointing direction angle with a PRP vantage point and the right eye illustrates the change in the same pointing direction angle with an ERP vantage point. Notice the difference in the light that is collected from the green shaded QVS of the AR display shown in the figure. This difference leads to significant differences in the measurement results of the Michelson contrast in the measured image field and the effective FOV when the LMD entrance pupil collects data from these two different vantage points. The ERP vantage point is how the eye rotating through the QVS would see the display.

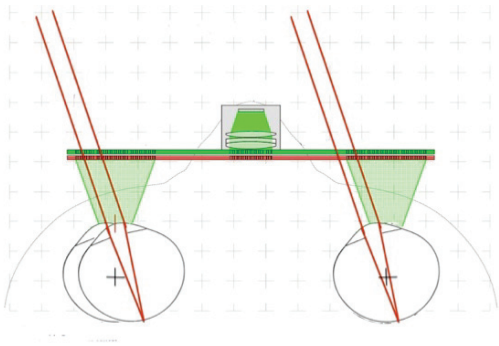

Figure 2. The left eye illustrates the Pupil Rotation Point (PRP) and the right eye illustrates the Eye Rotation Point (ERP) relative to the green shaded QVS of the AR glasses.

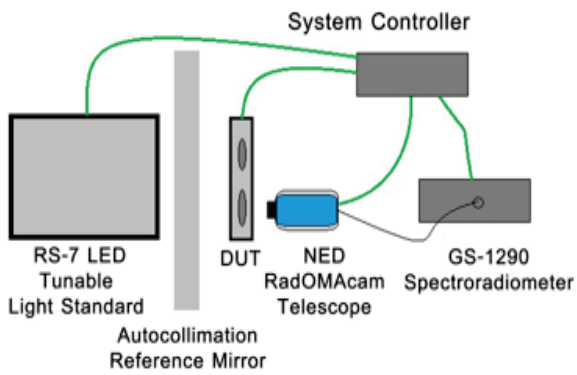

Figure 3. Overall measurement system design not shown is the telescope position system that controls the position and pointing direction of the telescope.

Display Measurement System

The LMD consist of both a spectroradiometer and an 2D image sensor and is part of the overall system shown in Figure 3. It includes a graphics generator in the system controller to display test patterns and color fields on the Device Under Test (DUT), an autocollimation reference mirror, LED based tunable light standard. The LMD is a compact size telescope with standard 5mm to 2mm diameter entrance pupil coupled to a CCD detector based grating spectroradiometer and integral 12 mega pixel image capture camera. The LMD contains a 2-degree diameter Field Stop Aperture for the collection of the luminance and color based on collected spectroradiometric data closely matching the foveal angular size. The compact telescope is mounted to a precision 6-axis industrial robot that controls the x, y, z position, the position of the vantage points as well as the pointing direction relative to the exit pupil of the NED The entrance pupil, which is located at the very front of the telescope, defines the limiting aperture for the auto focus objective lens. The lens, an advanced optics zoom system, can determine virtual image distance over a 0 to 10 diopter range. for the whole 16 by 12 degree captured 12 MP image. The system, described in other published work [6], can be configured into three different modes of data acquisition:

- View and define measurement area
- Spectroradiometric measurement
- Image capture

View and define measurement area: For the view and define measurement area mode, the objective lens focuses a 16 degree horizontal by 12 degree vertical sample area of the virtual image from the NED on a plane that contains fixed 2 degree field stop aperture that defines the circular angular measurement area centered on virtual image .

Spectroradiometric Measurement: The LED illumination source is removed from the spectroradiometer measurement path and a high spectral purity spectral data set with less than 1% polarization effect is acquired and analyzed for luminance as shown in Figures 4.

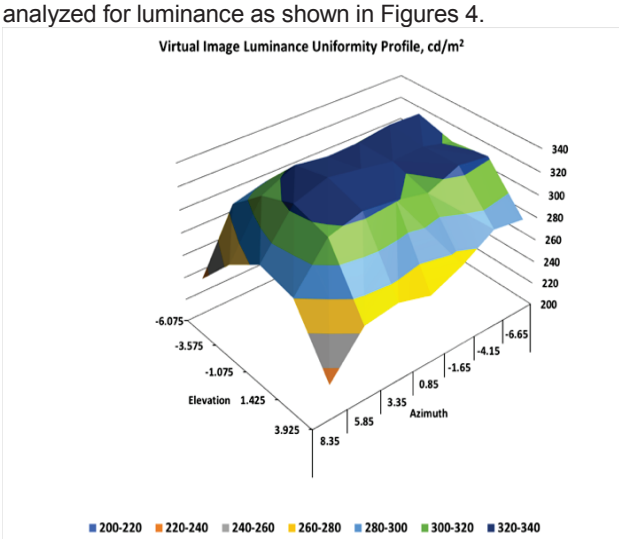

Figure 4. Luminance profile map of the measurement field displayed by a pair of Epson BT-200 Smart Glasses.

Image Capture and Analysis: In image capture mode, the camera acquires an image that is correlated to the spectroradiometric color and luminance in the measurement field area. The captured monochromatic images can then be used to produce a predictive model of the display color uniformity, reproduction fidelity, Michelson contrast and MTF with over 250 image capture pixels per degree of view, greater than the normal human eye visual acuity.

The DUT as shown in Figure 3 can also be evaluated for uniformity of the exit pupil and virtual image quality as a

function position in the exit pupil as shown in Figure 5. In this measurement result, a single X Y plane through the QVS was sampled while pointing at the center of a 1.5-degree white illuminated square pattern displayed in the center of the measurement field. The LMD entrance pupil was moved over a 10 mm by 18 mm area in 1 mm increments and at each location a spectral scan was acquired and the luminance results recorded. The top half of the figure shows the luminance profile sampled from this plane in the QVS.

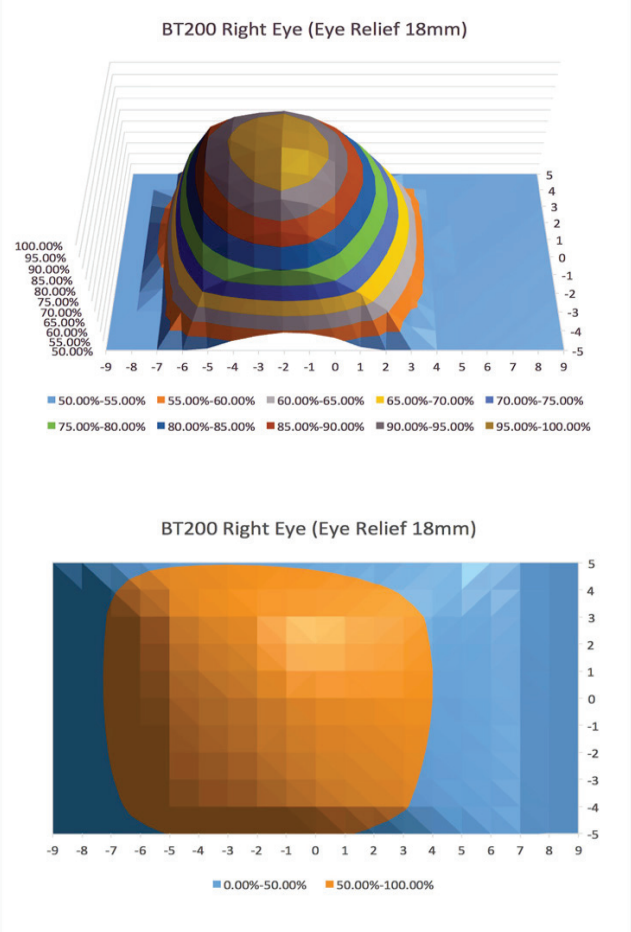

Figure 5. Luminance profile in and X Y plane through the QVS of one eye position of an Epson BT-200 Smart Glasses AR display at an 18 mm eye relief distance.

The lower half of the figure shows the perimeter of the QVS as the boundary between the orange and blue areas. The perimeter criteria is defined as where the luminance drops to 50% of the peak luminance in the QVS [6].

Measurement Data and Results

Characterization of the LMD 2D image capture resolution capabilities is accomplished with high contrast electronic test target. The test target can be set to a wide range of line spacings per degree with enough resolution to exceed the resolution capability of the LMD 12 mega pixel sensor with 3.45-micron pixel size. The theoretical resolution for the LMD is <15 arcsec or 0.004 degrees. Assuming a minimum of 5 pixels per minute, the theoretical measurement resolution capability is just over 1 arc minute or equivalent to the best human eye visual acuity for pupil sizes in the 2 to 5 mm range [5].

For the Michelson contrast data acquisition in different pointing directions and different locations within the design eye box, the 6-axis robot controls the position of the compact telescope to +/-25 micro meter precision and pointing direction with 0.001-degree resolution. The compact size allows positioning of the telescope entrance pupil at the display reference eye point between the earpieces of near eye displays. Full field of view data was acquired at just one eye relief distance for contrast transfer function (CTF) in 15 different pointing directions. At each of these pointing directions, a 16 x 12-degree image is captured.

Two different data sets were taken at each vantage of the LMD entrance pupil shown in Figure 2, the Pupil Rotation Point (PRP) and the Eye Rotation Point (ERP). Results for both of the configurations with different line pair spacing of horizontal and vertical lines generated on the display measurement field: Figure 6 shows the Michelson contrast values for the complete 20 by 12-degree FOV of the Epson BT-300 taken from the PRP vantage point. This shows fairly good Michelson contrast

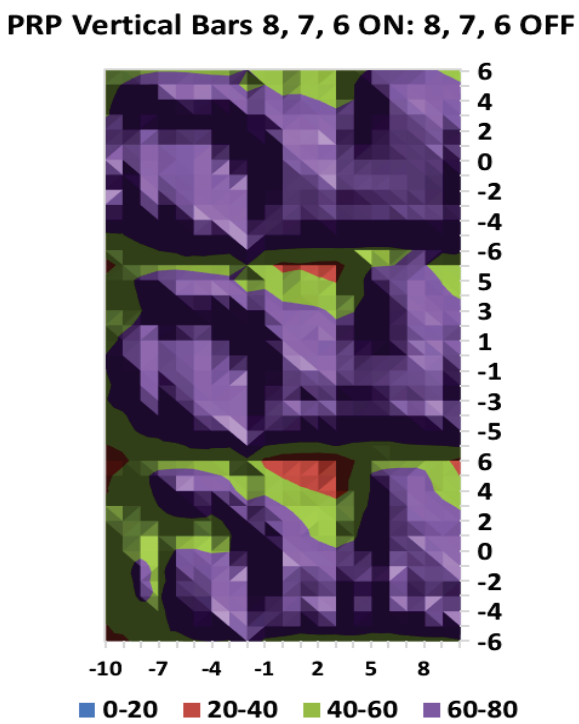

Figure 6. Michelson contrast in the Epson BT-300 measured from the center of the QVS rotating the LMD pupil at the pupil point (PRP). The legend at the bottom indicates the Michaelson contrast percentage values corresponding to each color. The vertical and horizontal axis are in degrees.

from one edge to another. The three graphs are all for a vertical line pattern with different pixel spacings moving from top to bottom stacked on top of one another. The top graph of the three is for 8 display pixel lines on/8 display pixel lines off the lowest detail displayed. The middle is 7 on 7 off test pattern and the bottom is a 6 on, 6 off test-pattern, the highest detail of the three patterns.

But when compared to the ERP data, which is what the user sees with the eye pupil rotating through the QVS, the results are dramatically different. The data shows a 2-degree reduction in the horizontal FOV from -10 degrees to the left down to -8 degrees where the Michaelson contrast drops to less than 20% at the -8 degree data collection direction. Also, interesting to note is the spot of poor contrast in the 4 to 6 degree elevation angle 2 to 4 degree azimuth angle pointing direction area in the PRP data. When you look at the EPR data, the spot of poor Michelson contrast is shifted in azimuth angle out to 6 to 8 degree azimuth angle pointing direction area.

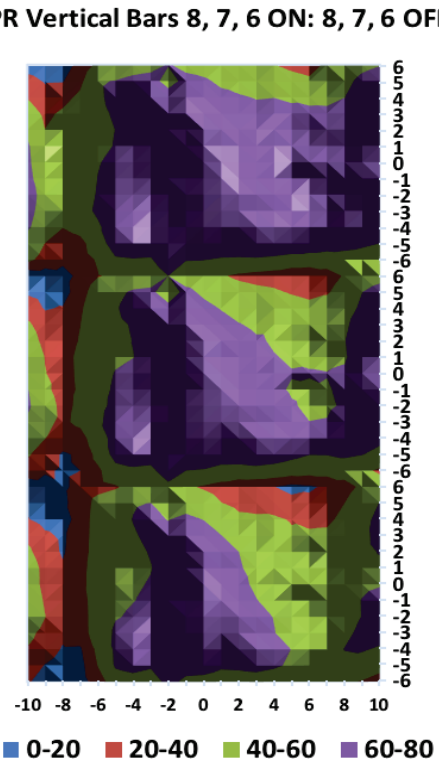

Figure 7. Eye Rotation Point (ERP) Michelson contrast data covering the 12 by 20 degree FOV of the Epson BT-300 Smart Glasses as a function of different white vertical line pattern spacings of 8 on/8 off, 7 on/7 off and 6 on/6 off going from top to bottom respectively. This data represents how the eye would see contrast differences on the display. The legend at the bottom indicates the Michaelson contrast percentage values corresponding to each color. The vertical and horizontal axis are in degrees. Note the low contrast region on the left side of the display.

Other data that was acquired is the parallax difference between the left and right eye pointing directions between the left and right eye optical axis pointing directions. This is acquired by translating the LMD entrance pupil from one eyepoint to another without changing the pointing direction during the translation process. The LMD used for the data collection contains and integral autocollimator that can verify pointing direction with respect to a plane flat mirror that is large enough to span the area of both eye line of sights from the NED. This is shown as the autocollimation reference mirror in Figure 3.

The process to measure the parallax is a simple process; first focus on a displayed cross hair pattern and change the pointing direction to center the LMD axis on the crosshair pattern through the right eye position from a point near the design eyepoint. The pointing direction set to the zero-degree azimuth and elevation angle reference. Move the LMD a distance, D, horizontally in the X axis direction to the left eyepoint. The measured azimuth, α and elevation β angle deviation is used to calculate the vergence to a first order by the equation

$$Vd = D / \tan \alpha$$

Parallax can also be used to determine the focus distance using the same equation with the distance D changed to the distance traversed across the single eye position QVS. Similarly, the image misalignment in the vertical planes between the two pupils of the DUT is given by the elevation angle β difference.

Conclusion

Near eye display performance parameters including geometric and chromatic distortion that have been shown to be contributing factors causing discomfort and headaches in Visual Strain Questionnaire (VSQ) based studies [7] were measured using methods that produce accurate and reproducible data. [8] The measurement methods are in the process of being documented in the IDMS version 1.1 scheduled for publication in 2020.

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