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Simulated-eye-design camera for high-contrast measurements

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ABSTRACT

Light-measurement instrumentation based upon high-quality charge-coupled-devices (CCD) is currently in use for measuring the characteristics of electronic displays. When such array detectors are used to measure scenes having high contrasts or wide color variations, they can suffer from the effects of veiling glare or lens flare and thereby inaccurately measure the darker luminances because of a mixing of the scene luminances or colors. The simulated-eye-design (SED) camera attempts to reduce the effects of unwanted light contamination by copying some of the characteristics of the eye. This first prototype shows an improvement of a factor of 2.7 in its ability to measure high contrasts over a similar camera that is not filled with liquid.

Keywords: liquid-filled camera, SED, CCD, contrast measurements, light measurements

1. INTRODUCTION

As new electronic display technologies become available, measurements of their characteristics become more important both for the accurate specification of display characteristics and for quantifying display quality in making comparisons between displays. Whenever these measurements are of a full screen of color or gray shade, there are few problems. However, whenever there is high contrast or multicolor subject material being displayed on the screen, an accurate measurement of any detail of the screen can be difficult owing to veiling glare—particularly the darker details can be corrupted with light from the brighter areas. Veiling glare arises from reflection of the light between surfaces of a lens or from reflection of light from some mechanical part of the lens or other part of the camera. For example, consider making a measurement of an isolated black letter on a white screen. The contamination of veiling glare in the instrument's lens system from the white screen can dominate any light coming from the black letter. The same can be said for a variety of measurement methods used to evaluate displays.[1] In Fig. 1 we illustrate how veiling glare may be produced in a camera that might be used for display measurements. In Fig. 2 we show actual photographs from such a camera illustrating the glare produced.

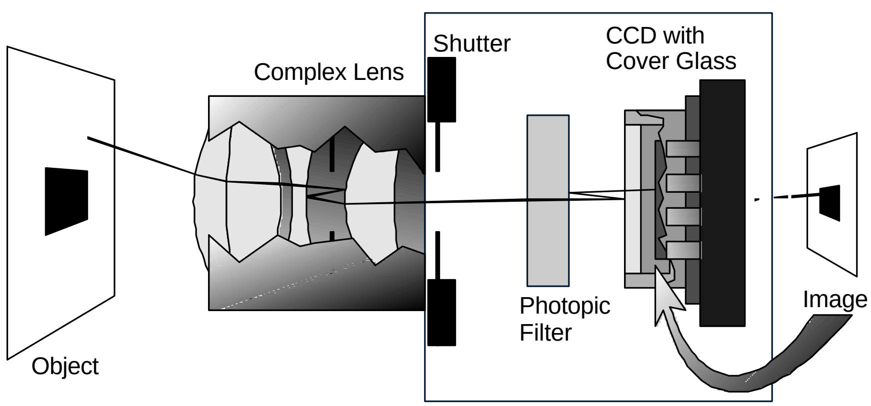

***Fig. 1**. Conventional photopically-corrected thermoelectrically-cooled (TEC) scientific-grade CCD camera with a complicated lens and many air-solid surfaces that produce reflections. One ray from a white area on the object is shown reflecting off of various surfaces onto the image area of the black rectangle. (This is for illustration purposes only; it is not intended to be a ray tracing.)*

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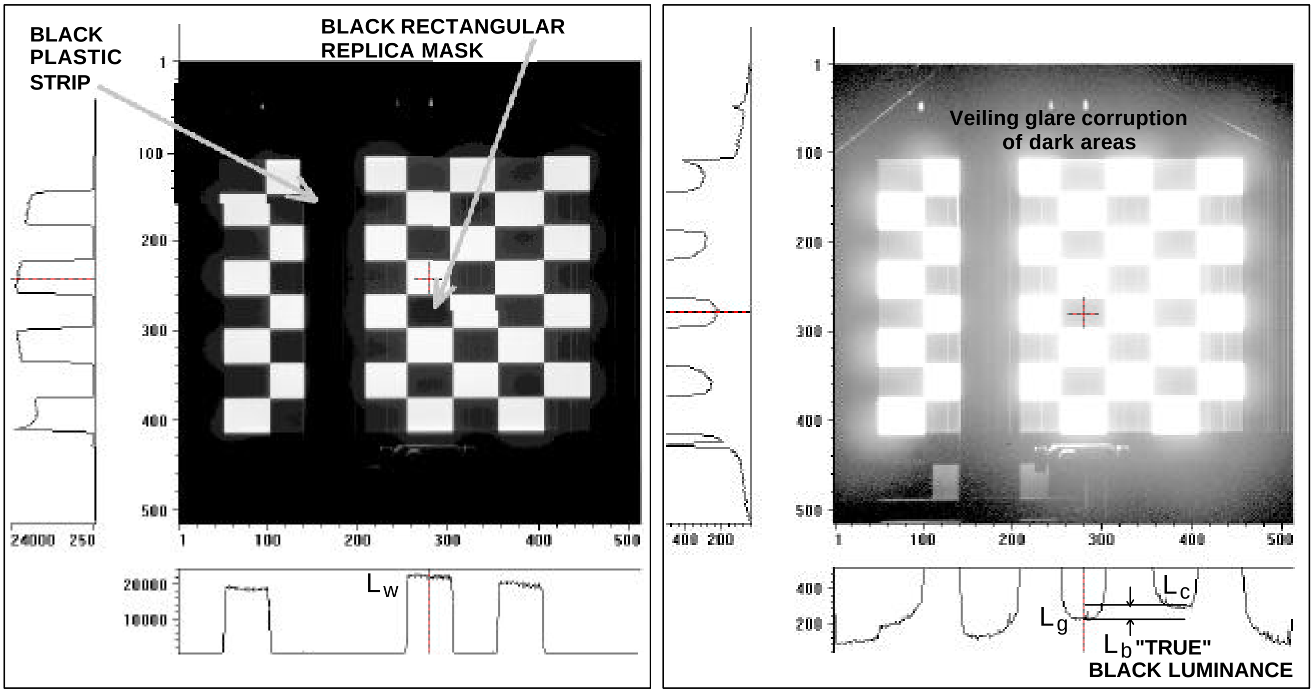

Fig. 2. *A checkerboard pattern is displayed on a laptop computer employing an active-matrix liquid crystal display (AMLCD). A black plastic strip covers a vertical region of the display at the left of center, and another black plastic rectangle the size of the checkerboard rectangle covers one of the black rectangles. The left photograph shows a scientific grade CCD camera (as in Fig. 1) image with the full dynamic range of the image (approximately 16-bits). The right side shows the same photograph with the dark regions intensified to demonstrate the glare introduced in the optical path visible as corruption of the black areas around the display, in the black strip overlaid on the display, and in the black areas in a checkerboard pattern. Note the difference in black levels between the replica mask black and the checkerboard black.*

Figure 2 illustrates how the veiling glare can dominate the actual luminance of the black checkerboard rectangle. Here, the CCD counts are proportional to the luminance of the object. The contribution of veiling glare is observed in the replica mask luminance L_g that measures approximately 230 counts, whereas the black rectangle luminance L_c measures approximately 310 counts. The true black luminance $L_b = L_c – L_g$ would then be 80 counts. In this case, the checkerboard black is contaminated by veiling glare that is almost 300 % of the black luminance (L_g/L_b). If we were not aware of veiling glare and did not attempt to correct for it by using a replica mask we would claim a contrast of $L_w/L_g = 72$ where the luminance of white is $L_w = 22\,200$ counts. Using the replica mask to correct for the glare gives a contrast of $L_w/L_b = 278$, which is much closer to the more carefully measured value of 250:1 obtained by using aperture and cone masks.[2,3]

The purpose of this research is to construct an optical system that, like the eye, can “see” high-contrast objects well and avoid as much veiling glare as possible. This is not to say that the eye doesn’t have veiling glare problems, but it is much better controlled than in many optical instruments. The starting point in this design is to use a simple glass lens behind which is placed a liquid. The liquid is in contact with the rear of the lens and continues to the silicon chip of the CCD. In such a case, the glass cover plate that normally protects the CCD has been removed. We thereby limit the number of reflective interfaces as much as possible in this simulated eye design (SED). The idea of using liquids in the optical path is not new.[4,5] Obviously, many have two eyes that work marvelously well. This paper reports on our first prototype camera based upon SED optics for the purposes of attempting to make glare-free measurements on displays. Future attempts will, hopefully, improve performance dramatically so that only small corrections—if any—will be needed to accurately measure the detail of high-contrast objects.

2. SIMULATED-EYE-DESIGN CAMERA

Figure 3 shows two similar camera configurations. Both have a CCD placed on a movable rod to provide focus adjustment. One camera is filled with air. The SED camera is filled with silicone liquid (polydimethylsiloxane, trimethylsiloxy-terminated; viscosity of 1 cm^2/s [100 cs in older units]—about like maple syrup). Since the CCD is exposed to the liquid without the benefit of a protective cover glass, a pure silicon-based liquid is chosen. The lens on each camera is an uncoated 25 mm diameter plano-convex lens with a focal length of 25 mm. Given an index of refraction of the glass lens of $n_1 = 1.673$ and an index of refraction of the liquid of $n_2 = 1.41$ the reflectance R for normal incidence at the liquid-glass interior surface is

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = 0.73\,\%, \qquad (1)$$

whereas for a normal uncoated air glass interface the reflectance is approximately 6.3 %.[6] An aperture having a diameter of 5 mm is placed directly in front of each lens. The camera bodies are made from black acetal plastic.

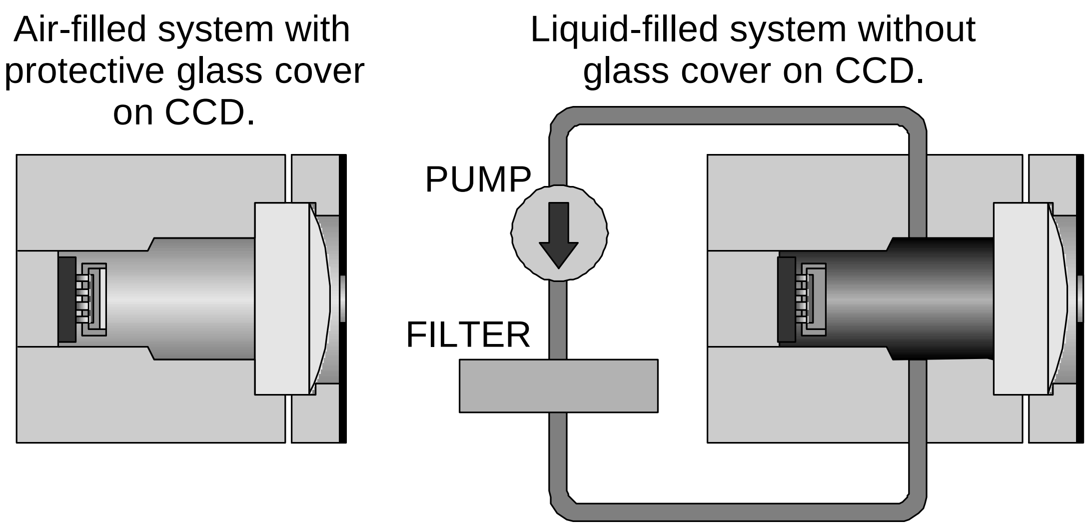

Fig. 3. *An air-filled camera compared to the liquid-filled SED camera. A simplified liquid handling system is shown attached to the SED camera.*

In future experiments different liquids will be tried that will much better match the index of refraction of the glass (or whatever material is used at the front surface) and further reduce the interfacial reflections or virtually eliminate them. Good antireflection coatings can easily achieve a reflectivity for any surface well below 1 %, it is true; but there are other reasons to employ liquids within the camera. The use of liquids also reduces the reflectance of other dielectric objects (the plastic interior, painted surfaces, etc.) within the camera—this is commonly seen in the way wet sand looks darker than dry sand and in the way wet streets look darker than dry streets. It was decided to use the same lens for both the simple camera and the SED camera for the purposes of comparison. Future tests can compare optimally designed optics for both types of cameras.

The disadvantage in using liquids is that they must be virtually free of particles to be useful for this application. A liquid circulation and filtration system is used to remove particles from the liquid. Figure 4 shows the rather complicated plumbing arrangement employed that permits changing the filter and making modifications to the SED camera without removing the liquid from the system. Table 1 shows some valve configurations for a few of the functions of the plumbing system. When the SED camera is initially filled with liquid it is always filled under vacuum to assure that all voids are filled with liquid. A 9 cm diameter hardened paper filter is used with pore size listed at approximately 20 μm—see Fig. 5. Using continuous filtration, however, virtually all particles are eventually removed from the liquid. We could observe the particle content in the liquid by using a 0.5 mW red solid-state laser beam through the view port (an inexpensive laser pointer will suffice). Particles become rather visible from forward or backward scattering out from the laser beam. Eventually, the liquid became clearer than the glass lens, but such clarity is obtained after several days of continuous filtration. (Extended pumping over a long period of time apparently introduces a charge layer on the surface of the CCD chip causing nonuniform background counts over the surface that cannot be tolerated. When this happens, the CCD must be removed from the SED camera and cleaned off with solvent before it operates properly.) The filter is sealed using a flat polyethylene ring against the metal surfaces of the filter holder (a polytetrafluoroethylene ring would be preferred since it would more easily deform to seal the filter paper). Nichrome wire meshes are placed above and below the filter to support the filter during use and when vacuum filling the pluming system with liquid. The meshes also permit the full exposure of the filter surface to the liquid. The sharp edges of the nichrome meshes are bent toward the metal part of the filter to avoid puncturing the filter material. During the use of the SED camera, particles gradually find their way into the optical path whereby the liquid in the camera has to be recirculated. We are constantly plagued by particles and have to remove the lens to clean the rear surface on a regular basis. Added to this complication is the cavitation produced by the gear pump when moderate pumping speeds are used. It is difficult to slow the pump down sufficiently to completely eliminate all cavitation presumably because the liquid is so viscous. To avoid any bubbles from reaching the SED camera, the liquid is circulated down through the filter, and the flow rate is limited to approximately 4 cm^3/s. Any cavitation bubbles can collect in the chamber above the filter that holds the nichrome mesh. Should too much gas accumulate above the paper filter, the plumbing system will permit evacuation of the gas by applying a vacuum to the filter while the rest of the plumbing system is isolated—see Table 1.

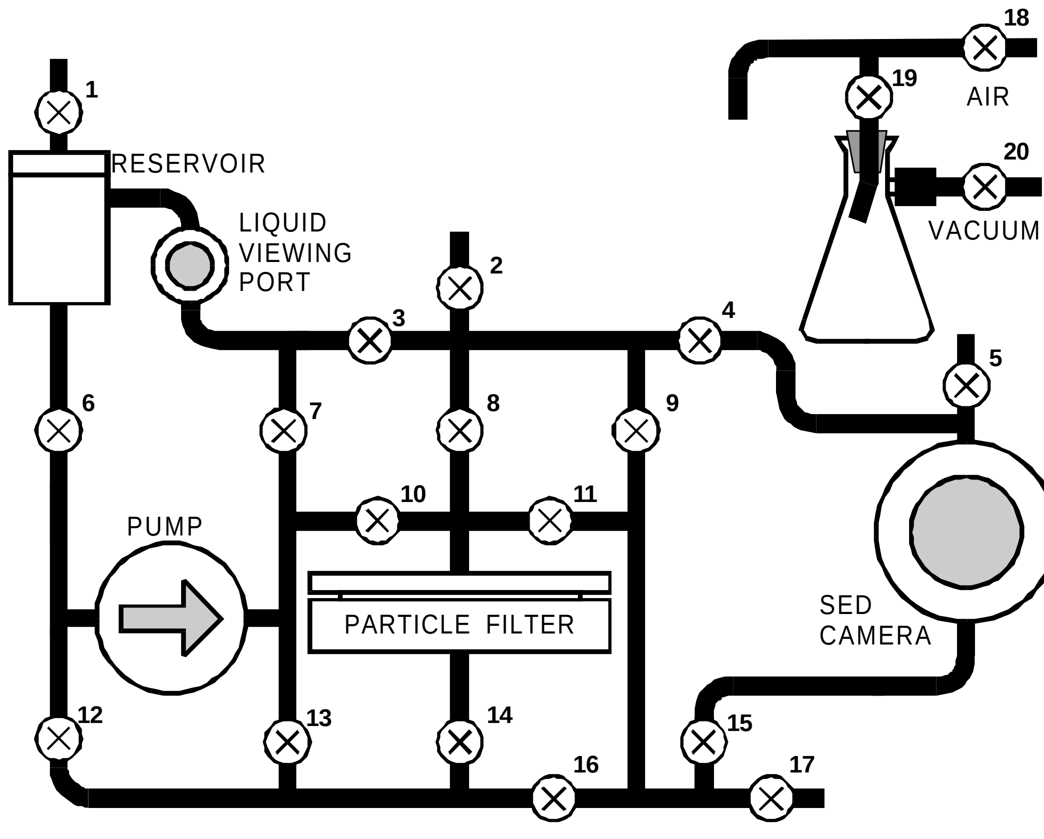

Fig. 4. *Plumbing system for liquid circulation and filtration.*

Table 1. *Plumbing Configuration*

Function	Vacuum/Air Connection	Pump Status	Valve Status (black means closed, white means open, gray means either)																			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Normal liquid flow		on	□	■	□	□	■	□	■	■	■	□	■	■	■	□	□	□	■	■	■	▒
Remove bubbles from filter	1 - Vacuum	off	□	■	□	■	■	■	■	□	■	■	■	■	■	▒	▒	▒	■	■	□	□
Remove liquid from camera		on	□	□	■	□	■	■	□	■	■	■	■	□	■	■	□	□	■	■	■	▒
Remove liquid from filter		on	□	□	■	■	■	■	□	□	■	■	■	□	■	□	■	■	■	■	■	▒

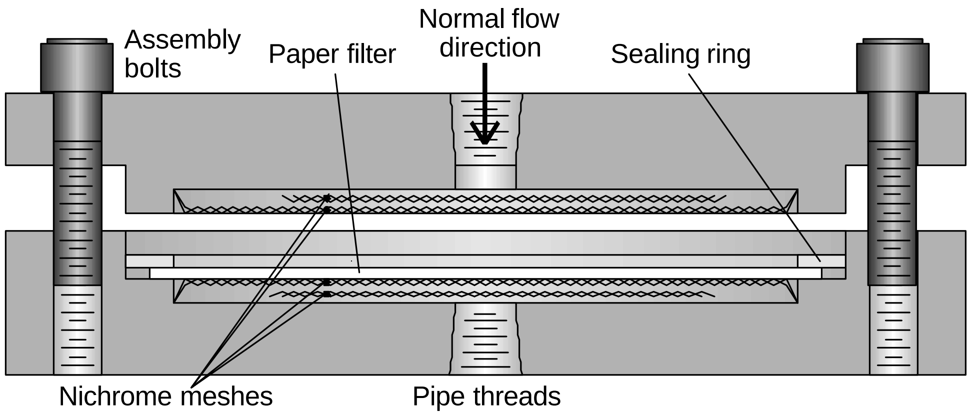

Fig. 5. *Cross-section of filter. Nichrome meshes support the filter paper (white) during pumping and vacuum filling. The edges of the larger nichrome mesh hold the mesh in the top metal part so it won't fall out when the top part is inverted for assembly. The view shows the configuration just prior to assembly. The filter and seal are exaggerated in thickness for purposes of illustration.*

The front of the lens is placed approximately 55 cm away from the exit port of a cubical uniform light source having an exit-port diameter of 15 cm—see Fig. 6. The maximum nonuniformity across the exit port of the light source is no greater than 2 %. The light source is continuously adjustable from zero to 3025 cd/m^2 and is based upon a fluorescent lamp (thus only a minimal amount of infrared light is produced). A photodiode and ammeter monitor the luminance of the source. The linearity of each CCD is checked against the photodiode current and found to be better than 7 % based on a comparison of the standard deviation of the ratio of the CCD counts to the photodiode current.

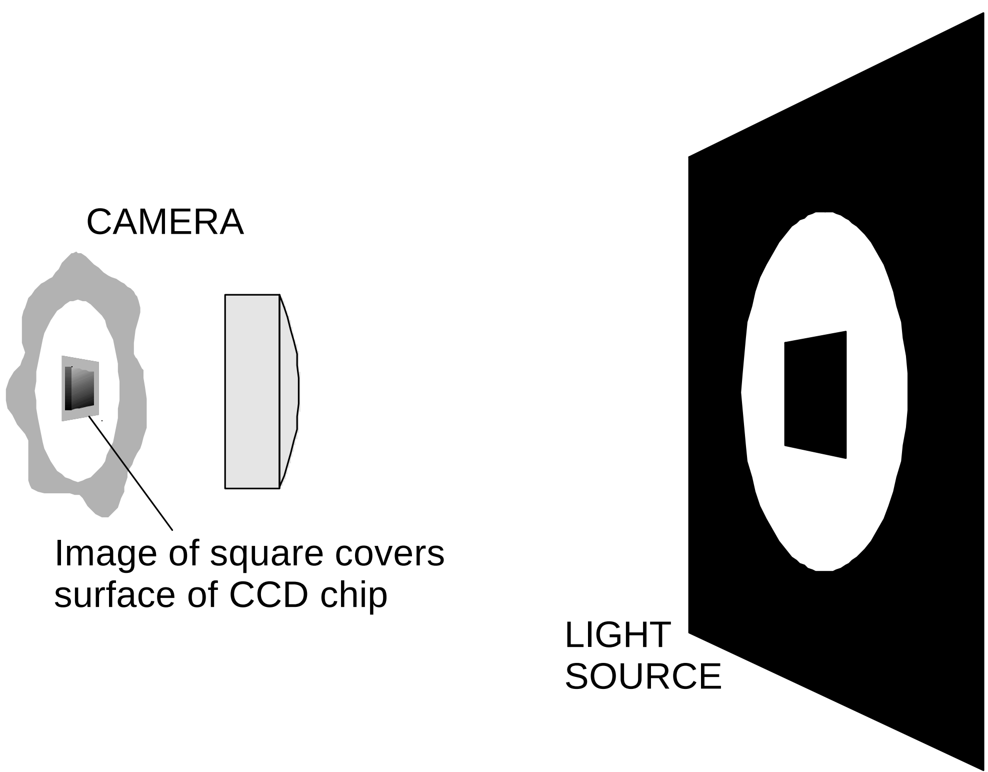

Fig. 6. *The cameras view the exit port of a variable uniform light source having an opaque black square target at its center.*

At the center of the exit port is placed a 50 mm square matte-black plastic target. The image of the square target is arranged to overfill the entire CCD detector surface so that no direct light from the exit port is imaged onto the CCD surface—see Fig. 6. If the optics were perfect, no light would fall on the CCD since there is essentially no light coming from the square target. Because of stray light within the camera systems a certain amount of veiling glare is produced so that the image of the square is not perfectly black. This method of measuring veiling glare is similar to the CIE method for characterizing veiling glare.[7] (In our case, fully implementing the CIE method would require a source with an exit-port diameter of 50 cm. We are limited by a 15 cm diameter exit port.)

This method of testing for veiling glare, where the entire surface of the CCD is employed as the detector, is necessary because of the nature of the CCD and its electronics. An eight-bit CCD camera system (192 horizontal × 165 vertical pixel array) is chosen because we are able to obtain inexpensive CCD chips that are socketed so that different CCD chips can be connected easily. In fact, the system permitted connecting the CCD chip to its electronics via a multi-wire connector approximately 20 cm long. The checkerboard photograph in Fig. 2, taken with a 16-bit camera, shows that the veiling glare typically produces contamination on the level of a few percent. For an eight-bit CCD detector, one-percent effects (two to three counts) can be at the level of the noise or nonuniformity of the system. Additionally, streaking and blooming needed to be avoided. Such a simple CCD detection system does not lend itself to making accurate high-contrast measurements of images with both whites and blacks on the CCD surface. These problems associated with the CCD are avoided by covering the entire CCD with the image of the black square target and using the entire surface of the CCD as the detector. It is hoped that using higher-quality 16-bit CCD camera systems in future SED cameras will avoid these problems and permit a more critical evaluation of camera performance using a variety of targets.

3. RESULTS

The data are collected in a two step process. First, with the square target in place the light source is adjusted to provide a moderate amount of veiling glare over the CCD surface. We adjust the light to obtain mid-range values (approximately 120 counts) at the center of the CCD to avoid blooming at the corners. An average value for the CCD counts L_g is obtained along with the monitor current J_g from the lamp-luminance monitor. Second, the square target is removed and a small square aperture (approximately 12 mm square) is inserted to provide a no-glare calibration of the CCD. The luminance of the light source is reduced so that the CCD reads a mid-range value L_s within the small square that is approximately the same as the central value when the square target is used. This mid-range value along with the associated monitor current J_s represents a calibration C of the source in terms of CCD counts per microampere. This method attempts to avoid some of the non-linearity of the CCD. From both luminance values a measured background B is subtracted. The luminance of the source in terms of CCD counts $L_0 = CJ_g$ when the square glare target is in place can now be determined. Finally, the glare factor G of the camera can be calculated as the fractional amount of veiling glare compared to the white luminance expressed in percent. The data and calculations are shown in Table 2. Comparing L_g with L_0 confirms that we are dealing with stray light contamination less than 1 %, but that is for this large square target that covers the CCD. Further, to attempt to accurately measure high-contrast detail in one CCD picture will require a 16-bit camera system. It is not difficult to imagine that as the black areas of the image get smaller (no longer covering a significant portion of the CCD array), the contamination from stray light can increase well beyond 1 % levels.

Table 2. *Comparison of Simple Camera to SED Camera.*[8]

	L_g (counts)	J_g (μA)	L_s (counts)	J_s (μA)	B (counts)	$C = (L_s - B)/J_s$ (counts/μA)	$L_0 = CJ_g$ (counts)	Glare Factor $G = (L_g - B)/L_0$
Simple Camera	167	60.3	120	0.395	4.58	292	17 600	**0.92 %**
SED Camera	161	136	128	0.374	2.18	336	45 600	**0.35 %**

4. CONCLUSION

The improvement of the liquid SED camera system over the air-filled simple camera system is a factor of 2.7. We hoped for a much greater effect, but this is the first carefully made prototype. We can anticipate improving the optics of the system in several ways: (1) A better index matching of the liquid to the solid front lens will further reduce reflections. (2) Careful attention to making the liquid as free of particles as possible will reduce the scattering of light—this is presently felt to be the greatest impediment to success. (3) Better placement of the aperture (perhaps behind the lens inside the liquid—

as with the human eye) may improve performance. (4) Careful attention should be given to be sure all interior surfaces are as black as possible. This would include the side of the lens that is usually ground. We would polish the side of the lens and paint it black to make it much more light absorbing. (5) It may be possible to use a thin quasi-spherical dome made of plastic instead of the glass lens (much like the cornea of the eye)—indeed, if vacuum filling is not required, a flexible membrane might permit focusing by changing the liquid pressure.[9] (6) If a solid piece of glass can be placed directly on or very near the CCD surface using a suitable index-matching liquid, it may be possible to arrange for a TEC CCD. The thermal gradient may be mitigated by the glass and permit the room-temperature liquid to be sufficiently free of thermal convection. (7) The unprotected surface of the CCD presently limits the kinds of liquids that can be used within the camera. If a coating directly on its surface can protect the CCD silicon, this may allow the use of a more suitable liquid where index matching and particle content can be more easily controlled. (8) Finally, we would want to compare the improved SED camera with a high-quality air-spaced lens system designed for minimizing glare, rather than such a simple camera system employed here. Ultimately, the goal would be to produce SED cameras that will have glare factors significantly less than 0.1 %. Such cameras will greatly enhance the measurement of details of complex images. They will further aid in the metrology of displays that are currently very difficult to measure such as head-mounted displays.

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