CURRENT PROJECTS IN DISPLAY METROLOGY AT THE NIST FLAT PANEL DISPLAY LABORATORY

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ABSTRACT

The NIST Flat Panel Display Laboratory (FPDL) is operated through the Display Metrology Project (DMP) of the Electronic Information Technology Group in the Electricity Division of the Electronics and Electrical Engineering Laboratory of NIST. The DMP works to develop and refine measurement procedures in support of ongoing electronic display metrology, and applies the results in the development of national and international standards for flat panel display characterization.

1. INTRODUCTION

In the past, the NIST DMP has established diagnostics and tools to address such issues as reflections [1, 2], stray light [3] and color accuracy [4], and has supported the development of display standards [5, 6]. Current projects include the development of a liquid-filled camera to reduce stray-light contributions to the reference image, enabling more accurate luminance measurements of complicated scenes involving high contrasts [7]; a narrow-frustum probe for making accurate luminance measurements of small areas [8]; a variable-radius source method for separating reflection components [9]; a standard illuminated source with test targets for the assessment of display measurement capabilities [10], and tools and diagnostics for the measurement of near-the-eye displays. These projects are described briefly, with the exception of the display measurement assessment transfer standard, which is accounted elsewhere [11].

2. STRAY LIGHT MANAGEMENT

2.1 Stray light corruption. The accurate measurement of small area-black levels is an important aspect of display characterization. For example, techniques can be used to determine the resolution of electronic display systems by measuring the contrast of grille patterns or fully modulated sine waves of various spatial frequencies. Unfortunately, the measurement of the contrast of these patterns may be influenced by stray light, either from ambient and reflected light in the environment, or from veiling glare (light scattering) in the lens of the detector. Such stray-light corruption can lead to large errors in contrast determination providing an inaccurate characterization of the display. For large-area measurements, various techniques have been employed, including the use of frustums and masks, to minimize such unwanted effects and provide a more accurate measurement [12, 13, 14]. With some modifications, these same tools have been used for small-area measurements with similar results [15, 16]. However, this method can prove difficult to implement, involves additional apparatus (masks) to achieve the desired results, and in some cases may be limited to spatially resolved light-measurement equipment.

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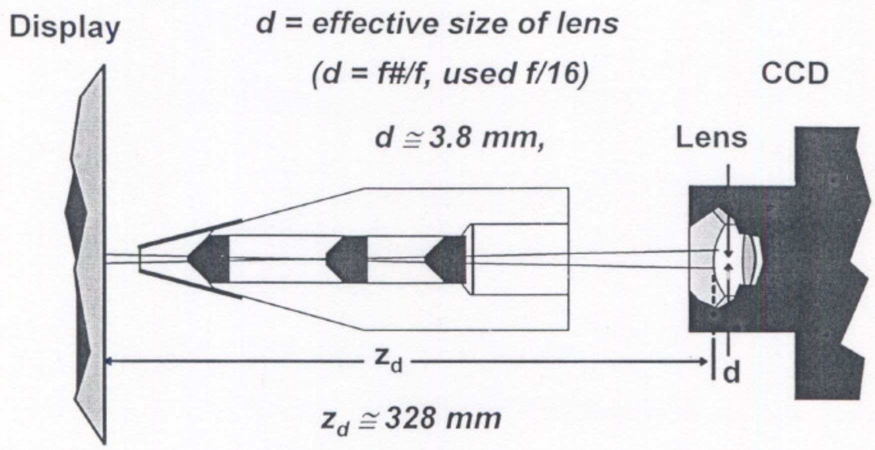

Fig. 1. CCD camera with Narrow Frustum SLET (NFS).

2.2 Narrow Frustum SLET. A robust technique was developed that adapts to a detector. It uses a stray-light elimination tube (SLET) within a narrow cone [8], referred to as a narrow-frustum SLET (NFS). Shown in Fig. 1, the NFS consists of a series of three small glossy black 90 ° frustums inserted in a narrow tube, and surrounded by a narrow frustum, also constructed of glossy black material. The three interior frustums have apertures of approximately 3 mm, 5 mm, and 3 mm, respectively. They serve to trap any light contributions from the edge of the narrow frustum aperture, and limit the field of view. The exterior narrow frustum has an aperture of 6 mm, and reflects stray light away from the measurement device. The NFS is mounted to the detector as shown in the photograph in Fig. 2 (in this case, a charge-coupled device [CCD] camera). Note the additional frustum placed at the front of the tube to prevent any reflections from the measurement apparatus onto the measurement area.

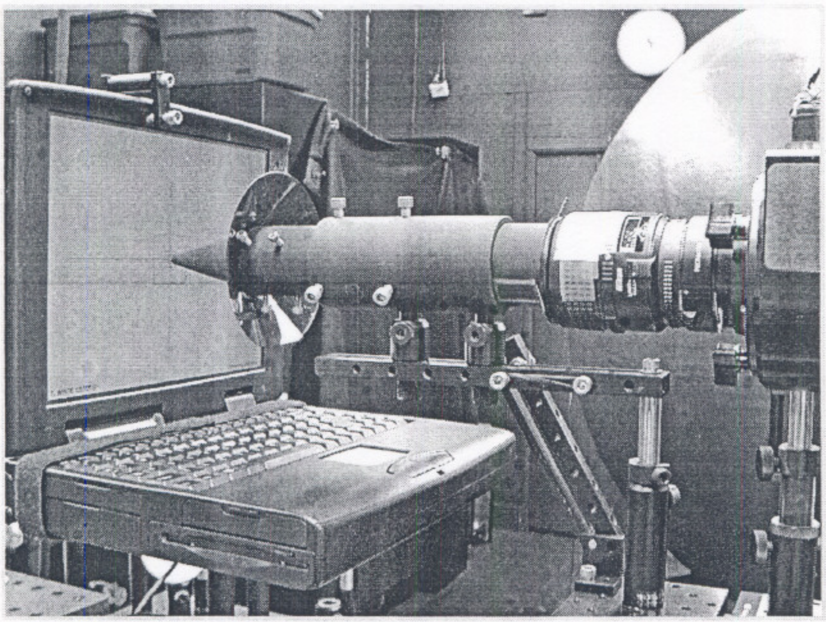

Fig. 2. NFS and CCD camera arranged to measure a display.

A similar design [17] was originally developed by Aldo Badano, presently at the Food and Drug Administration in Rockville, MD. This "collimated probe" has been used effectively to evaluate the performance of active-matrix liquid-crystal displays (AMLCDs) in medical imaging applications [18]. The NFS and the collimated probe have been compared, and for small distances from the display (approximately 1 mm or less) they can make very high contrast measurements with accuracies on the order of 1 % or better. However, they begin to demonstrate sensitivity to stray light at distances greater than 2 mm. Furthermore, contributions due to back reflections from the NFS onto the measurement area of the display were found to be negligible compared to the contamination arising from internal scattering [19]. Methods for reducing this scattering are under investigation at NIST.

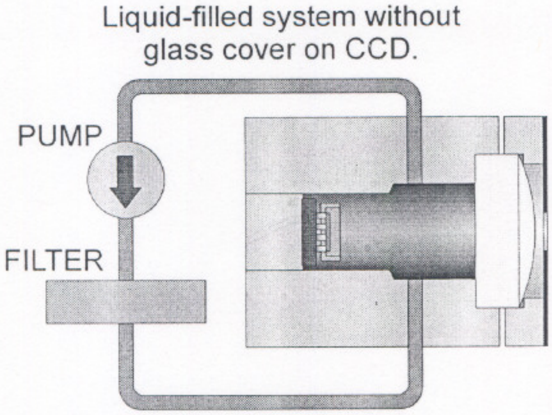

Fig. 3. A liquid-filled lens system.

2.2 Liquid-filled camera. NIST has developed a simulated-eye-design (SED) camera [7] in an attempt to minimize the effects of veiling glare. The SED technology is an optical system that attempts to improve high contrast measurements by removing various sources of reflections and scattering. In the prototype, a simple glass lens is placed before a CCD, but instead of air, the area behind the lens is liquid-filled up to the silicon chip of the CCD. The glass cover plate that normally protects the CCD has been removed. The barrel of this liquid-filled lens is made with black acetal plastic to further reduce reflections (see Fig. 3).

Since the CCD camera is exposed to the liquid, the initial prototype was filled with a silicone liquid having a viscosity of 1 cm^2/s, and an index of refraction $n_2 = 1.41$. The lens on the prototype was an uncoated 25 mm diameter plano-convex lens with a focal length of 25 mm, and an index of refraction of $n_1 = 1.673$. The reflectance R for the glass-liquid interface was $R = 0.73$ %, whereas for a normal air-glass interface $R \approx 6.3$ %. An aperture of 5 mm is placed directly in front of the lens.

In order to evaluate the contrast enhancement of the SED, the design was compared to a camera of similar design but air-filled rather than liquid-filled. A uniform light source with an exit port diameter of 15 cm was placed 55 cm away from each camera lens. At the exit port center was placed a 50 mm square matte-black plastic mask, large enough to fill the entire CCD image. Thus no light from the source was falling directly onto the CCD detector, and any light measured would result from veiling glare. The source, nonuniform to less than 2 % across the exit port, used an adjustable fluorescent lamp with a green filter to produce a narrow-band monochromatic light. A photodiode was used to monitor the source luminance.

The liquid-filled camera showed a 2.7 factor of improvement over its air-filled counterpart (for details, see Ref [7]), which did not reach our goal of a factor of 10, but was nonetheless encouraging. There are plans to improve the optics in several ways. First, more refined filtration techniques can be utilized to improve the purity of the silicon-based fluid. Even minute particles in the fluid will cause scattering of light within the camera. A better index matching of the liquid to the solid may be possible, which would further reduce reflections. NIST is in the process of investigating the particulate suspending qualities of different liquids that might be suitable for use against a CCD chip surface to determine any relationship between Rayleigh scattering (scattering off small particles including the molecules of the liquid) and other properties of the liquid. Polishing and painting the sides of the lens and interior surfaces of the camera would increase stray-light absorption. Placement of the camera aperture and exploration of different lens geometries are also being considered. It has been found that particulate contamination on the interior surface of the lens contributes substantially to the light scattering. Methods to remove the particles or eliminate them entirely through the use of solids are under investigation. The goal is to produce a camera that has a glare factor significantly less than 0.1 %. This would provide a measurement tool that could be placed at the pupil point of the eye and come close to measuring what the eye truly sees.

3. REFLECTION METROLOGY

3.1 Three-component model. Adequately characterizing the reflection properties of a display can prove difficult due to the presence of the haze component in the bidirectional reflectance distribution function (BRDF) [1]. The display industry has concerned itself with the two historical types of reflection: diffuse (where most consider this to be Lambertian reflection) and specular. Unfortunately, reflection characteristics can be much more complex than these two simple models can describe. To illustrate this, observe the data in Fig. 4. Here, a BRDF was measured for a sample material using the configuration on the left. As the plot shows, there exists a specular peak, a nearly flat Lambertian (inadequately referred to as diffuse) component, and then a transitional component that occurs between the two. This latter component, called haze in the display industry, is manifested as a fuzzy ball of light on a display surface that would surround the specular image (should it exist).

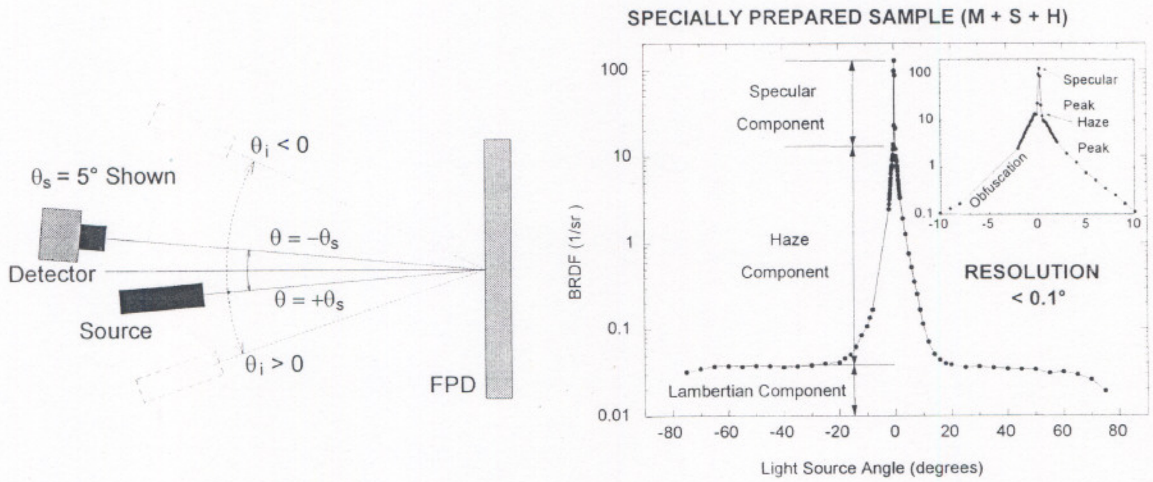

Fig. 4. The three components of reflection.

Over the years, only two measurements usually have been made to characterize the reflection (diffuse and specular). Sometimes three measurements are made. In the general case, a minimum of four parameters are required to specify reflection—specular (distinct image), Lambertian, and haze with a peak and width. Thus, a minimum of four measurements are needed, and possibly more, to accurately characterize reflection.

The haze parameters are particularly difficult to measure, for the measurement can be sensitive to the geometry of the apparatus [2]. Thus, such parameters as the LMD distance, lens diameter, focus, source size, and source distance come into play. For example, in one measurement configuration, a ±1°

misalignment of the source can result in a 30 % error in the measured reflected luminance. Furthermore, haze reflection need not be symmetrical. Star patterns and spikes further complicate a full characterization of reflection, requiring a complete time and data intensive BRDF measurement. Separating out the specular component also may be daunting. A finer sampling of data with a smaller measurement aperture (typically much less than 1°) is required to accurately capture the specular peak and separate it from the haze peak. Note that the graph in Fig. 4, the BRDF extends almost four orders of magnitude. Some displays only have haze and can exhibit five orders of magnitude or more in reflected luminance, with no appreciable Lambertian component.

3.2 Measurement solutions. Ideally, reflection measurement procedures must be robust; that is, they must provide results that are not subject to small apparatus imperfections, perturbations, irregularities or choice of equipment. They also need to be reproducible and unambiguous. Several simple techniques to better characterize reflections are being investigated at NIST--techniques that are readily accessible using simple equipment: (1) ambient reflection using the equivalent of an integrating sphere, (2) ring-light measurements, (3) large-source specular measurements, and (4) reflection of a variable aperture source (which also allows the separation of the haze peak and specular components).

Assume a worst-case scenario: uniform light from all directions illuminating a display, such as bright fog in a bubble helicopter. To make this measurement, place the display into a large integrating sphere (see Fig. 5) and tilt the display so that the measurement hole is approximately 8° off from the display normal. The resultant measurement gives you the diffuse reflectance, $\rho_{d/8}$. A variety of apparatus, such as rectangular sources (picnic coolers), can be used to reproduce sufficiently the uniform hemispherical surround conditions. The results tend to be insensitive to apparatus configuration and angular alignment.

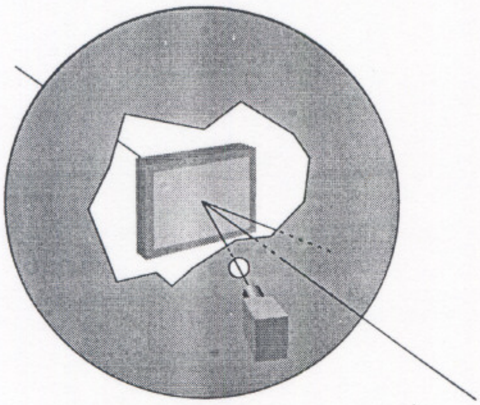

Fig. 5. Measuring direct hemispherical reflectance.

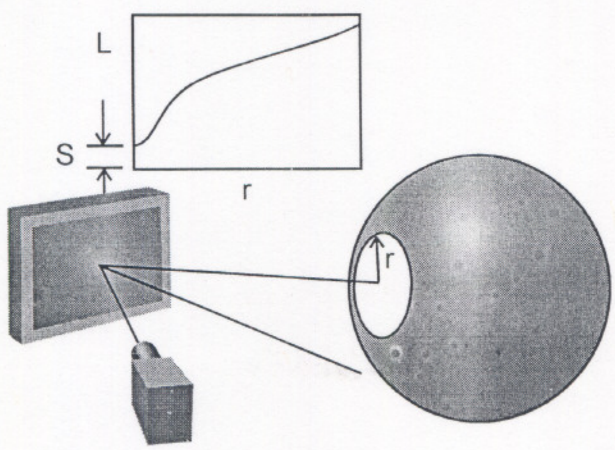

Fig. 6. Variable aperture source method.

Another approach to isolating the specular peak, shown in Fig. 6, involves measuring the reflected luminance of the source for a series of decreasing source apertures. As the aperture radius approaches zero, the Lambertian and haze components become smaller. If a quartic (or sixth order) curve is fitted to the data for small radii, the extrapolation to zero will reveal the specular component (see graph in Fig. 6). The constant term in the fit is indicative of a specular component; the quadratic term is indicative of the haze peak.

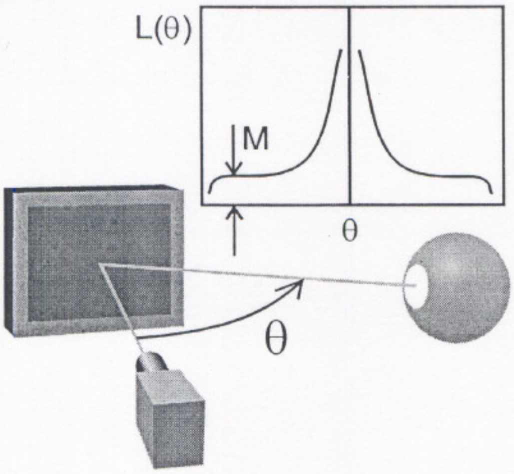

Fig. 7. Simplified BRDF.

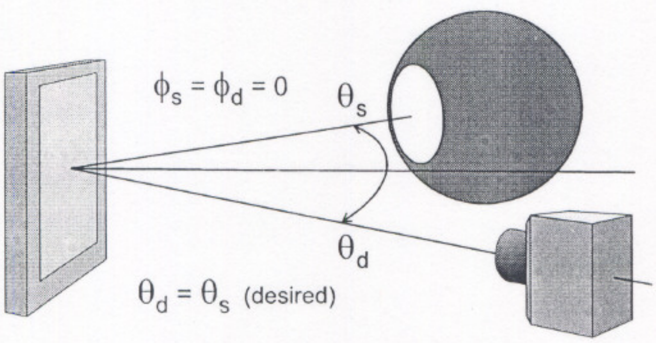

Fig. 8. Diffuse reflectance measurement.

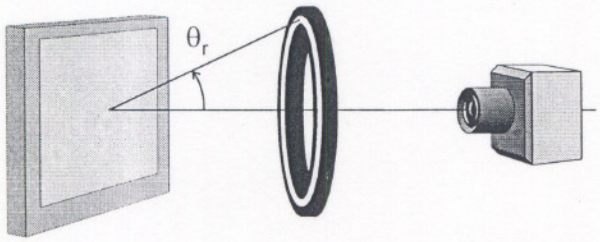

Fig.9. Using a ring light.

To approximate the Lambertian component, measuring the BRDF for large angles ($\theta \cong 70°$) may suffice (see Fig. 7). Using a source with an angular diameter of 1° or less, the luminance can be measured as a function of angle from the normal for angles greater than 30° or more. This avoids the high-resolution measurements required for the specular region and determining the detailed shape of the haze peak. This method is also useful for calculating the effects of isolated sources (such as the sun) at angles away from the specular. However, this method tends to not be robust, especially if the angles are 30° or less. Using a ring light (Fig. 9) instead of an isolated source will provide an excitation of the wings of the haze and any Lambertian component with the added feature of integrating all the affects of any spikes or irregularities in the BRDF.

The diffuse reflectance measurement integrates all three components together. The ring-light measurement combines the wings of the haze measurement with any Lambertian component. The large-source specular measurement provides a measurement of the specular combined with the region of the haze peak. These three measurement methods provide an integration of the reflection properties about the normal (or viewing direction) so that any single source direction is not preferred.

4. NEAR THE EYE DISPLAY (NED) AND HEAD-MOUNTED DISPLAY (HMD) DIAGNOSTICS

4.1 Introduction. Because NEDs and HMDs are used with optics that are optimized to the position of the eyes of a human observer, they can be difficult to measure. Traditional means of characterization and calibration prove ineffective, and the use of novel measurement techniques may result in inaccurate results. Conventional detectors may not be designed to properly measure NEDs, or the measurement may be sensitive to vignetting or distance from the display. We are interested in instrumentation that provides accurate luminance measurements of the virtual images generated in NEDs and HMDs. Essentially, methods are needed to determine whether the LMD is measuring the same luminance and color that a human observer sees (Fig. 10). NIST is addressing this issue by developing diagnostics that can establish confidence in a particular measurement apparatus.

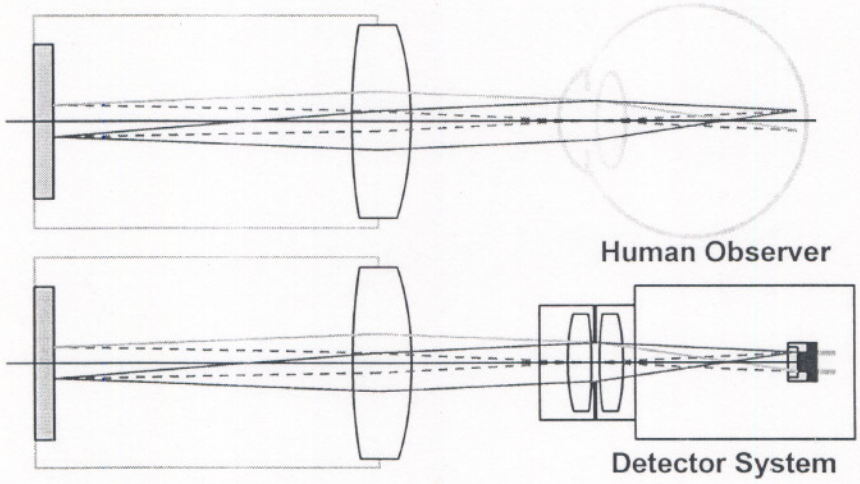

Fig. 10. Hypothetical configuration for NED measurement.

4.2 Ray-Bundle Diagnostic. The detector measures the amount of light emitted from a surface, illustrated in Fig. 10 as a bundle of rays. In a NED measurement, the light passes through the NED lens, into the detector lens, and illuminates the detector. This apparatus must be configured such that the light bundle is representative of the amount of light that would illuminate the retina of a human observer. A simple diagnostic can be used to verify that the measurement region being measured is not larger than what the eye would observe. As shown in Fig. 11, an iris is inserted between the NED lens and the LMD. If the measurement region is small, the iris size will approach the size of the entrance pupil of the detector (which should be some selected size of the human eye, e.g. 3 mm) before it interferes with the measurement result. Vignetting will be observable, but the small measurement region centered in the iris should remain relatively unaffected if the contributing ray bundle is small.

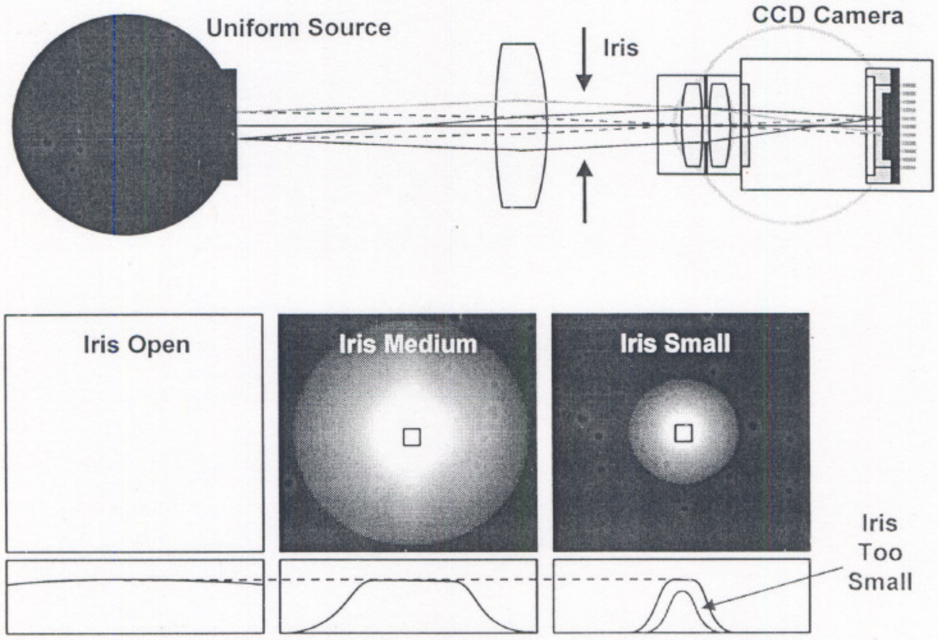

Fig. 11. Ray bundle diagnostic.

4.2 Insertion Mirror Diagnostic. One challenge of using an luminance meter to measure a NED is how to check the validity of the calibration of the measurement device for this particular application. Luminance meters are typically calibrated against a uniform source, usually a tungsten bulb attached to an integrating sphere with an exit port much larger than the aperture of the viewing optics of the NED. One approach is illustrated in Fig. 12. If the eye relief is large enough (e.g., a telescope eyepiece for glasses, 17 mm to 22 mm), we can use a small mirror to view a similar display or source that can be adjusted to the same perceived luminance and color of the NED. The mirror is placed in the viewing area such that it images a reference source — a display of similar technology and light source (see Fig. 13). The mirror remains stationary within the field, creating a bipartite image in the viewer's field of view. Both color and luminance can be matched, but to make a good luminance match, the color must match well.

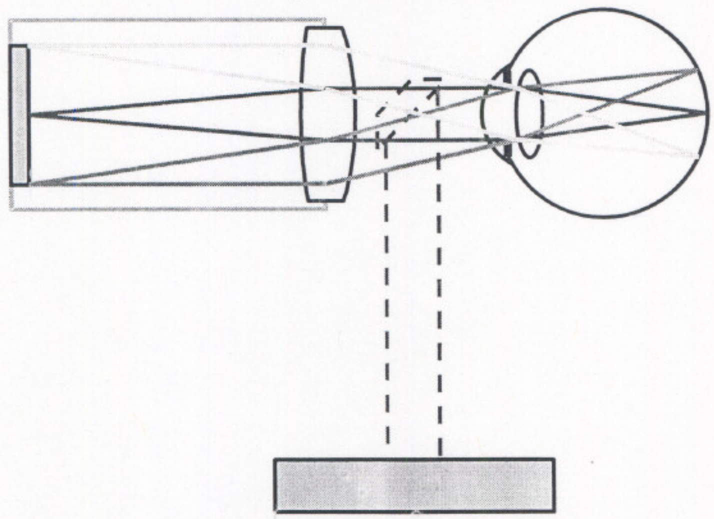

Fig. 12. Insertion mirror diagnostic.

As much as possible, the mirror should extend right to the edge so that no substrate glass is visible, to avoid a darkening vignette around the mirror. If a post is used to mount the mirror it will be visible. The front surface mirror must be large enough to permit the full ray bundle to be used. Since the mirror is not perfectly reflective, there may need to be some correction for careful work.

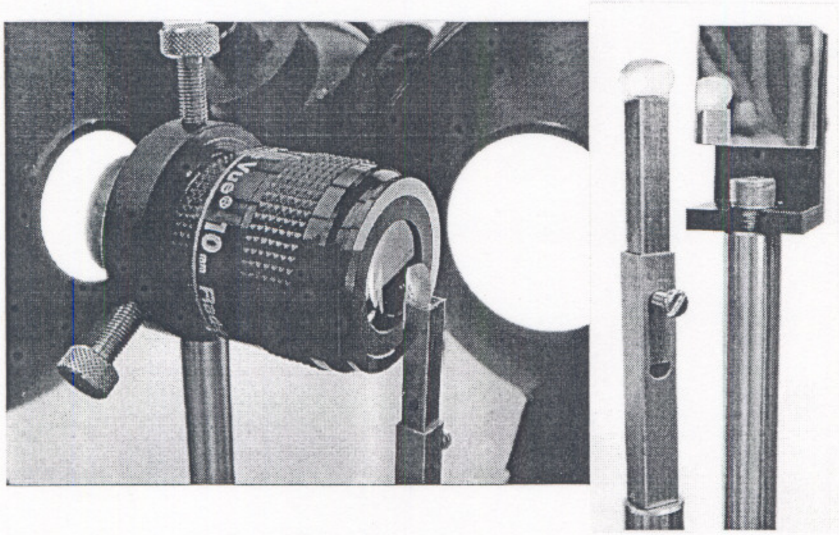

Fig. 13. Arrangement of insertion mirror using integrating spheres to simulate electronic displays.

This method can provide a check of the detector system calibration. It is something that can be done occasionally to verify that the NED detector is doing what it should. Once the reference source is adjusted so that it looks the same as the full screen virtual image in the NED, measure the reference source using ordinary instruments and compare results with instrument used to measure the NED virtual image (see

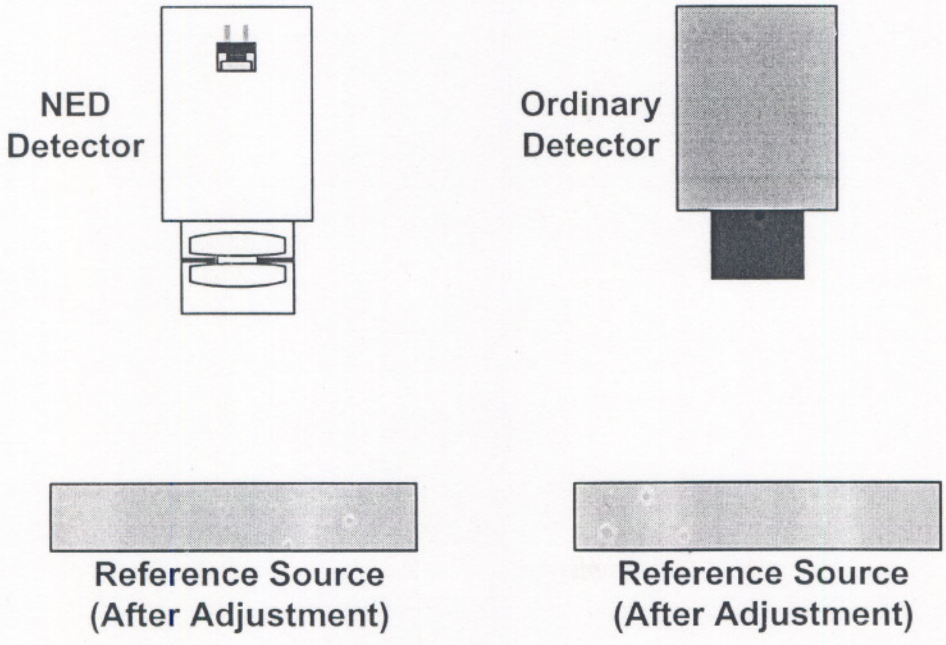

Fig. 14. Evaluating NED detector after bipartite image match.

Fig. 14). How well the NED detector results compare with the ordinary detector results will give the degree of confidence in its performance.

5. CONCLUSION

Accurate and meaningful display metrology continues to provide challenging obstacles. No longer is it adequate to think of only two types of reflection. Veiling glare must be minimized in order to make proper color and contrast measurements. Methods must be used that correctly indicate what the eye sees in near-eye displays. Further research at NIST should address and to some degree simplify the complications associated with the development of good display metrology.

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