Display-Metrology Issue

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SID

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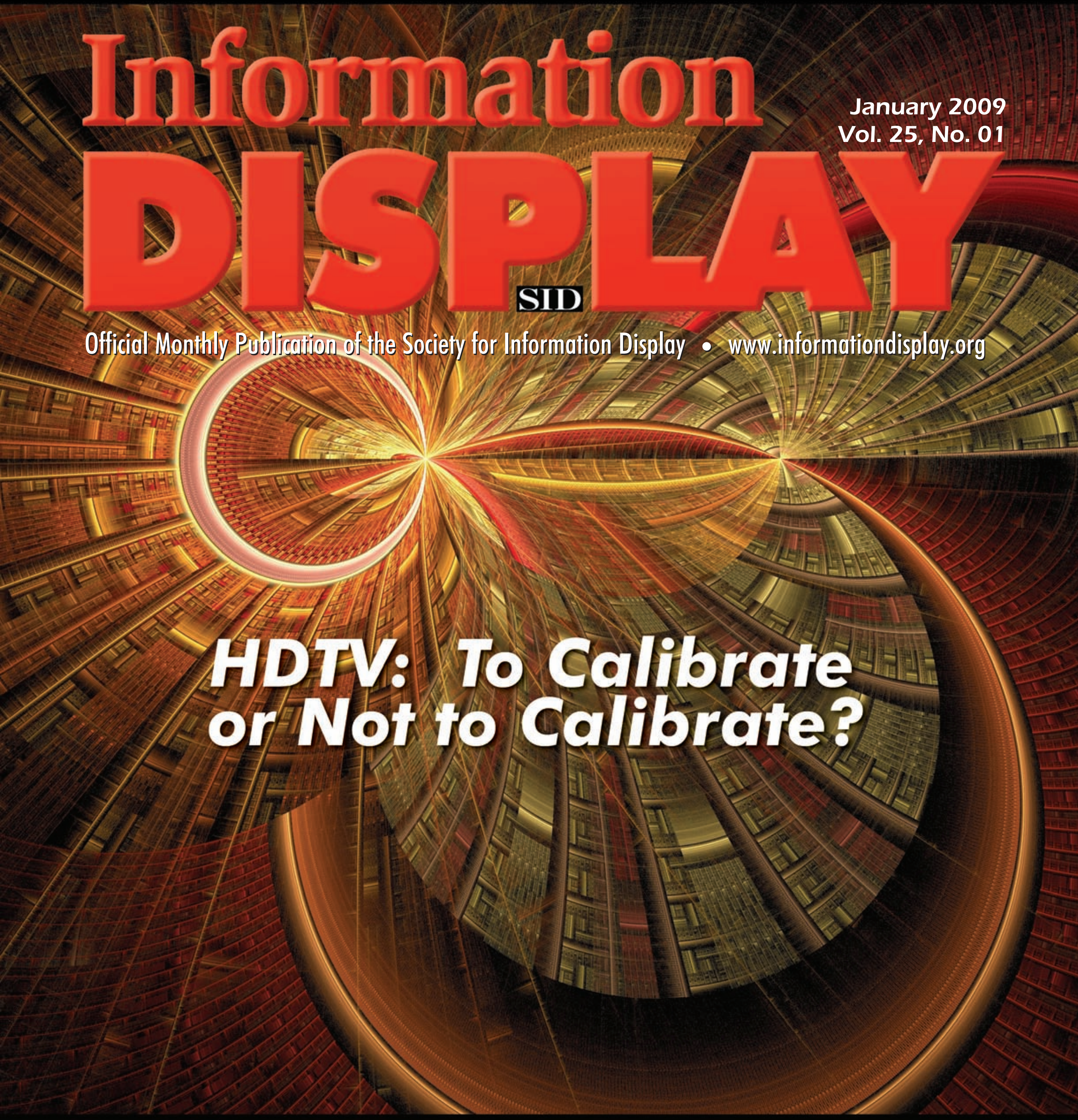

HDTV: To Calibrate or Not to Calibrate?

- 3-D Layout Perception in Stereo Displays
- Characterizing Autostereoscopic 3-D Displays
- Metrics for Local-Dimming Artifacts
- Minimizing the Effects of Veiling Glare
- HDTV: To Calibrate or Not to Calibrate?
- *Journal of the SID* January Preview

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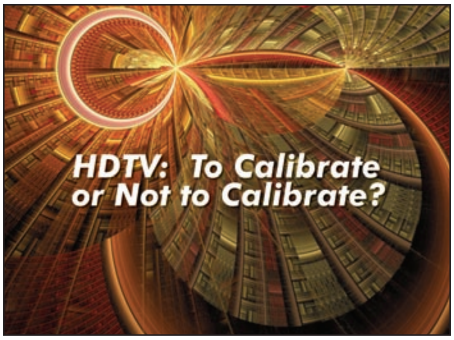
COVER: Display metrology occupies a very special niche of the industry, one that is often relied upon but not so easily understood. Current research topics in display metrology have evolved from the early days of basic photometry and measurement methods; to very complex problems of correlating human visual perception; to physical parameters of holographic, 3-D stereoscopic, and HDTV displays. HDTV calibration services, which have evolved based on the availability of low-cost measurement devices, are currently a profitable up-sell for retailers, but do consumers really care about or need them? See page 28 for arguments pro and con.



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LED Issue

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- Large-Screen LED-Backlit LCD Production
- LEDs as Backlights in Cockpit Displays
- Display Week 2009: San Antonio Travel Guide
- *JSID* February Preview

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editorial

Taking Measure of 2009

Happy New Year to everyone! By the time you read this in North America, most of our celebrations are over and we're back to work, while many of you in Asia are now enjoying your New Years vacation with time for family and celebration. Despite these difficult economic times, I am finding these celebrations to be no less festive than previous years and look forward to the optimism that comes along with the new calendar. Here in North America, the new year means we'll be holding our annual Paper-Selection Program Committee meeting for the upcoming 47th annual SID International Symposium (which will take place May 31 – June 5 in San Antonio, Texas).

The Paper-Selection meeting is the critical part of the planning process for the Symposium, and despite the myriad tools available to hold virtual meetings, this valuable activity still takes place in live sessions with participants travelling to the meeting from literally all over the world. It involves a team of approximately 150 dedicated, highly credentialed volunteers, who collectively rate all 600-plus papers submitted for consideration. This carefully orchestrated process ensures that the best quality and most relevant papers get chosen for presentation. The live exchanges of ideas and candid interactions between fellow committee members work best in a face-to-face setting, and being part of this process is an exhilarating experience. The papers selected in January are presented in oral and poster sessions scheduled alongside the exhibition, business conference, seminars, and various other activities at Display Week.

To an outsider, this process may seem both outdated and a bit inefficient, but I cannot imagine any other way of getting this breadth of talented individuals all engaged in the same task at the same time. Plus, for me, it is a goldmine of information sources on the latest activities in the industry and plays a significant role in the selection of technical articles for *Information Display* magazine for the remainder of the year.

This month, our issue theme is Display Metrology, a topic we enthusiastically revisit each year. Display Metrology occupies a very special niche of the industry, one that is not so well understood, but vital to the success of just about every display product. Current research topics in display metrology have evolved from the early days of basic photometry and measurement methods, to very complex problems of correlating human visual perception, to physical parameters of holographic and 3-D stereoscopic displays. In recent years, we have covered everything from the latest developments in conoscopy for rapid LCD viewing-angle characterization, to pursuit-camera systems for flat-panel motion-artifact measurements. (Yes, the term "pursuit camera" means what it says, the photometer literally pursues the image in motion across the face of a display capturing the dynamic blurring artifacts created.) These are innovative technologies applied very creatively to solve relatively complex metrology problems.

When looking beyond the pure science of display metrology, one can see that the real goal is to aid developers in creating the best possible displays. Often the definition of "best" is hard to define, but good metrology can be your best friend in bridging the gap between physical hardware performance and the experience of the observers – the human side of the equation. When applied correctly, good metrology helps us realize both an improved user experience and reduced hardware cost by allowing us to focus our creative energy on the features and performance metrics that really matter.

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DisplaySearch: LCD-TV Revenue Expected to Fall for the First Time in LCD-TV History

AUSTIN, TEXAS – For the first time since the technology debuted in 2000, revenues for LCD TVs are expected to be lower year over year in 2009, according to the latest research from **DisplaySearch**. The market-research firm announced on December 17, 2008, that it was revising its TV market forecast for 2009 to include the latest projections.

DisplaySearch is forecasting that LCD-TV revenues will drop 16% in 2009 to $64 billion, and total TV revenues will fall 18% to $88 billion. DisplaySearch expects that 2009 will be the most difficult year yet for the TV industry and supply chain, citing key factors such as reductions in forecasted TV prices and revised forecasts for Y/Y shipment growth for LCD and PDP TVs in 2009, which are projected to fall 7% and 6%, respectively, when compared to 2008.

Overall shipments of TVs are expected to increase, just not as fast as in previous years. For example, the LCD-TV market is expected to ship 102.2 million units in 2008, which would be a 29% increase from 2007 (this marks a reduction of 3.6 million from DisplaySearch's Q3'08 forecast for 2008). But in 2009, the LCD-TV market is forecast to ship 119.9 million units, which would be an increase of just 17% compared to the previous year (this figure has been reduced by 11.5 million units from the Q3'08 forecast for 2009). Additionally, unit growth in developed regions such as Japan, North America, and Western Europe will be just 2% year over year, largely due to the impact of the worldwide economic crisis. DisplaySearch forecasts that LCD-TV growth in emerging regions will be 45% in 2009, which is robust but still lower than the 68% growth in 2008.

"The TFT-LCD industry is going through the hardest time in a decade, as shipments and revenues dramatically decline," commented **David Hsieh**, Vice President of DisplaySearch. "To cope with the weak demand, capacity utilization for Taiwanese panel manufacturers is below 60%, Korean manufacturers are reducing utilization to less than 80%, and Japanese manufacturers are re-adjusting fab allocations.

"Currently, most panel prices are below cash cost, and some lower than the BOM (Bill of Materials) cost. However, the biggest challenge may be in Q1'09, since downstream demand is unclear as long as panel prices continue to fall. The industry will need to take additional steps to reduce capacity utilization, since falling panel prices are not stimulating demand under the current economic conditions. Continuing to reduce panel prices will cause continued pain for the whole supply chain, including panel makers, materials makers, and set makers."

Plasma (PDP) TV shipments are expected to grow 24% to 13.9 million in 2008, largely unchanged from the Q3'08 forecast. This segment is expected to grow 5% year over year in 2009 to 14.6 million units, a 5% reduction from the Q3'08 forecast for 2009. This is primarily due to the rapid decline in prices of 32-in. LCD TVs. Another factor is the smaller number of PDP players in the market as a result of aggressive pricing from the top PDP-TV brands.

DisplaySearch's total global TV forecast is 206.4 million units in 2008, up 3% from 2007; 2009 shipments are forecast to be 205.3 million units, down 1% Y/Y – the first time in recent memory that there has been a drop in unit shipments. In addition to a reduction of units, the revenue decline in 2009 will affect the TV supply chain in 2009.

— Staff Reports

LG Display Unveils "Trumotion 480Hz" LCD-TV Panel Featuring 4-msec Motion-Picture Response Time

SEOUL, KOREA – **LG Display** announced December 30, 2008, that it has developed what it is terming the world's first "Trumotion 480Hz" LCD-TV panel (pictured), which has an 480-Hz refresh rate, accelerating the advent of ultra-high-speed images without sacrificing picture quality.

According to a company press release, LG Display's "scanning backlight" enables the backlight to be repeatedly turned on and off to reduce motion blur. When combined with the company's 240-Hz technology, the display can refresh 480 images per second.

In addition, LG Display's "Trumotion 480Hz" display boasts a motion-picture response time (MPRT) of 4-msec, eliminating motion blur for fast-moving images and enabling a realistic, crystal-clear picture.

"The world's first Trumotion 480Hz LCD-TV panel is planned to hit the market in the second half of 2009. LG Display will provide its customers with unique, high-end products while delivering crisp picture quality for fast-moving images." noted **Eddie Yeo**, Executive Vice President and Head of LG Display TV Business Unit.

— Staff Reports

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Measure the Right Thing the Right Way

by Thomas G. Fiske

At the beginning of 2009, we find ourselves facing challenging financial times and a troubling business climate. The free-wheeling fiscal orthodoxy of the past several years has fallen on hard times as we live through a disconcerting and unsettling period of turmoil in most of the world's financial markets and in many areas of business. And we are also in for a rethink in the world of politics, as a new U.S. administration and Congress take power in Washington this month. At the risk of overusing a tired phrase, we are in the midst of a paradigm shift of significant proportion – at least where money and politics are concerned.

In the field of electronic displays, we are constantly confronted with new technologies, applications, and manufacturing processes. While perhaps not as significant as the new realities in the financial and political spheres, the new technologies in the display world necessitate some new thinking in how we supply these new technologies, introduce new applications, and create and address new markets. One necessary part of this new thinking is the area of display-system evaluation and measurement – and how to relate those objective physical measurements to the human visual system in particular and the overall human experience in general.

In this issue of *Information Display*, we feature this year's installment on display measurement and characterization. We have contributions from experts in the rapidly expanding field of 3-D displays and high-dynamic-range (HDR) displays. There is a proposal about how to measure small-area character contrast, plus a timely suggestion regarding how to maximize your enjoyment of that new flat-panel HDTV you found under the tree last month.

Two articles in this issue address 3-D displays: one from a measurement perspective and one from the viewpoint of human perception. Nokia researchers Marja Salmimaa and Toni Järvenpää describe a preferred measurement methodology for autostereoscopic displays and review the status of several standardization efforts around 3-D display measurement and characterization. Professor Martin Banks and co-workers from the UC Berkeley School of Optometry and the Center for Neural Science at New York University discuss how the human observer perceives stereo pictures. They conclude that 3-D perception of stereo pictures depends on viewer position relative to the display screen. This position-related effect for 3-D perception is much stronger for 3-D pictures than for 2-D pictures and has significance for designers of stereo viewing systems. Digital 3-D cinema providers take note.

Anders Ballestad and his colleagues at Dolby Laboratories in Canada present an article about the characterization of HDR displays. The conventional metric of contrast ratio makes little sense when you are are essentially dividing by zero (unless, of course, you are in marketing, where the big, impressive contrast numbers look good on your product brochure). The engineers at Dolby present a more relevant and perceptually meaningful metric based on static- and dynamic-halo artifacts.

We are treated to another fine article from display-measurement expert Edward F. Kelley of NIST. Known for his engaging writing and speaking style, he relates some important (and doable) suggestions about how to obtain meaningful measurements for the contrast of small, dark characters on a light display surface.

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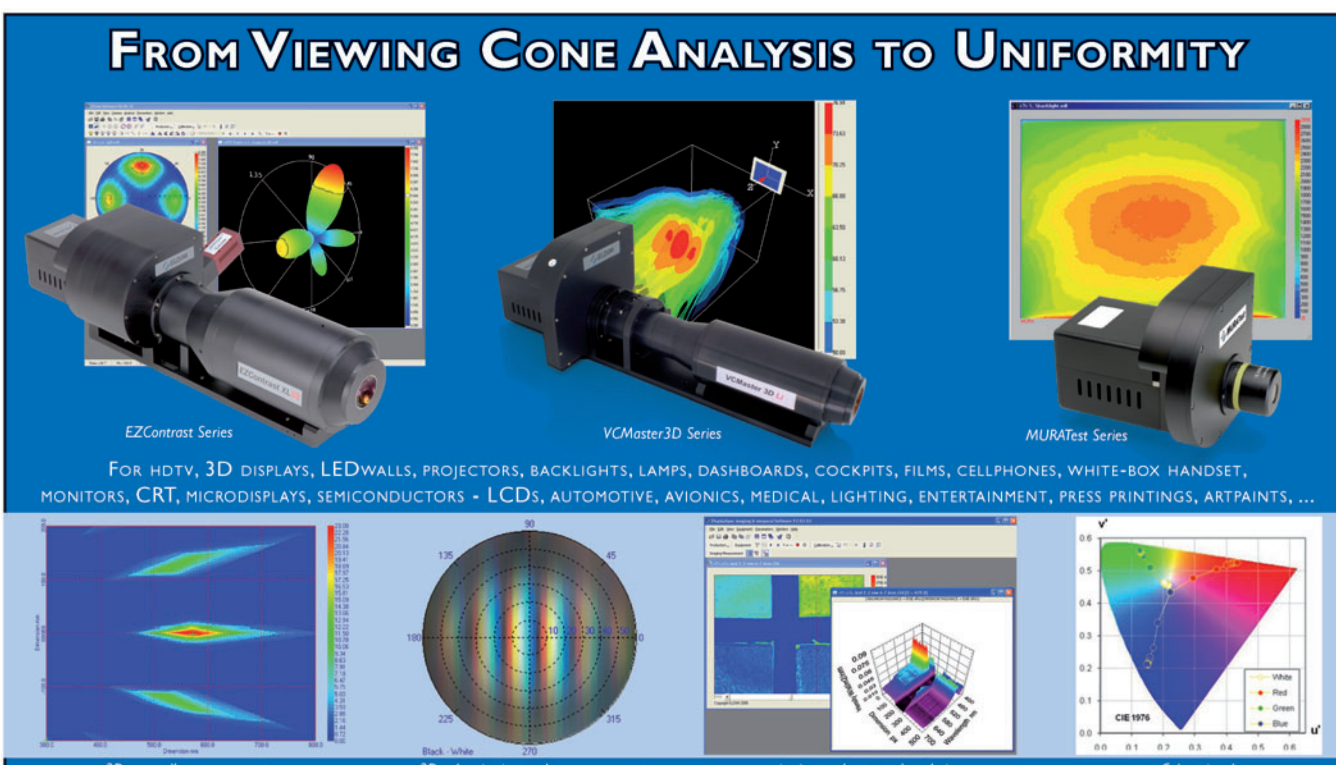

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The Information Display Society – What's in a Name?

The Society for Information Display (SID) was founded in 1962 in the Los Angeles area, starting with a handful of electrical engineers with an interest in electronic displays. In the intervening 47 years, SID has grown steadily in both membership and scope, in ways that those early founders could not have imagined. As President, one of my tasks is to help chart SID's future, and as part of this process, it's important to look at the past to see how SID has gotten to where it is now. It's interesting to not only see what SID is, but also what it is not, as a guide to the future.

The name "Society for Information Display" provides some clues. SID is a Society, for sure, numbering around 6000 members and 32 chapters across Asia, Europe, and North America. SID does many of the things that a Society does – hold meetings and conferences, publish a magazine and journal, support the development of standards, and provide many levels of display-technology education. SID also provides significant networking opportunities for both members and the companies involved in the display industry. So, that part of the definition is relatively straightforward.

"Display" is also an easy part of the name to understand. The modern SID has a nearly exclusive focus on electronic displays. Looking through the topics covered at SID meetings and publications, one could easily believe that the development of liquid-crystal displays, plasma displays, OLED displays, active-matrix backplanes, and the like dominate SID activities. Could the name "Society for Electronic Displays" be an accurate name for the present day SID? That sounds a workable definition for today's SID, but doesn't completely capture SID's scope.

Things get a bit ambiguous when considering "Information." For those unfamiliar with SID, the focus of the name could be on the word "Information" rather than "Display." Information gets conveyed in many different ways, from static images on paper, to electronic displays, to audio and tactile sources. "Display" implies a visual medium, though, and the modern SID focuses nearly exclusively on visual information transmission. While topics such as sound quality and audio compression would not necessarily be unwelcome at a SID meeting, that is not a community that plays a major role at SID.

What about other aspects of information display? Human perception is an area of "Information" that has a major focus at SID. Understanding how the human visual system receives the stimulus from an electronic display, along with how to do configure the display to provide the desired experience to the viewer, is a critical component for an effective electronic display. This is an area with both a substantial past and a promising future. With the growing interest in 3-D displays, and the active community within SID developing and evaluating 3-D technologies, this human link will remain an important and growing component of SID activities.

This discussion so far has centered on technology, but in recent years SID has taken a more holistic approach toward the entire display industry. While technology remains central, there is strong recognition that the business cycle impacts the ability of technologist to do their jobs, and that the business of displays plays a major role in setting the technical agenda for display engineers. So, SID has embraced its role in providing information and insight to the people responsible for charting the course of the companies that make up the display industry.

So what's in a name? Today's SID has certainly transcended the scope intended in its first naming, and evolved in interesting ways to meet the needs of its members. Using "meeting the needs of members" as a working definition, there are many paths

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Characterizing Autostereoscopic 3-D Displays

Image rendering and display parameters of autostereoscopic 3-D displays differ from that of ordinary 2-D displays. Therefore, a separate methodology for verification of the optical characteristics is required. The industry is currently lacking standardized measurement methods for 3-D displays, thus the reported results from the measurements may not always be comparable. Standardized methodology is needed, and the metrology and the metrics have to be defined without bias with regards to any particular stereo technology. This article explores several ways of characterizing autostereoscopic displays.

by Marja Salmimaa and Toni Järvenpää

RECENT DEVELOPMENTS in 3-D display technologies have enabled rich and highly immersive 3-D content delivery. The world around us is three dimensional, thus mimicking the three dimensionality and real depth in display content increases the feeling of presence in the scene, making the objects in the scene seem more realistic.[1,2] This realism is utilized in 3-D films shown in movie theaters with systems supporting the delivery of 3-D content and in the broadcast of 3-D TV which is already happening in Japan. Still, 3-D content consumption requires investment in special equipment by the end user, and comparing the alternatives may be difficult – even for the display professional. The 3-D experience is something different compared to what people are used to. The 3-D stereo technology chosen for the basis of a display design will affect the resulting image quality, and each technology will have its own particular strengths and weaknesses.

Image Formation in 3-D Displays

The basic idea behind 3-D displays is that they are able to show slightly different content for each eye. The sensation of depth arises from this difference, which is also called horizontal disparity. Some technologies, such as the ones used in the 3-D movie theaters, require the wearing of special glasses, but autostereoscopic displays can produce the sensation of depth without any viewing aids. Most common autostereoscopic displays utilize either parallax barriers or a lenticular lens as the structure that divides the display pixels into two (or more) views and directs the different pixel information to the left and to the right eyes of the user. Figure 1 introduces the basic working principle of these two stereo techniques.

These examples represent spatially multiplexed stereo-display implementations. In addition, temporally multiplexed implementations exist,[3,4] but here we discuss measurement systems verified for the former. In any

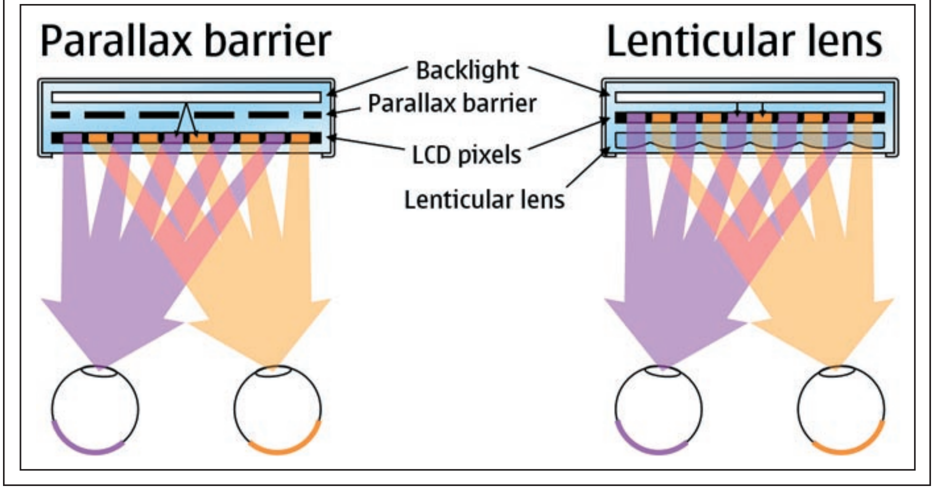

Fig. 1: *Basic working principle for parallax-barrier and lenticular-lens autostereoscopic displays.*

Marja Salmimaa *and* ***Toni Järvenpää*** *are with Nokia Research Center, P.O. Box 1000, FI-33721, Tampere, Finland; e-mail: Marja.Salmimaa@nokia.com.*

case, the method by which the content is shown introduces characteristics specific to that method as well as imperfections which affect the visual quality of the rendered content and the visual experience of the user. These imperfections should be studied so that an acceptable user experience can be ensured and so that the artifacts caused by these imperfections do not cause discomfort to the user. Conventionally, the visual experience with 3-D displays has been studied by using subjective testing.[5-10] However, objective optical characterization methods are needed to validate display design and to provide for reliable manufacturing control.

Measurement Systems for 3-D Displays

Measuring and characterizing 3-D displays is not straightforward. The technology used for stereo-image creation affects the measurement methodology, and, as already indicated, the methods are not yet standardized. Typically, optical characteristics of the autostereoscopic displays are strongly angle-dependent as the exigencies of the two-eye-view construction for stereo images require this. With an angular scan over the angles of interest, the luminance (and sometimes color) profiles can be obtained, and the remainder of the characteristics are derived from these values.[11,12] However, the properties of the measurement system may greatly affect the results,[13] the angular aperture of the measurement devices being one example. The angular aperture or resolution is typically too large for 3-D displays which have large luminance fluctuations versus viewing angle and results in large errors.

The most commonly used measurement systems for autostereoscopic 3-D displays include goniometric photometer systems, conoscopes, and imaging photometers. A goniometric photometer is suitable for making luminance measurements of two-view 3-D displays. In this case, the angular aperture of the photometer is affected by the measurement spot size and the clear aperture of the optics. Because all the views of the 3-D display need to be measured separately with different test images, the number of actual measurements for multi-view displays is relatively high. As an illustrative example, consider an angular scan performed over the angles from –60° to +60° with a step size of 1°. This results in 121 measurements. If 16 target images are used, this yields altogether 1936 measurements. With fast test-image update and a well-practiced procedure, one measurement may take 15 sec. In this case, one measurement session would be 8 hours long! For a uniformity check, the measurements should be repeated for multiple points on the display surface, which means, in practice, that one working day would not be enough to measure one display sample. A more efficient measurement approach is required.

Another alternative is to use a conoscope, an imaging photometer with integrated Fourier optics. The angular resolution of the conoscope is limited by the optics and the sensor of the measurement device. With a conoscopic system, the luminance of the display can be measured simultaneously from one measurement spot over all angles. These systems are able to measure luminance and

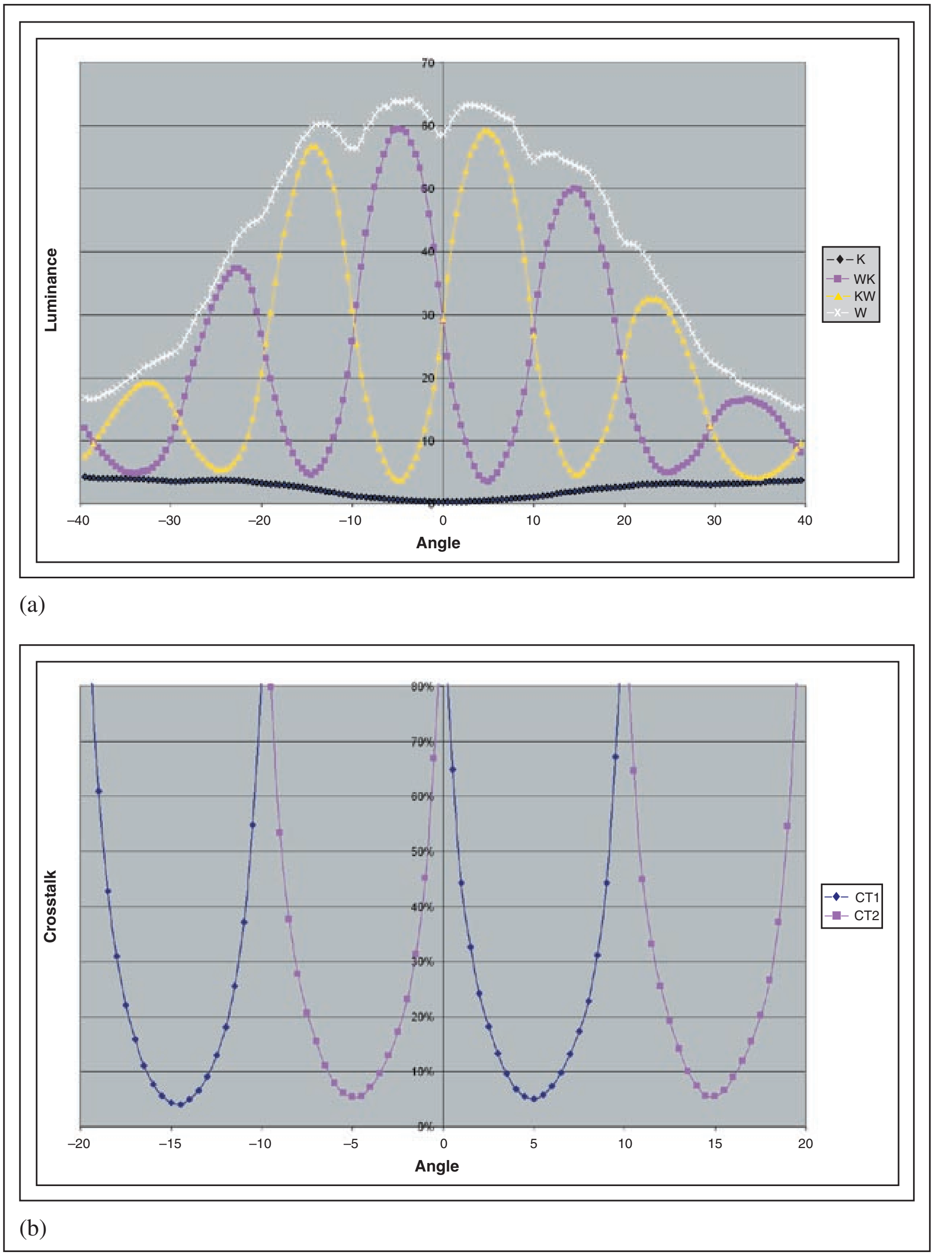

Fig. 2: (a) Example luminance profiles for a two-view autostereoscopic display and (b) calculated crosstalk profiles for the same display.

color over a wide range of angles in minutes with a resolution not obtainable with scanning systems in any reasonable time. Appropriate cross-sections and calculations from such a data set are sufficient for determining most of the optical characteristics of autostereoscopic displays. Figure 2 shows the typical cross-sections and calculated crosstalk profiles for a two-view autostereoscopic display.

Measurement results shown in Fig. 2 are obtained with a conoscope. The angular range for the measurement is from –60° to +60°, and the angular step size is 0.5°. In Fig. 2, results of the angular range from –40° to +40° are shown. K indicates the results of the measurements with a full-screen black test image. W symbolizes the results measured with a full-screen white image. The WK luminance profile is measured when view one was white and view two black, while this is *vice versa* for the KW luminance profile. Angles are in degrees and luminance values in cd/m^2.

A third possible device for measuring 3-D displays is an imaging photometer. In practice, this can be done using an imaging camera with a photopic filter and optics with a small enough clear aperture. We have built such a measurement system in our lab. The system employs a V(λ)-filtered high-performance 12-bit scientific CCD camera system with a 4-mm aperture. Figure 3 shows the system with a simulated measurement set-up.

Figure 3 shows, in addition to the imaging photometer, the universal display holder for the device under test and a motorized five-degress-of-freedom motion base for the camera. The calibration of the system is challenging due to the relatively high number of variables affecting the end result, but the system can also be used for virtual display measurements.

3-D Display Characteristics

3-D display characteristics include luminance, contrast, and color, analogous to the optical characteristics familiar to 2-D displays. In addition, 3-D displays introduce optical characteristics unique to their construction, including unwanted artifacts. One of these is 3-D crosstalk, χ_{3D}, which is the interference of the left- and right-eye views. Montgomery *et al.*[8] define the crosstalk as the leakage of the left-eye image data to the right-eye image data and vice versa as a fraction of the window brightness. With multi-view displays, this can be extended as the leakage of the unwanted image data.[11]

Fig. 3: Imaging photometer system built in-house. The white background was added so that the parts of the system can be easily seen. Measurements are made in a dark-room environment.

Another example is the optimum viewing distance (OVD),[11] also called the nominal viewing distance z_{nom}.[15] As described in Ref. 11, the OVD calculation for a two-view display can be based on the angle between the crosstalk minima of the different views. This means that OVD for a two-view display can be calculated by the following equation (θ_1 and θ_2 represent the crosstalk minima angles):

$$OVD = \frac{IPD}{2\left[\tan\left(\theta_2 - \theta_1\right)/2\right]}.$$

Table 1 summarizes the measured and calculated results of the characterization for a two-view sample display.

Still another important parameter for 3-D displays is the amount of freedom of movement without perceiving a pseudoscopic image (an image that appears to have inverted stereo characteristics). This is the horizontal cross-section of the theoretical viewing freedom (VF),[13] sometimes called the viewing zone width δv.[15] Related to that is the horizontal cross-section of the actual viewing freedom[13] determined by the predefined threshold values for some of the 3-D characteristics – also called the sweet-spot width δw.[15]

The process of determining the actual viewing freedom of the autostereoscopic display and the effect of the measurement device properties on the results is discussed in Ref. 13. This process requires a selection of a proper 3-D crosstalk value that is used as a criterion for the limits of the actual viewing freedom. The selection of the crosstalk threshold is ambiguous, and various publications are introducing different numerical values for the visibility threshold of the crosstalk or the threshold reducing the viewing comfort

Table 1: Measurement results for a two-view sample display

χ_{3D} minimum angle (°)	–4.9	+4.9
3-D crosstalk χ_{3D} (%)	5.3	5.1
	5.2	
3-D luminance (cd/m^2)	63.8	62.8
	63.3	
3-D contrast ratio	110	132
(:1)	121	
OVD (mm)	368	

of the 3-D displays. As an example, results from the actual viewing-freedom calculations for a two-view sample display are presented in Table 2. Here, in the calculations, the crosstalk threshold is 7% and the measurement results used in the analysis are obtained at the center of the display.

The theoretical viewing freedom and the actual viewing freedom are examples of terminology which need to be harmonized in the standardization process.

Related Standardization Activities

Up to this time, the characterization and comparison of the optical properties of autostereoscopic 3-D displays has been challenging and the standardized methods for the measurements have been lacking. Fortunately, working groups in both the ICDM (International Committee for Display Metrology) and ISO/TC 159/SC 4/WG 2 are discussing definitions and characterization methods for autostereoscopic 3-D displays – and the topic is being discussed in the IEC. The new ICDM document will include a section for stereoscopic display measurements with autostereoscopic 3-D display measurement being one part. An ISO Technical Report (TR) is being prepared with the scope of defining optical characterization methods for autostereoscopic 3-D displays, taking into account several display technologies and their ergonomic characteristics. The first draft of the TR includes contributions from Finland and the Japanese Ergonomics National Committee (JENC). Other experts from the U.S. and Europe may also participate in the work. At the moment, the TR is strongly based on the requirements arising from visual ergonomics. A common conclusion has been that crucial topics to be addressed include a pseudoscopic image; 3-D crosstalk; interocular differences in luminance, contrast, and chromaticity; uniformity; and temporal stability.[16] The aim is to propose the TR to the ISO/TC 159/SC 4/WG 2 in the next meeting organized in conjunction with the SID 2009 International Symposium (Display Week 2009) in San Antonio, Texas, in June.

Conclusion

Autostereoscopic 3-D displays require their own methodology for verification of their optical characteristics compared to ordinary 2-D displays. Thus far, standardized methods for such measurements have been lacking. Hopefully, the results from the work of all ongoing standardization activities will be consistent and complementary to each other so that finally it would be possible to introduce rationalized optical characterization methodology for autostereoscopic 3-D displays; methodology that confirms the ultimate goal of better visual ergonomics of the displays and can be used as an efficient tool and support in subjective tests and in the design of 3-D displays.

Table 2: Summary of the results for the actual viewing freedom for a two-view sample display

Left view viewing freedom in degrees	Right view viewing freedom in degrees
1.5	1.5

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Perception of 3-D Layout in Stereo Displays

As stereoscopic displays become more commonplace, it is more important than ever for those displays to create a faithful impression of the 3-D structure of the object or scene being portrayed. This article reviews current research on the ability of a viewer to perceive the 3-D layout specified by a stereo display.

by Martin S. Banks, Robert T. Held, and Ahna R. Girshick

STEREOSCOPIC DISPLAYS have become very important for many applications, including vision research, operation of remote devices, medical imaging, surgical training, scientific visualization, virtual prototyping, and more. It is important in these applications for the graphic image to create a faithful impression of the 3-D structure of the object or scene being portrayed. Here we review current research on the ability of a viewer to perceive the 3-D layout specified by a stereo display. To do so, we will first consider conventional displays (*i.e.*, pictures such as photographs) and then consider stereo displays.

Conventional pictures (photographs, cinema, computer-graphics images, *etc.*) are very useful because in the convenient format of a 2-D surface they allow viewers to perceive 3-D scene information. At one level, it seems obvious why pictures provide such useful information: A conventional picture viewed from its center of projection (CoP) generates the same retinal image as the original scene, so a well-positioned viewer understandably perceives the depicted scene as similar to the original scene. Such pictures, however, would not be very useful if the viewer's eye always had to be positioned at the CoP to create an acceptable impression. Imagine, for example, that there is only one seat in the cinema that produced a percept that was acceptably close to the depicted scene. Fortunately, when pictures are viewed from other locations, the perceived scene does not seem significantly different, even though the retinal image now specifies a different scene[1]; thus, people can sit in various locations in a theater and gain an acceptable impression of a motion picture.

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We have been experimentally investigating the ability to compensate for incorrect viewing position when viewing conventional pictures. In one set of experiments,[2] we had subjects judge the aspect ratio of an ovoid-shaped object in a depicted scene rich with geometric cues. The CoP of the stimulus was directly in front of and 45 cm from the computer display. Subjects viewed the stimulus binocularly from a variety of positions ranging from the appropriate one (the CoP) to positions too far to the left or too far to the right. We accomplished this by rotating the display rather than by moving the subject. [Imagine an overhead view of the apparatus. The observer's head position was fixed and the CRT display was rotated about a vertical axis. Different amounts of rotation corresponded to different "viewing angles" on the abscissa in Fig. 1(b). When the viewing angle was zero, the observer was positioned at the CoP of the stimulus; otherwise, the viewer was not at the CoP.] The rotation caused large changes in the shape of the projected ovoid in the retinal image. We found that subjects nonetheless perceived the shape of the ovoid on the display screen essentially correctly – provided that they viewed the display binocularly – even when they were more than 30º from the CoP. Thus, human viewers can compensate for incorrect viewing positions and thereby achieve essentially complete perceptual invariance with conventional pictures.

In another set of experiments, we investigated the perception of a 3-D shape depicted in a conventional picture. The stimulus was a vertical hinge in an open-book configuration; an example is shown in Fig. 1(a). The hinge was presented in perspective projection on a conventional display screen. Subjects viewed the stimulus from a variety of positions ranging from the appropriate one (the CoP) to positions too far to the left. We accomplished this by rotating the display rather than by moving the subject. Of course, the retinal images for a given hinge stimulus on the computer display differed depending on viewing position. By using a psychophysical procedure, we found the hinge angle that on average was perceived as 90º.

Figure 1(b) plots predictions and results. The hinge angle that was perceived as 90º is plotted as a function of viewing angle; different colors correspond to different base slants.

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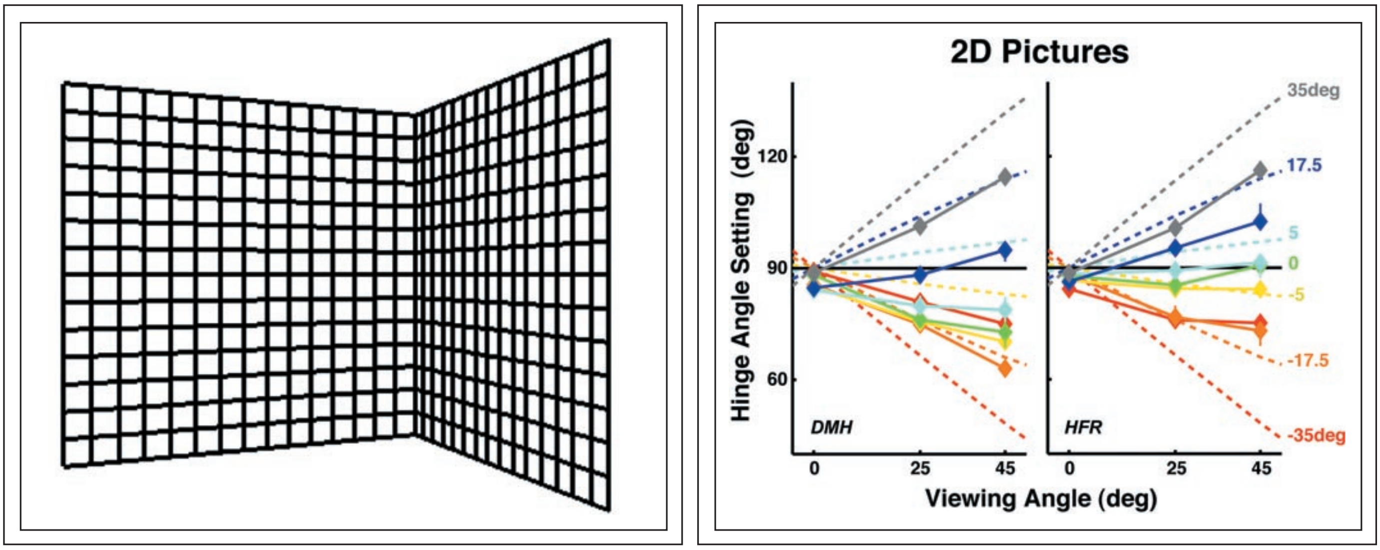

Fig. 1: Hinge stimulus, predictions, and results for the experiment with conventional pictures. (a) An example of the hinge stimulus. The stimulus was presented on a conventional flat-screen display and viewed binocularly. Viewing angle (the angle between a line from the hinge to the center of projection and a line from the hinge to the viewer) was varied by rotating the display about a vertical axis. (b) Predictions and results. The hinge angle in the depicted stimulus that was on average perceived as 90^o is plotted as a function of viewing angle. The left and right panels show data from subjects DMH and HRF, respectively. The compensation prediction is represented by the horizontal black lines at 90^o. The no-compensation predictions are represented by the dashed colored lines, each line representing a different base slant. The symbols represent the data, the colors corresponding to different base slants. Error bars represent 95% confidence intervals.

If subjects were able to compensate for incorrect viewing position, a hinge that was depicted as 90^o would be perceived as such: responses would follow the horizontal black line at 90^o. If subjects were unable to compensate for incorrect viewing position and instead estimated the hinge angle from the geometric pattern in the retinal images, a 90^o hinge would no longer be perceived as such; responses would then follow the dashed colored lines, one for each base slant. The results were generally in between the compensation and no-compensation predictions, so they show that human viewers of 2-D pictures are able to compensate partially for incorrect viewing position and thereby achieve some degree of perceptual invariance. This result is reasonably consistent with our previous work,[2] but shows that the amount of perceptual invariance depends on the depth variation in the stimulus.

Perception of Stereo Pictures

Stereo pictures have all the properties of conventional pictures plus binocular disparity (*i.e.*, spatial differences in the two retinal images); disparity yields the compelling sensation of depth we enjoy when viewing 3-D content. The viewing parameters are often not correct in practical uses of stereo displays. For example, the great majority, if not all, of the people viewing a stereo movie will not have their left and right eyes at the appropriate CoPs. We next examined whether viewers can compensate for incorrect viewing position with stereo pictures as they do with conventional pictures.

The standard model in the stereo-cinema literature equates changes in the pattern of disparities at the retinas with the predicted 3-D percept[3]; *i.e.*, it assumes that viewers of stereo pictures do not compensate for incorrect viewing position. This is a significant assumption that should be seriously examined, particularly in light of the fact that viewers of conventional pictures do compensate for incorrect position. We will return to this assumption later. The standard model uses a ray-intersection algorithm. Each corresponding point within a pair of stereo pictures is projected onto the left and right retinas. From the retinal points, rays are projected out through the centers of the eyes into space. The intersection of those rays is the predicted 3-D location of the specified point in space. Applying the ray-intersection algorithm to each pair of corresponding points in the stereo picture produces a 3-D percept of the entire virtual scene. For the geometrically predicted 3-D percept to match the original scene, several image acquisition, display, and viewing parameters must be appropriate for one another. The acquisition (camera) parameters include orientation (whether the cameras' optical axes are parallel or toed-in), inter-camera separation, and focal length. Display parameters include the magnification of the pictures and whether one or two display devices are used to present the pictures (in vision research, two displays are commonly used, one for each eye; in most everyday applications, one display is used and both pictures are presented on it). Whether one or two displays are used, the lateral separation between the two pictures must be appropriate to preserve the correct vergence angle for the viewer's eyes. The viewing parameters are the positions of the two eyes relative to the CoPs of the stereo pictures and the vergence angle induced by disparate points on the display.

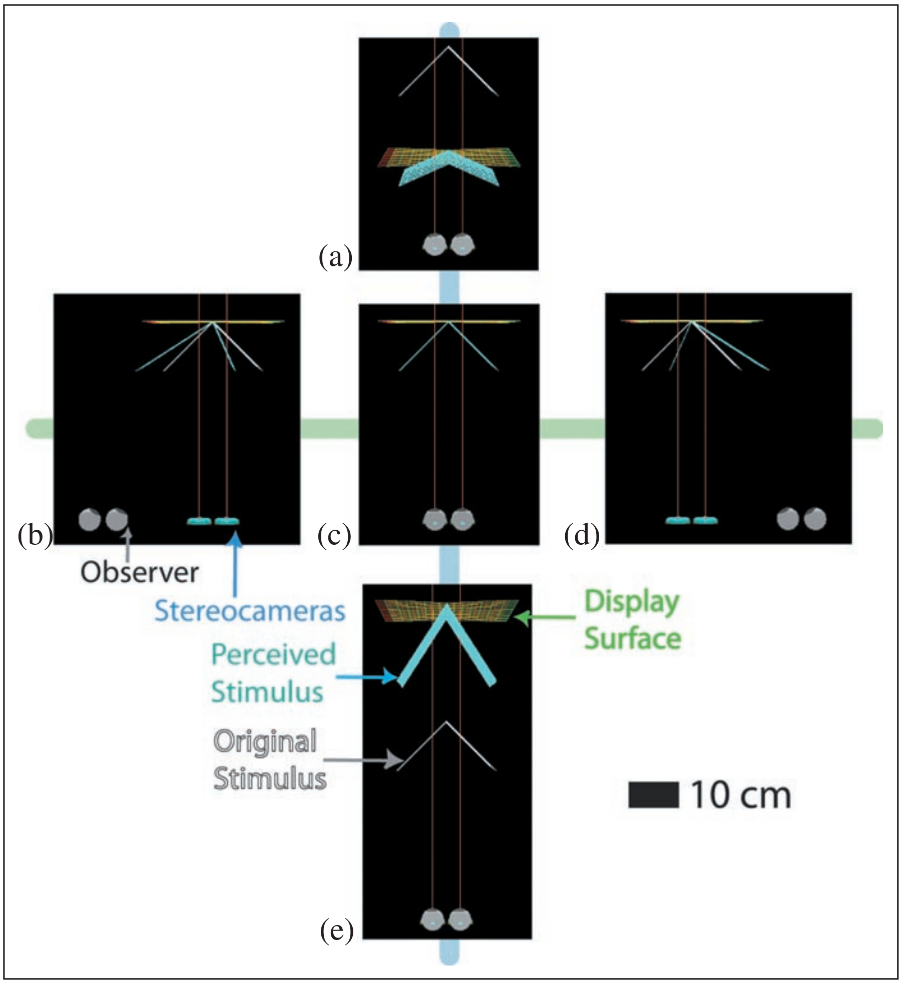

Fig. 2: *Predicted 3-D percepts for the hinge stimulus for different viewing situations. Each panel shows an overhead view of the observer (gray), stereo cameras (blue), display surface (yellow), original stimulus (gray), and the predicted perceived stimulus (blue). The parameters used in the simulation are the following. Acquisition (camera) parameters: Parallel orientation of optical axes, inter-camera separation of 6.2 cm, focal length of 6.5 mm. Display parameters: one display device, picture magnification (projected size divided by film size) of 69.2. Viewing parameters: viewing distance of 45 cm, inter-ocular distance of 6.2 cm, viewer positioned such that midpoint of inter-ocular axis is on central surface normal of display device, viewer oriented with face parallel to display surface, stimulus is a 30 x 30-cm vertical hinge with a hinge angle of 90º. (c) With all parameters correctly set, the original and predicted perceived stimuli are identical. (a) The viewer is too close to the display. The predicted perceived hinge angle is greater than 90º. (e) Viewer is too far from the display. The perceived angle is now less than 90º. (b) Viewer is translated to the left of the display. The predicted hinge rotates toward the viewer and the predicted angle is less than 90º. (d) Viewer is translated to the right of the display. The predicted hinge rotates toward the viewer and the predicted angle is less than 90º.*

We used a software implementation of the geometric approach to investigate the effects of viewer position and orientation on retinal images.

To allow comparison with our experimental results (Figs. 1 and 4), the stimulus in the simulation presented here was a vertical hinge. All of the parameters are correct in Fig. 2(c), so the predicted 3-D percept is identical to the original hinge photographed by the stereo cameras. Figures 2(a) and 2(e) show the predicted consequences of positioning the viewer respectively too close to or too far from the display. When the viewing distance is too short, the predicted perceived hinge angle is larger than 90º; when the distance is too great, the predicted angle is smaller than 90º. Figures 2(b) and 2(d) show the consequences of translating the viewer to the left or right: the predicted perceived hinge rotates toward the viewer and the predicted angle becomes less than 90º. These predictions are derivable from previous analyses in the stereo cinema literature.[3]

When the viewer translates, the intersecting-ray approach still works because all pairs of corresponding points in the retinal images produce rays that intersect in space. The fact that they intersect can be understood from epipolar geometry.[4] An epipolar plane is the plane containing a point in visible space and the centers of the two eyes. If the viewer is translated relative to the correct viewing position but does not rotate the head, it can be shown that the rays produced by point pairs in the stereo pictures lie in the same epipolar plane[5] [Figs. 3(a) and 3(b)]. Any two non-parallel rays that lie in a common plane are guaranteed to intersect, so the intersecting-ray approach yields a prediction for those viewing situations.

Unfortunately, many common stereo viewing conditions violate epipolar geometry and therefore preclude a solution based on ray intersection. One such condition occurs when a viewer is positioned to the left or right of center and rotates the head to face the center (a yaw rotation). In this case, most of the rays produced by the corresponding points in the retinal images do not intersect [Fig. 3(c)]. The standard model relies on ray intersections, so with yaw rotations it cannot predict a percept. Interestingly, human viewers in this situation still have a coherent 3-D percept. The standard model, therefore, has to be modified. One modification of the model forces the non-intersecting rays into a common epipolar plane,[3] but there is no evidence that the human visual system uses such a method. The non-intersecting rays introduce vertical disparities at the retinas and research has shown that those disparities are used to estimate the 3-D layout of the scene.[5,6] A more complete model of the perception of 3-D pictures would incorporate the use of vertical

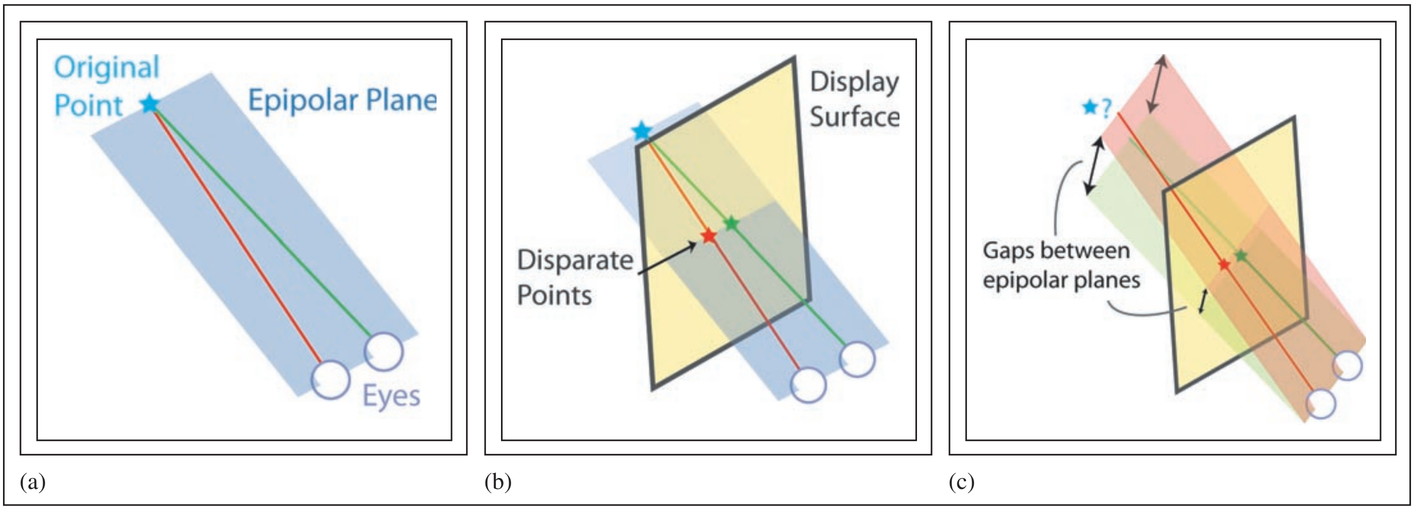

Fig. 3: *Epipolar geometry. (a) In the natural environment, an epipolar plane is defined by a point in visible space and the centers of the two eyes. (b) If the acquisition, display, and viewing parameters are correctly set, the epipolar planes produced by two corresponding points in the left- and right-eye pictures will coincide and the rays projected from the eyes through those points will intersect in space. (c) If the viewer's head is rotated about a vertical axis (yaw rotation), the corresponding points in the left- and right-eye pictures produce rays that generally do not intersect because they lie in different epipolar planes.*

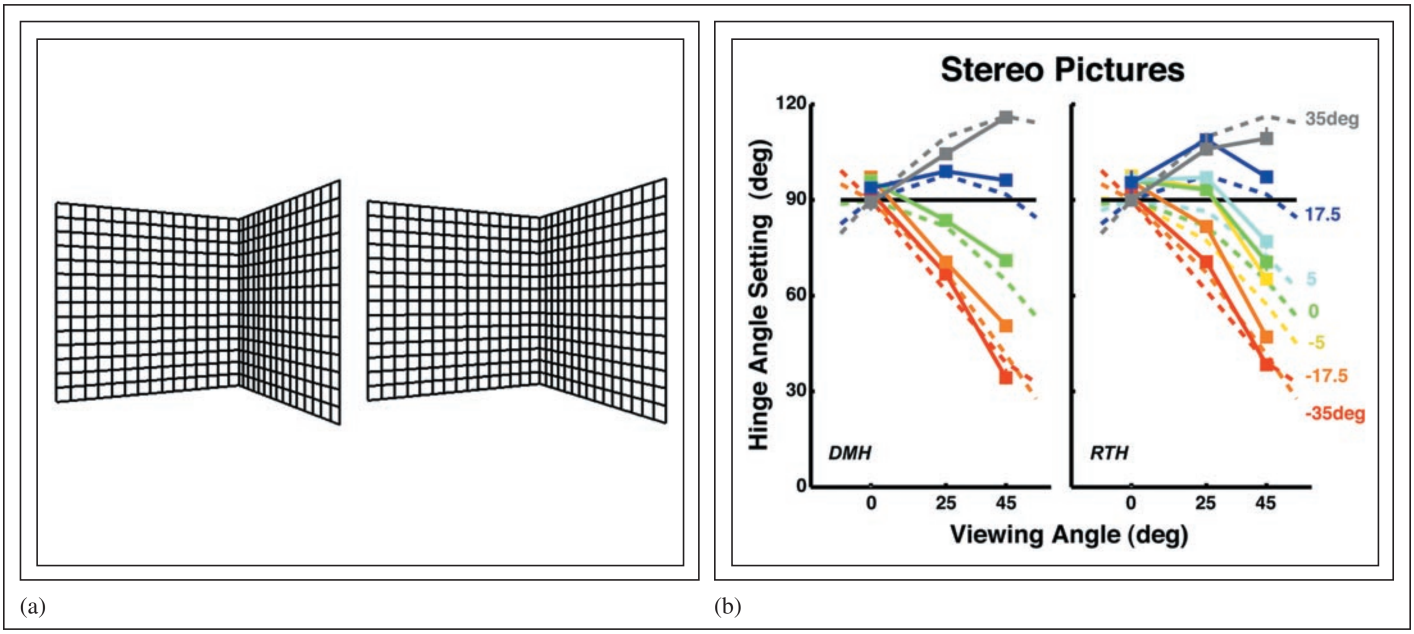

Fig. 4: *Hinge stimulus, predictions, and results for the experiment with stereo pictures. (a) An example of the hinge stimulus. Cross-fuse the stimulus (direct the right eye to the left image and the left eye to the right image) to see it stereoscopically. Separate stimulation of the two eyes was accomplished by using liquid-crystal shutter glasses that were synchronized to the computer display. Viewing angle was varied by rotating the display about a vertical axis. (b) Predictions and results. The hinge angle in the depicted stimulus that was on average perceived as 90º is plotted as a function of viewing angle. The left and right panels show data from subjects DMH and RTH, respectively. The compensation prediction is represented by the horizontal black lines at 90º. The no-compensation predictions are represented by the dashed colored lines, each line representing a different base slant. Because the viewer was translated and rotated from the correct viewing position, epipolar geometry was not strictly followed. We made the predictions based on the disparities at the horizontal meridians of the eyes where rays from the eyes do intersect in space. The symbols represent the data, the colors correspond to different base slants. Error bars represent standard errors.*

disparities. With an appropriate modification, the model would be able to make predictions for 3-D percepts for a wider range of viewing situations, including combinations of viewer translation and rotation that are likely to be encountered in the viewing of stereo pictures.

As we noted, the standard model[3,5] assumes that the 3-D percept is dictated solely by the retinal images, which is equivalent to assuming that viewers do not compensate for incorrect viewing position. This is a significant claim with far-reaching implications for the creation and presentation of stereo content. Thus, we decided to test the assumption in an experiment similar to the one described in Fig. 1. The hinge stimulus, which is shown in Fig. 4(a), was similar to the one used in the conventional picture experiment [Fig. 1(a)] except that now its 3-D shape was specified by disparity along with the perspective cues present in the 2-D version of the experiment. As before, subjects viewed the stimulus from various positions ranging from the appropriate one to positions that were too far to the left. Figure 4(b) plots predicted and observed hinge angles that were perceived as 90^{o}. If subjects were able to compensate for incorrect viewing position, any hinge that was depicted as 90^{o} would be perceived as such: the results would lie on the horizontal black line at 90^{o}. The no-compensation predictions were generated from the model in Fig. 2. If subjects did not compensate for incorrect position and instead estimated the hinge angle from the retinal disparities, a 90^{o} hinge would no longer be perceived as 90^{o}; the results would then follow the dashed colored curves. As one can see, the results were nearly identical to the no-compensation predictions.

As the results in Fig. 4(b) show, misperceptions occur when the viewer's eyes are not positioned correctly relative to a stereo picture. The percepts are well predicted from the ray-intersection model (Fig. 2). The results of this experiment coupled with the results for viewing of conventional pictures have profound implications: percepts from stereo pictures are significantly more affected by incorrect viewing position than are percepts from conventional pictures.

We hasten to point out that other visual cues are frequently incorrect in stereo displays – blur and accommodation are two prominent ones[7,8] – and they too can cause misperceptions. Those perceptual effects are, however, beyond the scope of this brief review.

Conclusion

In summary, our findings to date indicate that human viewers of stereo pictures are unable to compensate for incorrect viewing position. As a result, the 3-D percept seems to be determined only by the disparities in the retinal images. Further research is needed to determine whether other information, such as motion parallax, can aid compensation. At the moment, however, it appears that the perceptual invariance that makes audience viewing of conventional pictures acceptable does not occur to nearly the same degree with stereo pictures. Designers of stereo viewing systems should therefore carefully plan the acquisition, display, and viewing parameters so that the viewer can have a 3-D percept that is as faithful to the original scene as possible.

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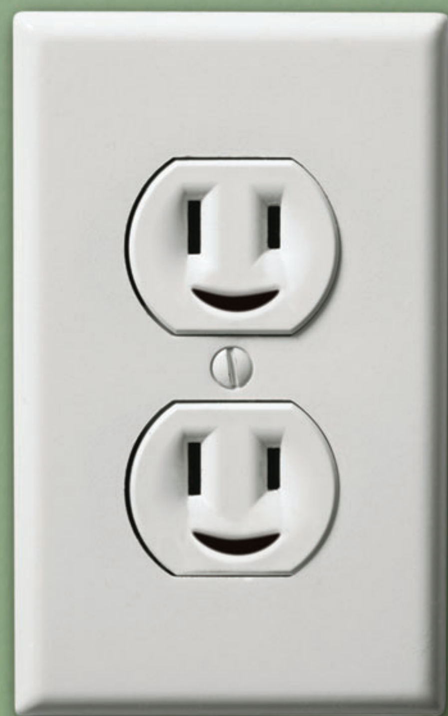

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Metrics for Local-Dimming Artifacts in High-Dynamic-Range LCDs

Local-dimming LCDs exhibit qualities and artifacts that cannot be captured by common performance metrics. For example, a local-dimming display can obtain perfect black levels when the backlight is turned off completely, and the effective measurement of "contrast" will therefore return an infinite value. In this article, robust and meaningful metrics are introduced for the static- and motion-halo artifacts, and good agreement with psychophysical experiments is shown.

by Anders Ballestad, Thomas Wan, Hiroe Li, and Helge Seetzen

THE continued development of light-emitting-diode (LED) backlit liquid-crystal displays (LCDs) has led to the emergence of local-dimming displays, which are entering the marketplace with a promise to deliver high contrast, lower power consumption, and improved image quality. Advanced local-dimming systems also offer increased luminance capabilities for true high-dynamic-range (HDR) imagery. With this broader shift toward dynamic backlighting, it is necessary to consider appropriate performance metrics for such devices.

In principle, any display can be characterized by its external performance characteristics such as peak luminance, contrast, color gamut, spatial resolution, *etc*. While these specifications can certainly be measured for local-dimming displays, the unique architecture of such displays renders several of them irrelevant. For example, conventional measures of frame-sequential contrast have little value for local-dimming displays because a full-screen black image will result in no light emission by the backlight and thus infinite "contrast." Just as global dimming can return an infinite frame-sequential contrast ratio, local dimming can have a rather dramatic effect on the local contrast, as measured by an ANSI checkerboard. However, due to light scattering in the optical cavity between the backlight modulator and the light-blocking modulator (the LCD panel), the local contrast will most certainly not be as high as the measure of global contrast, and a solid definition of the two should be established and understood.

The unique architecture of local-dimming displays also introduces new artifacts as a result of the dynamic backlight modulation. Conventional metrics do not capture these potential artifacts, and, yet, their impact on the image quality of the display can be considerable if bad design choices are made. In the absence of metrics for these artifacts, any local-dimming configuration achieves very high contrast as a result of the metric limitation outlined above, and comparing different local-dimming designs becomes impossible except by visual inspection. In this article, the most relevant of these novel artifacts are described and metrics for physical characterization of the issues are provided. The results of initial user studies are used to determine the perceived severity of these artifacts for different local-dimming designs. The result of the user studies is important because it provides a perceptual scale over the physically based metric. The result is used to validate the sensitivity of the metric to the measured and perceived artifacts. The weighted metric can then be used to evaluate the perceptual performance of a given display and be used to assist in the design of a new display as a performance design factor.

Local-Dimming Architecture

Before introducing the specific artifacts of local-dimming displays, it is important to understand the architectural differences between local and static backlight designs. For a conventionally backlit LCD, the backlight is of uniform intensity across the entire display area and typically does not vary in average intensity between scenes (global dimming). Therefore, the light-extinction capa-

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bility of the LCD panel is primarily responsible for making the lowest attainable black level. Local-dimming displays employ an array of addressable light-emitting elements behind the LCD panel. Each light source can be adjusted in intensity across the entire range of full output to no output. Figure 1 shows a sample configuration of a local-dimming display.

The physical layout of the light-emitting elements can vary, and recent commercially available products have ranged from less than 100 to more than 2000 elements for Dolby Vision reference displays (Fig. 2).[1] Likewise, while the light sources of choice are usually LEDs for their appealing environmental and control characteristics, the configuration of the light-emitting element can vary significantly. Local-dimming displays with a large number of elements tend to use a single LED per element, while those with a lower number of elements often combine multiple LEDs into a single block of emitting area. Integration of multiple LEDs in such a design can be achieved through individual wave plates per element or simply by allowing for sufficient diffusion within the optical cavity of the display.

The specific design of the light-emitting element is remarkably irrelevant for the image quality of the local-dimming display. Of course, the choice of design impacts other aspects of the display such as energy efficiency and physical depth of the device, but only the spatial and angular distribution of light emitted by the element is relevant for image quality. The local-dimming array can therefore be described by the pitch between individual light-emitting elements and the point-spread function (PSF) of light emitted by the element. The concept of a PSF still applies even if the light-emitting element is a much larger structure composed of multiple LEDs because the easiest representation for such an arrangement is still just the positioning of individual (though possibly complex) PSFs in intervals given by the center-to-center pitch of the array.

Different algorithmic solutions can be used to drive the light-emitting arrays but, in general, the drive values for the elements are obtained from the corresponding local image data. The LCD image is then adjusted in some fashion to compensate for the variable low-resolution light field generated by the light-emitting elements under those drive conditions. The form of compensation can vary from a very general estimate to a detailed mathematical prediction of the light field. Independent of the specific choice of algorithm, it is important to understand that the compensation by the LCD for the low-resolution variation on the light-emitting array is a critical part of the local-dimming design. No or incomplete compensation will exaggerate

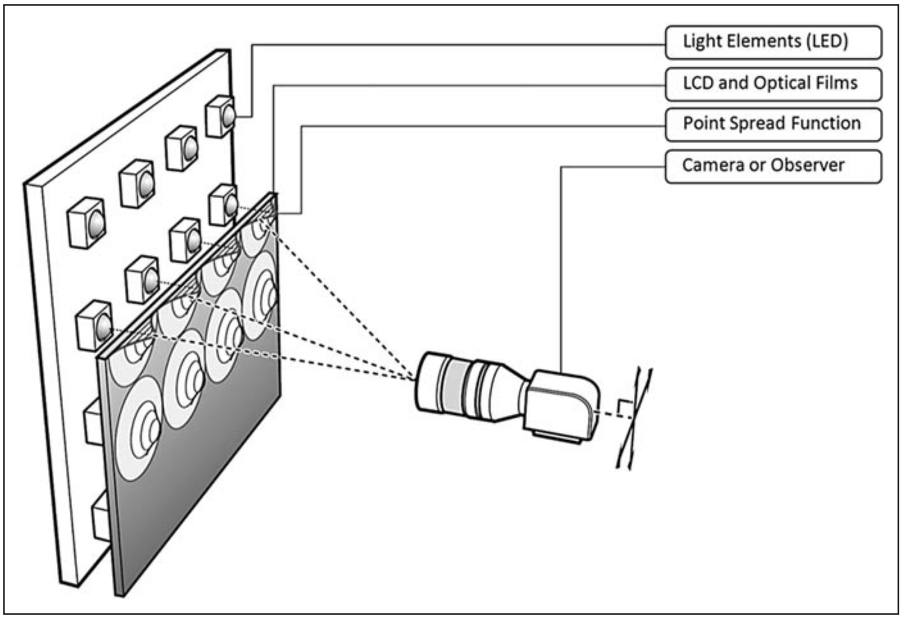


Fig. 1: *Typical local-dimming architecture. The point-spread function is the light profile provided by each LED (or light element) onto the LCD.*

Fig. 2: *SIM2 Dolby Vision local-dimming display.[1]*

the local-dimming specific artifacts significantly as described in the following sections.

Algorithmic compensation as described above can only succeed if enough light is generated by the backlight in each region of the image. This is particularly challenging for large regions of high brightness where the backlight needs to be uniformly bright. To achieve this condition, the PSFs from neighboring light elements need to overlap spatially so that no lower luminance gaps appear between light elements. This solution addresses large, bright areas but can lead to complications for small, bright features. When displaying small, bright objects on black backgrounds, the generated backlight can be larger than the intended pattern itself, and the finite-contrast panel cannot hide the excess light, resulting in the appearance of a cloud or *halo* of light around the object.

An example of particularly difficult content for the PC application of local-dimming displays is the ubiquitous mouse pointer. Scrolling movie credits and Microsoft Windows® "star-field" screen saver are other common examples of content that would suffer equally from this artifact. When viewed on a black background, the LCD cannot compensate for the light that leaks through the finite-contrast panel around the intended bright pattern; for all other non-zero background gray levels, the artifact can be removed by compensating for it on the LCD.

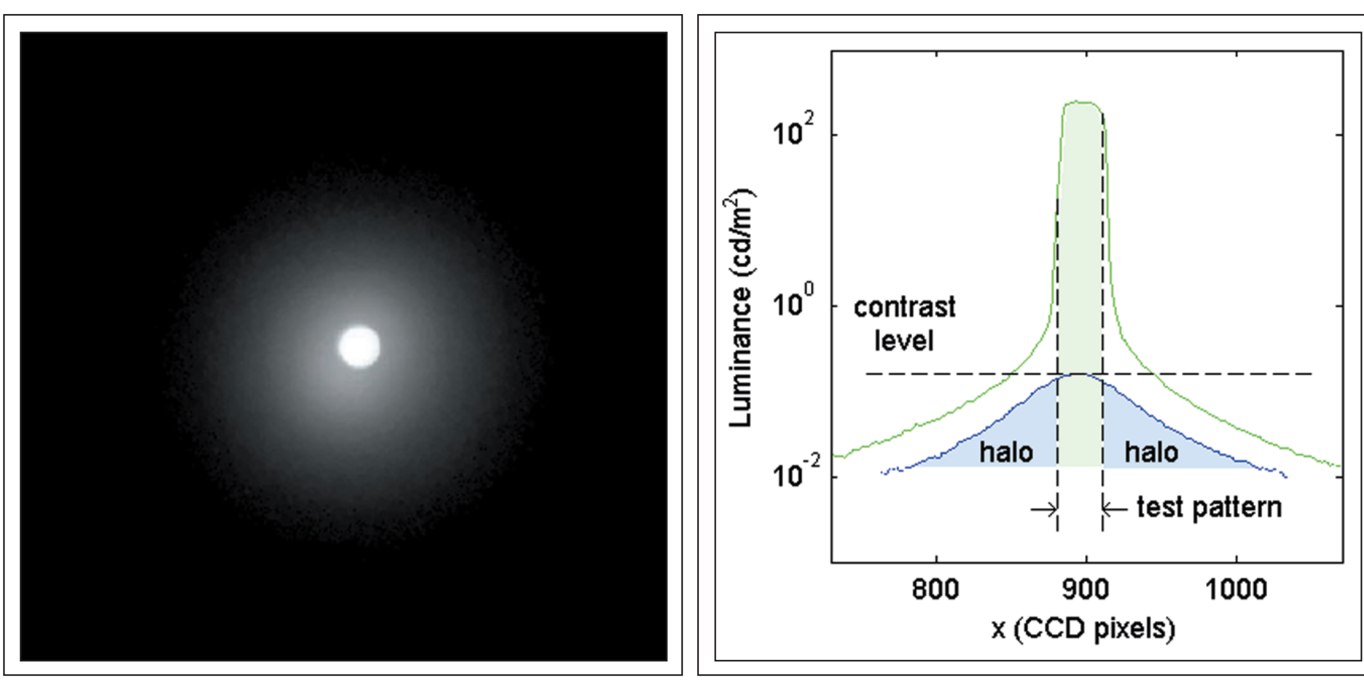
Static Halo

The halo is in effect an unwanted cloud of light around a given intended pattern. The halo is only noticeable if it is of intermediate extent, *i.e.*, it cannot be observed if it is really small, or really big, but this latter case is in effect a flat-backlight reduced-contrast display and not a local-dimming display. The severity of the halo can for small PSFs be described by the following expression:

$$\textit{halo metric} = \textit{total halo luminance} \,/\, \textit{total image luminance}. \qquad (1)$$

This expression will not capture the extreme part of the spectrum where the backlight is flat, so a correction term will be necessary if one is to estimate the halo for very large PSFs; for example, $(1\text{-}A^m)^n$, where A is the ratio of light in the measured halo relative to an infinitely extended halo (which then equals a flat-backlight display) and m and n are fitting parameters. Typically, however, the filling factor A is quite small for any reasonably sized PSF.

The shape of the halo is also important, as is its center of mass relative to the intended pattern, but the severity of the halo artifact is typically captured consistently by the expression given by Eq. (1). In order to perform this calculation, an image of the entire display was collected using a luminance-imaging camera, such as a Lumetrix 400A imaging photometer system.[2] The halo test image displayed was a small circle, which is representative of a small feature of interest that may cause a halo. Because the metric aims to quantify the severity of the artifact for any given display and any given backlight-generating algorithm, these need not be specified. A luminance image taken under the prescribed experimental conditions on a local-dimming 37-in. 1080*p* display with 1380 individual LED light elements spaced approximately 19 mm apart is shown in Fig. 3(a), with a horizontal cross-section shown in Fig. 3(b) (green line), both plotted on a log scale.



(a) (b)

Fig. 3: *(a) 2-D log-luminance image of the test pattern at the low LCD transmission level – the halo is visible around the test pattern. (b) Cross-sections of high-LCD-transmission image (green line) and halo (blue line) (log-scaled).*

The luminance image presented to the camera is adjusted to construct the true physical display halo. To achieve this, three luminance images are captured of the same test pattern at maximum, low, and lowest LCD panel transmission with the same backlight intensity level for all three. Using the difference between the three captures, the effect of camera scatter can be isolated and the true display halo and also the boundary between the halo and the test pattern can be determined. Both the true halo (blue line) and the test pattern (green line) are shown in Fig. 3(b), and the scattering in the test pattern is obvious.

Motion Halo

While having a halo is not necessarily desirable, much of it can be covered up by the fact that observers are used to it in the form of veiling luminance, or scattering in the eye.[4] This puts an upper limit on just how many backlight elements are necessary on the backlight which can be readily calculated using known veiling-luminance models.[5,6] For example, if a halo with a full-width half maximum (FWHM) of 1 in. is just hidden by veiling luminance, then one would need on the order of one light element per square inch of display area.

However, if the halo is visible, *i.e.*, if it is larger than what can be hidden by veiling luminance, then a temporal change in its size or shape can be noticeable. Furthermore, if the test pattern moves small distances, but the halo stays put (as it is related to the static position of the light elements), then the relative center-of-mass difference of the pattern and the halo will also change. This will result in the illusion of the halo "walking" or "wobbling" along with the smoothly moving test pattern.

The following describes a test metric for this motion-halo artifact. A 22-pixel-radius white dot is set against a black background. The photometer is placed in a stationary position perpendicularly 2 m away from the center of the display and images the dot as it traverses a 300-pixel-radius path around the center of the display. (The photometer settings were set to *f*/5.6 with a focal length of 12.5 mm, which makes the photometer aperture about 2.2 mm across.) Figure 4 shows the result of these measurements on the same 37-in. locally dimmed display that we discussed above. The mean halo metric was found to be 0.0050 and its standard deviation 0.0007. The FWHM/2 of the PSF of this particular display is 33 LCD pixels.

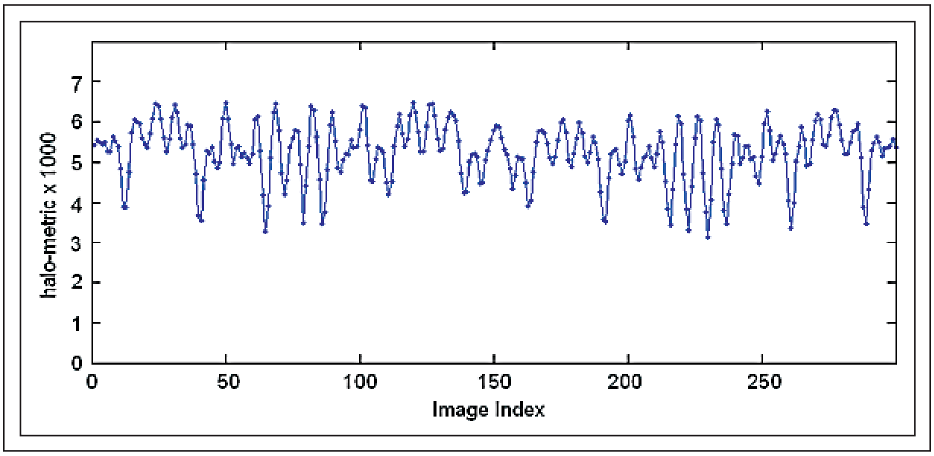


Fig. 4: *Results from the motion-halo-artifact measurements on a 37-in. local-dimming display with 1380 LEDs. The graph shows the halo size for 300 successive images taken of a dot with a radius of 22 pixels traversing a larger radius (a 300-pixel circle) in a clockwise orientation around the center of the display. The mean halo metric is 0.0050 and its standard deviation is 0.0007.*

The motion- halo metric is described as being the ratio of the halo-metric mean to the standard deviation. Therefore, the motion-halo artifact can be detected by simply calculating the static-halo metric for a series of successive still images. For the example shown, the percentage variation in the motion-halo metric is 0.0007/ 0.0050 × 100 = 14%.

Both of these metrics provide a numerical technique to measure halo artifacts. They are easy to execute with conventional test devices and relatively insensitive to small measurement error. The final step is to evaluate the perceived quality impact of these artifacts.

User Studies on Static- and Motion-Halo Artifacts

Because the number of local-dimming displays in the marketplace is still small, a flexible simulator is used to map out the range of light-element configurations expected in the marketplace. This simulator system comprised a high-luminance projector whose image was relayed onto the back of a conventional 40-in. 1080*p* 1000:1-contrast-ratio LCD panel, both having a refresh frequency of 60 Hz. If the images on these two spatial modulators are synchronized, then the projector image can be used to simulate the light field of a local-dimming display.[3]

The severity of the halo artifacts was studied by using two methods. *Ratio-scaling* was used to map out the general user response to the static-halo artifact for halo sizes ranging from non-existent to flat backlight. In a second set of experiments, the *method of constant stimuli* was used to find the threshold for both the static- and the motion-halo artifacts. Participants sat in a dark room at a distance of 3 m in front of the display system when the experiment was performed. Fourteen participants completed the user studies (the average age was 31 years old, and there were nine female participants). The dot size was changed to a radius of 10 pixels in order to minimize the effects of veiling luminance, and the following results are therefore not directly comparable with the experiment in the previous section. The general shape of the simulated backlight was obtained by fitting it to a measurement of a PSF from an HDR display with 1380 light elements. The lateral extent of this PSF was then varied. The results from the static-halo user response are shown in Fig. 5. The threshold for the static-halo artifact under these experimental conditions was found to be at a PSF size of 20 ± 9 pixels (FWHM/2), for which the corresponding *A* parameter is indicated by the black vertical line in Fig. 5.

We have also plotted the expression in Eq. (1) in Fig. 5, both with (solid line) and without (dashed-dotted line) the large halo correction term $(1-A)^2$, where the constant "2" was obtained by fitting. Veiling luminance is also included in this fit by adding a constant 0.6% of the contribution from a flat backlight to both the numerator and denominator of Eq. (1). For all reasonable halo sizes, the

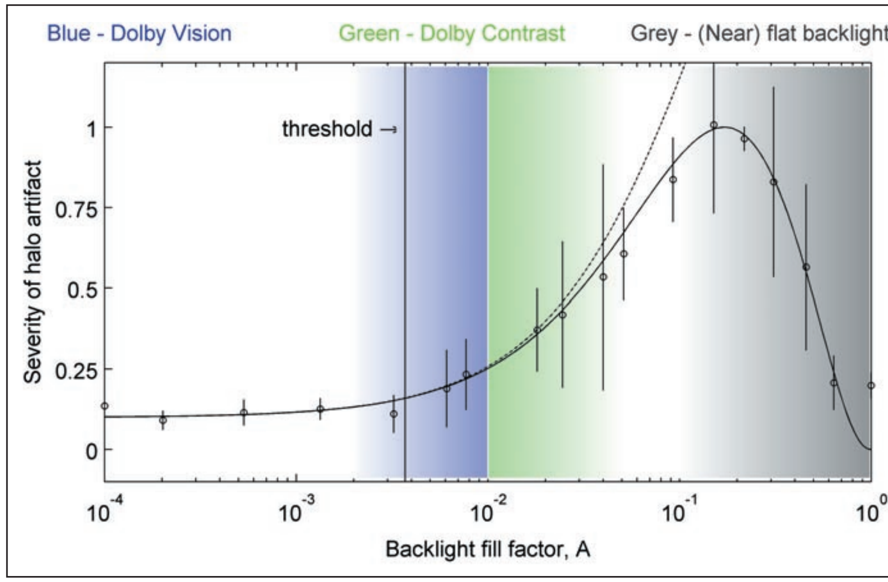


Fig. 5: *Results from ratio-scaling user studies for the static-halo artifact. The dashed-dotted line shows the expression from Eq. (1), and the solid line shows Eq. (1) multiplied by the large halo correction term* $(1\text{-}A)^2$*. The threshold for the static-halo artifact was determined to be 20 ± 9 LCD pixels (FWHM/2). Dolby Vision is a high luminance (1500 cd/m*^{2} *or higher) high-LED-density display design, and Dolby Contrast is a more conventional (up to 650 cd/m*^{2}*) medium-LED-density design.*

correction term for large halos is not necessary, and the expression in Eq. (1) alone is adequate.

For the user studies investigating the motion-halo experiments, the measurements displayed in Fig. 4 were mimicked by moving a small dot around in a big circle, and allowing for the halo size to vary along the way. A mean halo size of 45 pixels (FWHM/2) was used. The motion halo was found to be more visible the larger the amplitude of the oscillation got, and a threshold of 2.7 ± 0.8 pixels was determined. This means that the user will observe the artifact if the motion-halo metric exceeds 6% (oscillation amplitude divided by mean halo size: 2.7/45). In this experiment, the halo size oscillated at 2 Hz. For larger frequencies, *i.e.*, faster-moving features, there will be a cutoff where the artifact is no longer visible due to under-sampling.

Conclusion

A method for characterizing the static- and motion-halo artifacts in locally dimmed displays has been outlined and metrics developed. Psychophysical experiments verified the expected functional form and, furthermore, produced thresholds for both artifacts under a given set of test conditions. The static and motion-halo artifacts are fundamentally related to the architecture of local-dimming displays. Metrics sensitive to the specific artifacts enable the designer to optimize for the desired quality and avoid poor performance, as even the smallest halo can result in a wobble effect, or conversely, a larger halo can remain unseen if its size remains largely constant.

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Character Contrast

It is extremely difficult to accurately measure the contrast of a dark character on a light display. This article describes various ways to approach this problem.

by Edward F. Kelley

MEASURING THE CONTRAST of a dark character on a light display surface is one of the most difficult measurement results to obtain with accuracy. It is even more difficult when the display is subjected to ambient lighting conditions. With some display technologies, the full-screen contrast (sequential contrast) can be indicative of the contrast obtained when measuring small groups of pixels or even single-pixel character strokes. In general, however, that will not be the case because of light scattering within the display surface and any electronic irregularities that reduce contrast on a pixel scale. We are concerned here with an accurate measurement of the contrast regardless of how well the eye can see the contrast that we measure. Vision models can be applied after we attempt an accurate measurement.[1] Of course, it is assumed that the development of the appropriate vision models dealing with such detail contrasts properly accounted for scattered light in the detection systems employed, should that have been necessary.

Veiling glare is the problem. Light from the bright areas can scatter within the detector and contaminate the dark areas. The scattering can occur between the lens elements or off their edges, off other objects such as apertures and shutters, and off any interior surfaces. The reason for the adjective "veiling" is that this type of glare tends to be uniformly present, and often the user of the detector cannot see the contamination. When such scattering in the detector is extreme, it manifests itself as patterns of rings, spikes, and disks that are often called lens flare, which can be a useful artistic artifact to indicate a bright source of light in photography and videography.

However, for making accurate measurements, veiling glare is a serious problem. Often it is a much more important factor than one would think. For example, in the use of an array camera with a charge-coupled-device (CCD) or complementary-metal-oxide-semiconductor (CMOS) detection array, contamination of a small black area on a white screen can be well over 1000%![2] Is this an indication that the expensive scientific-grade camera that we just purchased is inadequate? No. We must be aware of the limitations of the instrumentation we use so that we do not expect the impossible. The path to good metrology is to be aware of the limitations and

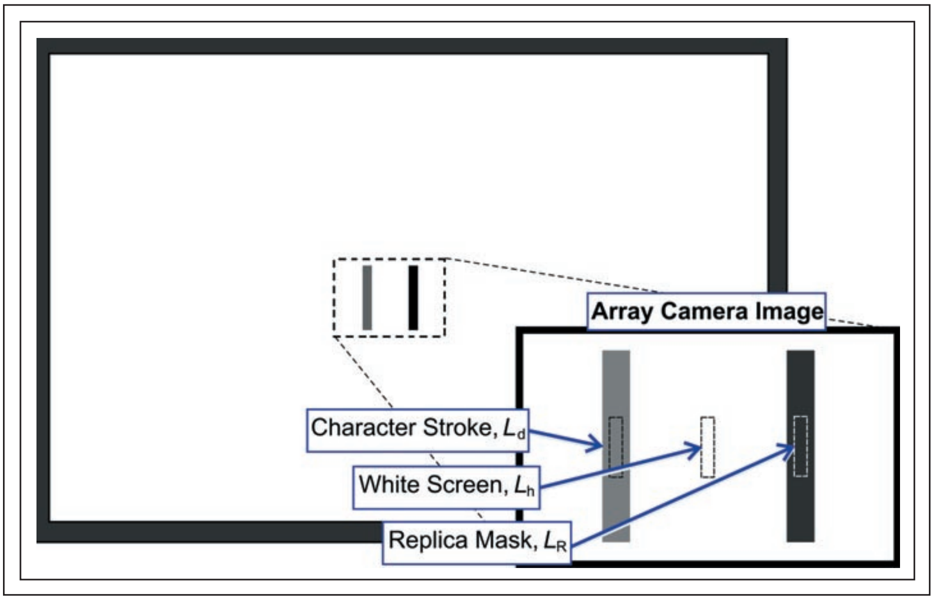

Fig. 1: *Small-area measurement for an emissive display in a dark room by use of an array camera. The luminance measurement areas are noted by small dashed rectangles in the array-camera image inset.*

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know how to work around them in order to obtain accurate measurement results. A good metrologist can often make a good measurement with a piece of junk whereas an inexperienced person can foul up a measurement with the best equipment available. Much depends upon attitude and awareness.

Errors in a small-area black of 1000% or more can be alarming. However, this should not be surprising considering what we are confronting. Take, for example, an emissive display with a full-white-screen luminance of 250 cd/m^2. If the contrast of a single-pixel-wide character on that white screen is actually 250:1, then the black character stroke would have an actual luminance of 1 cd/m^2. If the veiling glare in the camera contaminated that black luminance measurement by only 10 cd/m^2, then that black measurement would be 11 cd/m^2 instead of 1 cd/m^2, and the error introduced would be 1000%. The contrast would be incorrectly measured at 260:11 or about 24:1 instead of 250:1 – a 91% error in the contrast.

On the other hand, if we are viewing a relatively low-character-contrast display, such as a display in a high-ambient-light environment, the black character stroke for a display with an ambient white level of 250 cd/m^2 may have an actual ambient contrast of 5:1, or the black would actually have a luminance of 50 cd/m^2 under ambient conditions. The contamination of 10 cd/m^2 would amount to only 20% of the black luminance in this case, and the ambient contrast with glare would be measured at 260:60 or 4.3:1, an error of only 14%. For a display with an ambient contrast of 3:1 and an ambient white luminance of 250 cd/m^2, a 10-cd/m^2 veiling-glare contamination would amount to a 12% error in the black luminance of 83 cd/m^2 and result in an ambient contrast of 260:93 or 2.8:1 – that is only a 7% error. Thus, the higher the contrast, the more serious it becomes to ignore the veiling-glare contribution to the measurement. (As a very rough rule of thumb, in a non-trivial scene, many complicated camera lenses introduce approximately 4% or 5% of the average scene luminance as veiling glare, which is 10 cd/m^2, using our hypothetical 250-cd/m^2 display.)

Note that the veiling-glare contribution adds to both the black and the white measurements when measuring both white and black areas on the same screen at the same time. When we measure the full-screen contrast, known also as the sequential contrast, the effects of veiling glare cancels out in the division with the contrast calculation because the contamination in each full screen is directly proportional to the luminance of each screen. However, this is only for full-screen contrasts. Whenever different luminances are on the same screen, the veiling-glare contributions to those luminances do not cancel out when contrasts are being considered.

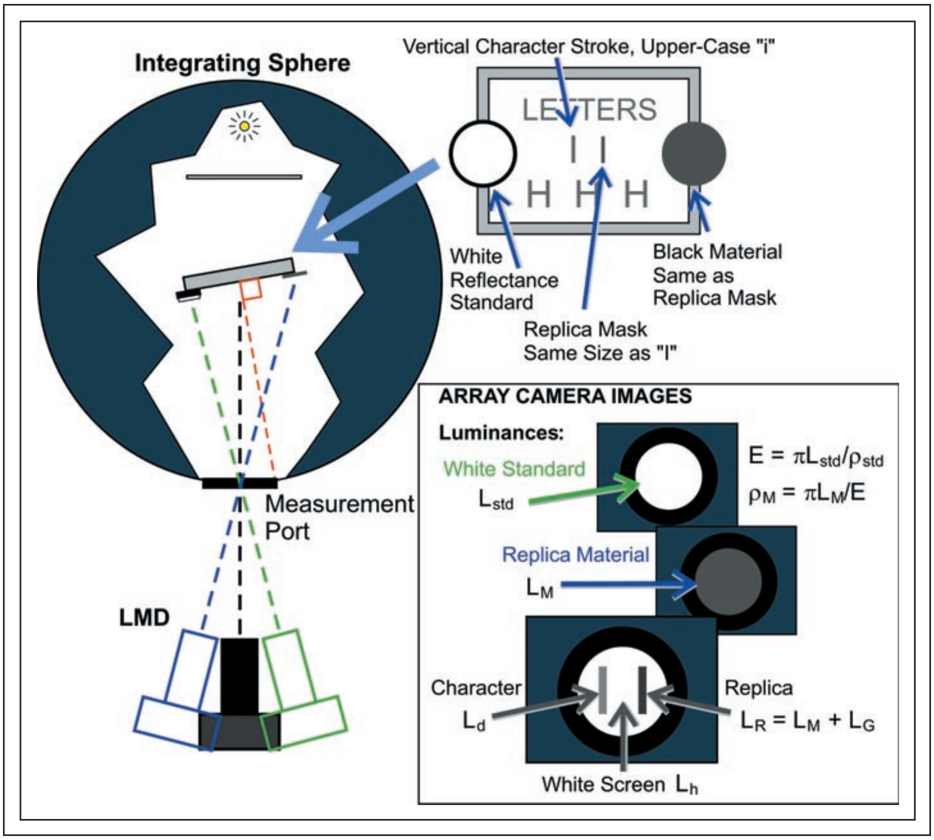

Fig. 2: Small-area measurements of a display in a uniform-ambient environment by use of a replica mask and an array camera for the light-measuring device (LMD). The replica-mask luminance L_M is measured assuring no bright areas are visible from the camera. The integrating sphere should be larger than shown here for illustration purposes.

Replica Masks

So, how do we use our cameras or small-area spot detectors to measure a small dark area on a white screen? One way is to employ a replica mask.[3] This is an object placed near the small dark area we want to measure that is the same size as the area to be measured and for which we know its luminance L_M. We measure the white-area luminance L_h, measure the black-pixel-area luminance L_d, and then measure the luminance of the replica L_R. If we know what the luminance of the replica should be (L_M), then we subtract that luminance from the measured replica luminance to obtain the veiling-glare luminance $L_G = L_R - L_M$. That veiling-glare luminance can then be subtracted from the measured white and the black luminances to obtain a better measurement result that accounts for the glare, $L_W = L_h - L_G$, and $L_K = L_d - L_G$. The ratio of the veiling-glare-subtracted white and black is the true contrast of the small area of black, $C = L_W/L_K$.

In the case of an emissive display in a dark room, we arrange for a black-opaque replica mask with its surface parallel to the display surface (see Fig. 1). A white display screen can light up a normal room; thus, the dark room must be of sufficient quality so that there is no contribution to the measured luminances from scattered light in the room or any objects in the room – this is essential. Addi-

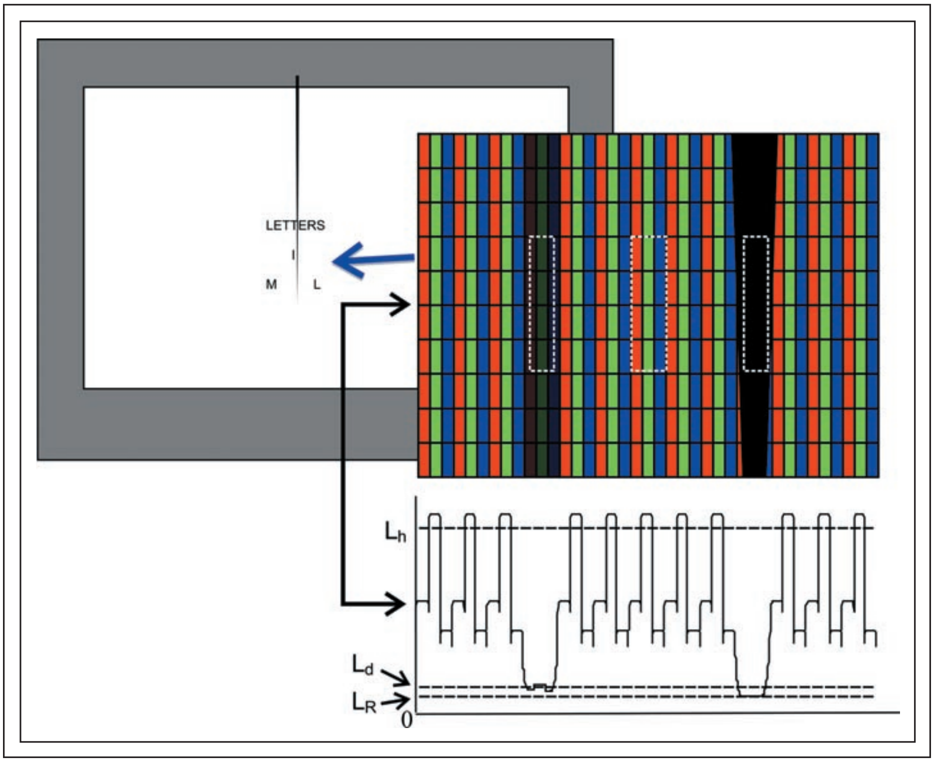

Fig. 3: Narrow triangular replica mask used to match the thickness of the character stroke of the sans-serif letter "I." The dark regions are measured with areas thinner than a pixel width in order to avoid the rounding of the luminance profile that occurs from glare from the immediate proximity of the bright subpixels. (The luminance profile shown is for illustration purposes only and is not necessarily scaled to actual relative levels encountered in practice.)

tionally, the light-measuring device (LMD) or detector, either an array camera or a spot luminance meter, must be sufficiently far back from the screen so that reflections off it do not contribute to the measured luminances. For some types of apparatus that problem may require making measurements from a slightly off-normal direction to avoid the influence of the detector in the measurement results. Particularly for high-contrast-capable displays, stray-light contributions from the apparatus or the room must be carefully controlled so that they are below the noise level of the measurements of the black areas. If the dark room's stray light is properly controlled, then the actual luminance L_M of the replica will be zero. For such a case, the measured luminance L_R of the replica is used as the glare luminance: $L_G = L_R$ with $L_M = 0$.

In order to make small-area measurements in a uniform ambient environment, the reflectance of the replica material will render it with a finite intrinsic luminance L_M that is not zero. Figure 2 shows a top view of a display in an integrating sphere. This is for illustration purposes only; the integrating sphere dimensions shown would not be large enough to provide a uniform illumination of the display. Generally, as a rule of thumb, the diameter of the integrating sphere should be approximately seven times the size of the object being measured. A large sample of the replica material must be placed within the uniform illumination region near the display. It must be large enough that the detector will not be exposed to any bright areas within the sphere when it measures the luminance L_M of the replica material (otherwise veiling glare in the detector will provide us with the wrong luminance of the replica material).

When an integrating sphere is used, the display must be turned away from the measurement port so that its normal is $\theta = 6°$ to10° from the center of the measurement port. If it would be useful to know the hemispherical diffuse reflectance ρ_M of the replica material, then a white reflectance standard may also be placed near the display to measure the illuminance E. Knowing the reflectance might be useful for using the replica material in other uniform-illumination situations, as with a sampling sphere rather than a large integrating sphere.

Making the proper replica is not always easy. For a large character, such as a 48-point sans-serif upper case "I" or another multipixel shape of that size, it may be possible to cut some opaque black plastic material to the exact same size (within 5% or so). However, for a character stroke that might be only a single pixel wide, it may be virtually impossible to cut such a shape successfully. Noting that most of the glare that contributes to the contamination of a narrow line or straight character stroke comes from the immediate white area next to the stroke, we can cut a very narrow triangle of black material using a razor blade and place it a short distance away from the character of interest, where the thickness of the triangle is the same as the character stroke (see Fig. 3). That should provide an adequate replica to determine the veiling-glare contribution. Whereas we would normally determine the white level by measuring full pixels, that may not be the right thing to do for the black pixels or the replica. Generally, there is a strong glare contribution at the boundary of a lit pixel and a dark area, so the luminance profile is not sharp, but rounded, as depicted in Fig. 3. To avoid that rounded boundary, we would use a smaller area within the dark pixels or replica to estimate the luminances encountered. Although this may not totally solve the problem, the contrast obtained usually gets us much closer to the actual contrast than if we did not attempt to account for veiling glare.

When using an array camera as our detector, we should always try to use sufficient magnification to obtain from 10 to 20 (preferably) detector pixels covering a single display pixel because of this rounding of the luminance profile into the dark areas – we want to clearly see the boundary region we need to avoid. Unless the display is of very low contrast, a 16-bit array camera is often needed to span the luminance range encountered. If that is not the case, or if the contrast exceeds the 16-bit camera's capability, then two exposures will be needed; one for the black reading and one for the white reading. In using array cameras, it is also important that they be photopic;

i.e., their spectral sensitivity must be very similar to the spectral luminous efficiency for photopic vision – the $V(\lambda)$ curve.

In discussing small-area measurements, we have mentioned only direct-view displays here. Front-projection displays may also have small-area measurements made by use of replica masks as well as replicas that produce shadows. The idea is the same. We subtract from the white and black luminance measurements the luminance of some region of the same size – a replica – that represents the amount of stray light that we encounter.[4]

Conclusion

Using replica masks to measure small-area and character contrasts can be one of the most difficult measurements to make. However, not using some technique to eliminate the effects of veiling glare can produce measurement results for small-area black levels and associated contrasts that are very inaccurate – even absurd. Ultimately, it would be very helpful to have deconvolution techniques that would allow us to fully account for veiling glare, but such techniques would have to be tested to agree with actual measurements such as those made with replica masks.

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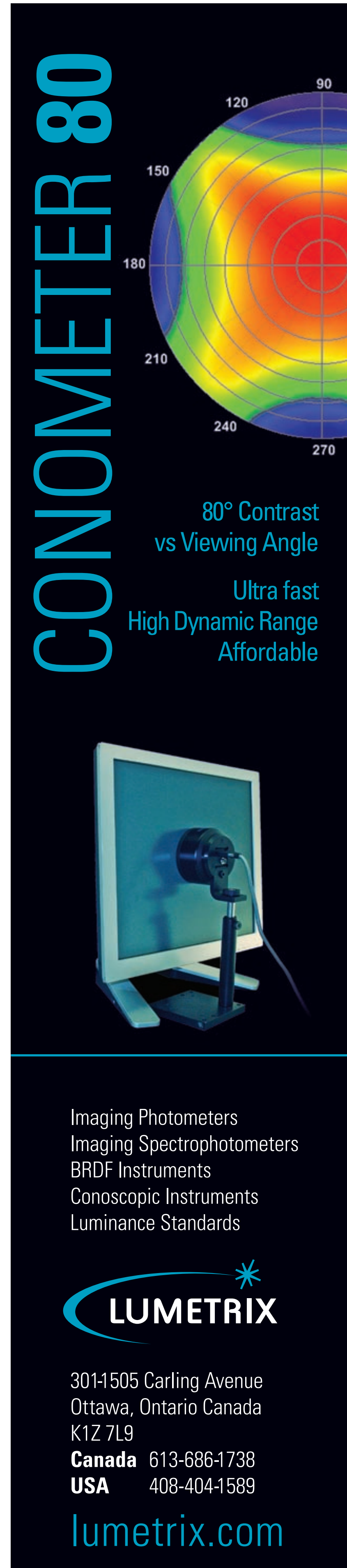

To Calibrate, or Not to Calibrate?

HDTV calibration services are a profitable up-sell for retailers. Do consumers really care about or need them?

by Pete Putman

THE EXPLOSIVE GROWTH in sales of HDTVs in the past 5 years has largely been driven by falling prices and the desire of consumers to upgrade older TV sets with HDTV capability. The current economic slump has forced prices down even more on larger screen sizes. As of late October 2008, when this article was written, it was possible to buy a 42-in. 1080*p* flat-panel HDTV for well under $1000 at wholesale clubs, while 50-in. plasma and 52-in. LCD TVs with 1080*p* resolution are now retailing for less than $2000.

These aggressive prices do not return as much profit to retailers as they would like. Consequently, the purchase of a new TV presents other incremental revenue opportunities, such as the sale of a Blu-ray DVD player, subscriptions to direct-broadcast-satellite or cable-TV services, accessory AV cables (often way overpriced), and white-glove installation services.

One add-on service that major retailers such as Best Buy and Circuit City now offer through their Geek Squad and Firedog brands is calibration. In theory, the calibrator sets up the HDTV to provide the best possible picture quality for the customer's viewing environment, making adjustments in both the TV's user and service menus to brightness, contrast, gamma, sharpness, and white balance. But is calibration necessary? If so, for which technologies and which TV models?

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The Need for Accuracy

Calibration services got their start back in the 1990s with the Imaging Science Foundation, which was started by SMPTE member and consultant Joseph Kane, Jr. His concept was that TV manufacturers were not calibrating their models to any particular set of standards, but rather were just trying to obtain the brightest picture with lots of edge enhancement – one that might attract a buyer on the showroom floor.

Kane's idea had plenty of merit. Most TVs sold to consumers had one or two picture presets at best, and some models did not have any at all! Viewer adjustments were limited to contrast ("picture"), brightness, color saturation, tint, and sharpness. The gamma of these sets was typically set to an S-curve response, coming out of black slowly to about 20% illuminance and then climbing quickly to about 80% where it flattened out (Fig. 1).

In addition to non-linear gamma, tube (CRT) TVs of the 1980s and 1990s often had their color temperature set very high, resulting in a "cold" picture with a bluish color cast. Other circuits exaggerated flesh tones and warm colors by boosting the levels of red; using bandpass filtering and peaking to create artificial detail around text, people, and objects; and elevating low levels of gray to provide more shadow detail.

Kane's system of education and calibration attempted to turn the TV business on its head by stressing accuracy and fidelity to the con-

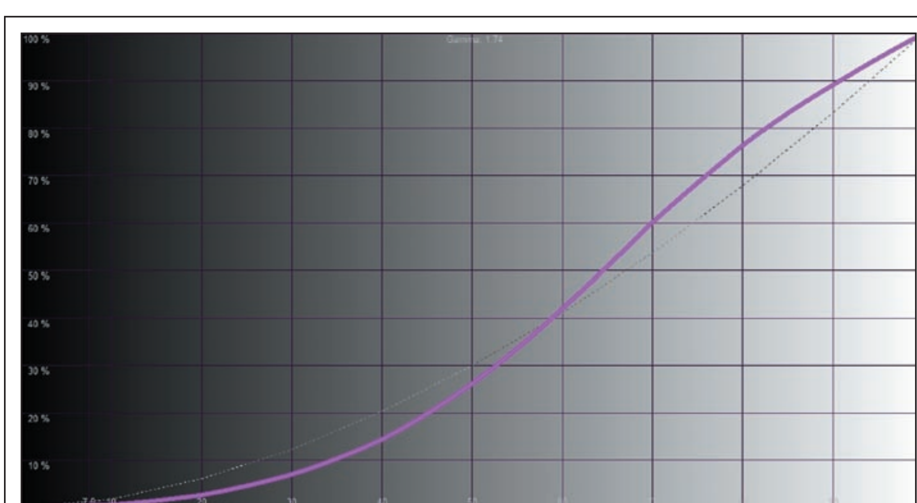

Fig. 1: Typical "S-curve" response (luminance vs. video level).

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tent being viewed, whether it originated on video or on film. He used existing standards for professional video monitors and called for manufacturers to turn off or remove altogether these image enhancements, which were actually degrading picture quality.

Calibration was a tough sell to buyers of generic TVs, but it gained a foothold in the rapidly growing home-theater market, particularly among dealers of high-end front- and rear-projection TVs. These products, which cost considerably more than everyday TVs and were often part of a complete systems-integration sale, benefited greatly from calibration.

Technology Catches Up

The need for calibration became even more apparent when first the laser-disc (LD) format and then digital videodiscs (DVDs) came to market. Laserdiscs, although limited to NTSC 480*i* image playback, offered more picture detail than the VHS and Betamax tape formats.

DVDs had an even greater impact, introducing component video, progressive scan, and anamorphic widescreen video to the mass market. It was now possible to double effective picture resolution from the 200 lines of videotape to 450+ lines on DVDs, in many cases obviating the need for edge enhancement and peaking.

Progressive-scan capability and widescreen transfers of film to video were significant drivers for the early generations of rear-projection and flat-panel HDTVs. The adoption of a digital HDTV standard and the start of HDTV broadcasts in the late 1990s provided even more impetus for sales in both the home-theater market and to everyday consumers.

It is worth pausing to consider just how much TV picture quality has improved in the past 20 years! Back in the late 1980s, laserdisc players were expensive toys for the affluent, while VHS players were growing in popularity as the movie-rental business expanded.

Today, anyone can purchase a small widescreen HDTV for less than $500 and play back movies from $130 upconverting DVD players that offer 1080*p* output resolution or download HD movies over high-speed Internet connections to hard-drive players, avoiding the rental stores entirely.

In Vogue, or Passe?

The question now is this: Do HDTVs still need to be calibrated? Or are manufacturers now focusing on image quality as a selling point just as important as screen size, resolution, footprint, and price?

The answer is "yes" in both cases. Some sets still benefit from calibration; in particular, front projectors that are part of a home-theater installation. And many manufacturers have gotten the message, including one or more picture presets on their new TVs that are already calibrated closely to industry standards for brightness, gamma, and color temperature.

The rapid move to 1080*p* resolution in every type of HDTV display has also come with a heightened awareness of picture quality. It is not unusual to find one or more factory picture presets (often marked "Cinema" or "Movie") that are very close to ideal in terms of calibration. These presets use a linear gamma response and turn contrast back down below "blowtorch" mode to reasonable levels.

More importantly, the HDTV's color temperature is set close to the D6500 standard used for professional video monitors. Edge enhancement is turned off; sharpness is set to minimal levels; and the red, green, and blue color matrix is weighted correctly in a 30/59/11 RGB color ratio for greater accuracy.

That's not to say that TV manufacturers have eschewed bright picture modes – they have not. "Dynamic" factory settings that result in bright pictures with S-curve gamma and a cold color temperature can still be found. "Sports" and "Game" modes, which are also brighter overall with higher black levels, and equally funky gamma curves are also likely to be found.

For the majority of HDTV purchasers, image quality can be improved by several magnitudes with a five-step quick fix: (1) Set the HDTV's contrast between 60 and 80 and brightness between 50 and 60. (2) Switch from "Dynamic" to "Standard" or "Cinema/Movie" picture mode. (3) Select a warm-color-temperature preset. (4) Turn down the sharpness control to 20% or less. (5) Turn off any other edge-enhancement processing. (Think about it: Why would HDTV content need detail enhancement?)

The fact that the customer's new HDTV looks so much better than their old tube TV makes the calibration up-sell a difficult task for retailers. Hook up a new HD cable or satellite box or Blu-ray player to that 42-in. 1080*p* LCD HDTV and it's like having filet mignon for the first time after years of living on "Hamburger Helper."

Never mind that a filet cooked medium rare tastes so much better than one cooked well done. Our new HDTV buyer simply does not understand any benefit to calibration and may perceive the offered service as simply another way to line the pockets of the salesperson with little in the way of results to show for it.

Make It a Little Better

There will always be those, however, who want to know their direct-view, rear-projection, or front-projection HDTV is set up accurately. These videophiles will justify the extra dollars for calibration; one that, if done correctly, will also take into account ambient room lighting and signal levels from set-top boxes and media players.

The advances in technology that have clobbered retail pricing on HDTVs (making them a "must have" on everyone's shopping list these days) have also brought down the costs of precision test equipment. It is now possible to buy an accurate, stable test-pattern generator for about $1600 and notebook-computer colorimeter software for $2000 that will suffice for a home-theater calibration (Fig. 2).

But equipment alone does not make anyone a certified calibrator. Some knowledge of how displays are supposed to look, and how each of the mainstream display technologies (LCD, plasma, CRT, DLP, LCoS, and HTPS-LCD) creates images, is a must.

It is not enough to simply re-balance RGB levels to achieve the desired color temperature. The display's gray scale must first be set up correctly to achieve the widest possible dynamic range while remaining linear, achiev-

Fig. 2: *Calibration hardware and software for the modern HDTV.*

ing the desired gamma response and producing photorealistic images.

After years of testing fixed-pixel HDTV displays, I have noticed that many flat-panel sets are capable of good gray-scale performance when they are not operated as tanning lamps. That usually means dialing back contrast levels and setting peak brightness somewhere in the area of 100–130 nits (29–35 ftL) – not bright enough for "Dynamic" mode on the retail floor, but more than adequate for everyday viewing in brightly lit rooms.

Excessive contrast levels always result in S-curve gamma response, with resulting compression of white and near-white values and corresponding "black crush" at the low end of the gray scale. The resulting images do not look natural to the eye. Black-stretch and dynamic-gamma options only make the problem worse, elevating low level and compressing high-level grays-scale values.

The audio equivalent would be using an equalizer to limit frequency response to mid-range octaves, similar to what can be heard through a telephone, and then running the amplifier near its power limit, which inevitably creates harmonic distortion. It's loud, all right, but not faithful to the original program content.

Once the gray scale has been set correctly for that particular HDTV (and that can be a tricky job), the next step is to adjust the red, green, and blue drive (contrast) and gain (brightness) so that the HDTV tracks a consistent color temperature from black to white. This is not always possible – some technologies do this much better than others – so a compromise may be needed, usually in the range of 50–70% gray.

Additional steps would be to dial back or shut down every possible form of artificial image enhancement. This can include dynamic gamma, black-stretch modes, color-transient improvement (only needed with analog composite and S-video inputs), and any other form of video AGC that will distort carefully tweaked gray scale. Sharpness and edge enhancement should also be minimized.

Depending on the sophistication of the HDTV's menus, one may be able to set the absolute coordinates for values of red, green, and blue. These, in turn, determine the displayable color gamut for HDTV, or possible shades of all three colors when mixed. These points usually cannot be changed and are a function of the particular color filters, LEDs, or color phosphors chosen by the manufacturer.

Those colors may not correspond to international standard color gamuts such as the ITU BT.709 color space for digital HDTV signals. Indeed, many LCD and plasma HDTVs have too much cyan mixed into their greens. While this results in a brighter, cleaner-appearing image, adding cyan results in a brighter image, but an inaccurate one because the green locus is shifted.

While this certainly adds to eye appeal, it is not accurate. A better choice would be to add more yellow and subtract cyan, which improves the rendering of flesh tones and shades of red, orange, and yellow. The advantages of staying close to a standard gamut will become more apparent as wider gamuts (such as xvYCC and the digital Cinema P3 color gamut) are encoded onto consumer media such as Blu-ray discs.

A good calibrator will not only make these adjustments once, but for every piece of equipment connected to the HDTV. Video signal levels vary from set-top box to DVD player, and one set of adjustments may not work for all video inputs.

It is worth mentioning that calibrated HDTVs do not use as much power as they do out of the box with factory "blowtorch" settings – a plus in a day and age where being "green" is of increasing importance.

Nobody's Perfect

There is one problem calibration cannot fix: upscaling problems with analog, standard-definition TV, and it's a major reason why HDTVs are returned to the store. The legacy NTSC system was designed for a maximum screen size of about 20 in. – nothing more – with a viewing distance of about 7 ft.

It's no surprise, then, that NTSC video is going to look soft and be riddled with cross-color and cross-luminance picture artifacts on a brand-new 52-in. 1080*p* LCD. Viewing photographs in a magazine with a magnifying glass would yield a similar sight – a bunch of coarse colored dots.

The key here is to make sure the customer isn't buying more TV than needed, particularly if all that's going to be connected is a basic cable service and a red-laser DVD player. In that case, an HDTV with 720*p*/768*p* resolution is more than adequate.

Believe it or not, the same quick fix can make low-resolution video look better on these sets – softening the image minimizes many of the signal artifacts. Turning down sharpness also minimizes digital (MPEG) video artifacts, such as mosquito noise and macroblocking from excessive compression.

Conclusion

Is calibration much ado about nothing or is it a worthwhile expenditure? As someone who has held the ISF certification since 1995 but does not perform calibrations for a living, I would say calibration is always worth it for home-theater front projectors, which is admittedly a very small market. However, based on the wider range of factory image presets I am seeing on current models of HDTVs, including variations on low-level Cinema and Movie modes, the answer for them is "probably not."

The quick five-step fix outlined earlier in this article makes such an improvement to image quality that the extra expense of a full-blown calibration usually is not warranted for casual viewers – only those videophiles who can't sleep at night unless they know for certain that their TV has been fine-tuned as much as possible.

Oh well, there are always those gold-plated Teflon-insulated HDMI cables to blow your cash on. ■

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Edited by Aris Silzars

Glare-limited appearances in HDR images

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Abstract — Intraocular glare and simultaneous contrast control appearance in high-dynamic-range (HDR) images. Unique test targets that simulate real images are described. These targets change the HDR range by 500 times, without significantly changing the veiling glare on the retina. These targets also have a nearly constant simultaneous contrast. The range of appearances possible from HDR images with different average luminances were measured. The targets displayed a maximum luminance range of 5.4 log units. Using magnitude estimates (MagEst) of appearances, the relationship between luminance and lightness from white to black was measured. With one exception, only small changes in appearance with large changes in dynamic range were found. It was also found that appearance was scene-dependent. The same dark grays (MagEst = 10) were observed with luminances of 10, 4.2, 1.1, and 0.063, depending on the percentage of white area in the surround. Glare from more white increases the retinal luminance of the test areas. Simultaneous contrast counteracts glare by making the appearance range (white–black) with a much smaller range of luminances. Appearance is controlled by both the optical scattered light and the spatial processing. A single tone-scale function of luminance cannot describe appearance controlled by scatter and spatial processing.

If the global physical properties of glare are considered, a surround that is, on average, equal to the middle of the dynamic range is prefered. This can be achieved by making the surround 50% max and 50% min luminance. Experiments have shown that the spatial distribution of white in the surround affects the appearance. To approximate real images, the half-white–half-black areas in differently sized squares were distributed.

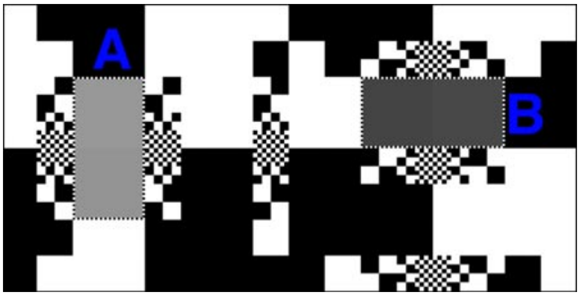

FIGURE 4 — Magnified view of two of 20 gray pairs of luminance patches. The left half (square A) has the same layout as the right (square B), rotated 90° counterclockwise. The gray areas in A have slightly different luminances, top and bottom. The gray areas in B have different luminances, left and right. The square surrounding areas are identical except for rotation. For each size there are equal numbers of min and max blocks.

Inverse display characterization: A two-step parametric model for digital displays

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Jürgen Stauder
Bongsun Lee

THOMSON R&D

Abstract — A simple additivity model is often used as a basic model for digital-display characterization. However, such a simple model cannot satisfy the needs of demanding color-management applications all the time. On the other hand, systematic sampling of the color space and 3-D interpolation is an expensive method in terms of measurement and computation time when precision is needed. An enhanced method to characterize the *XYZ*-to-*RGB* transform of a digital display is presented. This parametric method exploits the independence between the luminance variation of the electro-optic response and the colorimetric responses for certain display types. The model is generally applicable to digital displays, including 3-DMD projectors, single DMDs, CRTs, LCDs, *etc.*, if the independence condition is satisfied. While the problem to solve is a 3-D–to–3-D transformation (from *XYZ* to *RGB*), the proposed parametric model is the composition of a 2-D transform followed by a 1-D transform. The 2-D transform manages the chromatic aspects and, in succession, the 1-D transform manages the luminance variations. This parametric digital model is applicable in the field of color management, with the objective of characterizing digital displays and applying a reference look such as a film look.

The measurement data set includes two subsets:

- The "L" data subset: a gray ramp for the luminance-variation characterization.
- The "C" data subset: samples on three color planes for colorimetric characterization.

The "L" data subset covers the whole range of luminance variations, while the "C" data subset covers the whole range of chromatic variations. Figure 1 represents this data set. The black dashed line is the "L" data subset and the three colored planes are the "C" data subset.

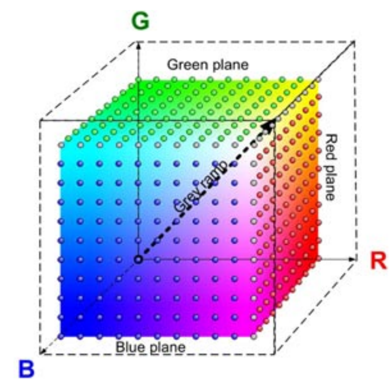

FIGURE 1 — Characterization dataset.

How to create appealing temporal color transitions?

Ingrid Vogels
Dragan Sekulovski
Bartjan Rijs

Philips Research

Abstract — Many applications, such as AmbiLight TV and atmosphere creation with dynamic light, generate colored light that changes gradually from one color to another. However, there is not much scientific knowledge on how to create suitable color transitions. This study investigates what is perceptually the most optimal way to create a temporal color transition between two colors. The first experiment measured the ability to distinguish between two temporal color transitions. The reference transition was a linear interpolation between two colors in CIELab, the test transitions were arcs defined in different planes going through the linear transition. Discrimination thresholds ranged between 2.5 and 12.5 ΔE_{ab}, depending on the color pair, direction, and duration of the transition. In the second experiment, several perceptually different color transitions were compared. The most preferred transitions were a linear transition in CIELab and a linear transition in RGB. The results suggest that it is possible to design a general algorithm for temporal color transitions that is appreciated by human observers, independent of color pair and application.

The test transitions were arcs defined in one of two planes: (1) the plane through start and end color parallel to the lightness axis, called the lightness plane and (2) the plane through start and end color perpendicular to the first plane, called the chromaticity plane [see Fig.1(a)]. The arcs were defined by three points: the start color, the end color, and a color in the corresponding plane at a distance *D* from the color halfway between the start and end color.

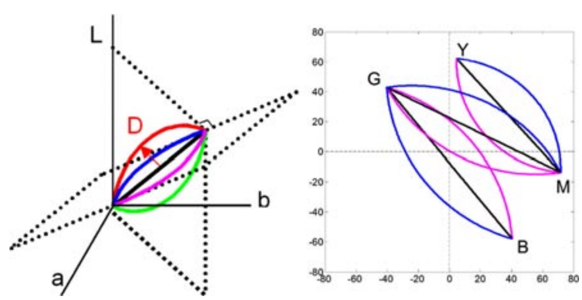

FIGURE 1 — (a) Examples of the reference transition (black line) and the test transitions with direction L_+ (red arc), L_- (green arc), C_{in} (magenta arc), and C_{out} (blue arc). (b) Projection of the reference transition and test transitions C_{in} and C_{out} on the *ab* plane for each color pair.

Correction of instrument measurement data for improving the visual color match between monitor and hardcopy

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Abstract — Soft proofing, which can confirm the color reproduction of printed matter on a monitor, is coming into wide use in the field of graphic arts. However, there is a problem in that the color on the monitor looks different from that of printed matter, even though the $L^*a^*b^*$ value of the monitor's white point has been adjusted to that of the paper by using a spectroradiometer. After the color rendition of an LCD is visually adjusted to that of the paper, the measured color of the LCD shows color with $L^*a^*b^*$ values corresponding to a more greenish-blue white than that of paper. For CRTs, this corresponds to a more bluish-white. In this paper, it was assumed that bright lines in the measured spectrums of the monitors and the illuminations spread to the next wavelength band by the optical systems of the spectroradiometer. To solve the problem, a method is proposed to enhance the bright line by using a three-tap digital filter. The effect of this method on two types of monitors under three types of illumination is also reported. After enhancing the bright lines, ΔE between the monitor and paper becomes smaller than that for the original one.

Figure 1 shows the device configuration used in this experiment. A color patch was displayed on the monitor. The brightness and hue of the color patch changes when the subjects click a button on the monitor. The target paper was placed next to the color patch on the surface of the monitor. The subjects observed the color patch and target paper from a 50-cm distance. The spectroradiometer was placed in the same location as the subjects.

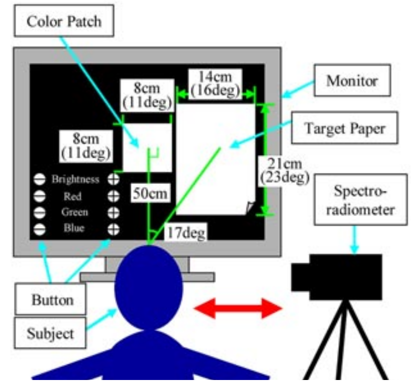

FIGURE 1 — Configuration of device used in the visual color-matching experiment.

White-LED backlight control for motion-blur reduction and power minimization in large LCD TVs

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Massoud Pedram

University of California

Abstract — A 1-D LED-backlight-scanning technique and a 2-D local-dimming technique for large LCD TVs are presented. These techniques not only reduce the motion-blur artifacts by means of impulse representation of images in video, but also increase the static contrast ratio by means of local dimming in the image(s). Both techniques exploit a unique feature of an LED backlight in large LCD TVs in which the whole panel is divided into a pre-defined number of regions such that the luminance in each region is independently controllable. The proposed techniques are implemented in a FPGA and demonstrated on a 40-in. LCD TV. Measurement results show that the proposed techniques significantly reduce the motion-blur artifacts, enhance the static contrast ratio by about 3×, and reduce the power consumption by 10% on average.

Figure 5 shows some sample responses of the HVS. When the flashlight stimuli with a fixed intensity but with different durations are presented under a dark-adapted condition, the HVS responds with a certain duration (called *visual persistence*) which is 10–100× longer than the duration of the flashed light in the millisecond range. Therefore, the HVS converts the impulse-type image display of CRTs which lasts about 70 μsec to a maximum of 7 msec of light perception. Therefore, under the typical refresh rate of 60 Hz, a screen image on a CRT will be perceived as non-overlapping. Consequently, motion blur does not occur in CRT monitors. All the impulse-type image-display techniques for motion-blur reduction are based on this understanding of the motion-blur phenomenon and how it can be eliminated.

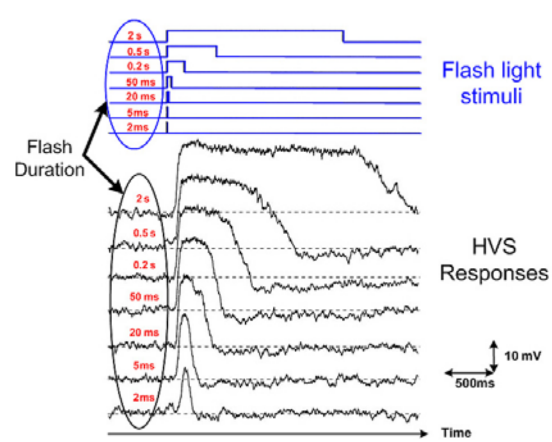

FIGURE 5 — Sample responses in HVS when different flash-light stimuli (with varying duration) are given.

Compact and efficient green lasers for mobile projector applications

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Abstract — Efficient and very-compact projectors embedded into mobile consumer-electronic devices, such as handsets, media players, gaming consoles, and GPS units, will enable new consumer use and industry business models. A keystone component for such projectors is a green laser that is commensurately efficient and compact. A synthetic green-laser architecture that can achieve efficiencies of 15% is described. The architecture consists of an infrared distributed Bragg reflector laser coupled into a second-harmonic-generation device for conversion to green.

Figure 1 illustrates the laser architecture. The output beam of the laser diode is coupled into a second-harmonic-generation (SHG) device through a pair of lenses. The first lens collimates the output beam, and the second lens focuses the beam down to a small spot size for coupling into the SHG with an angled facet to minimize back-reflected power.

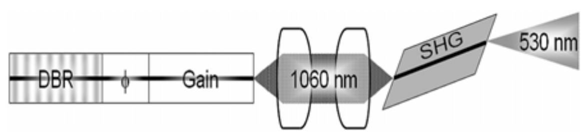

FIGURE 1 — Illustration of green-laser architecture.

Multistable electro-optical modes in ferroelectric liquid crystals

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Gurumurthy Hegde
Peizhi Xu

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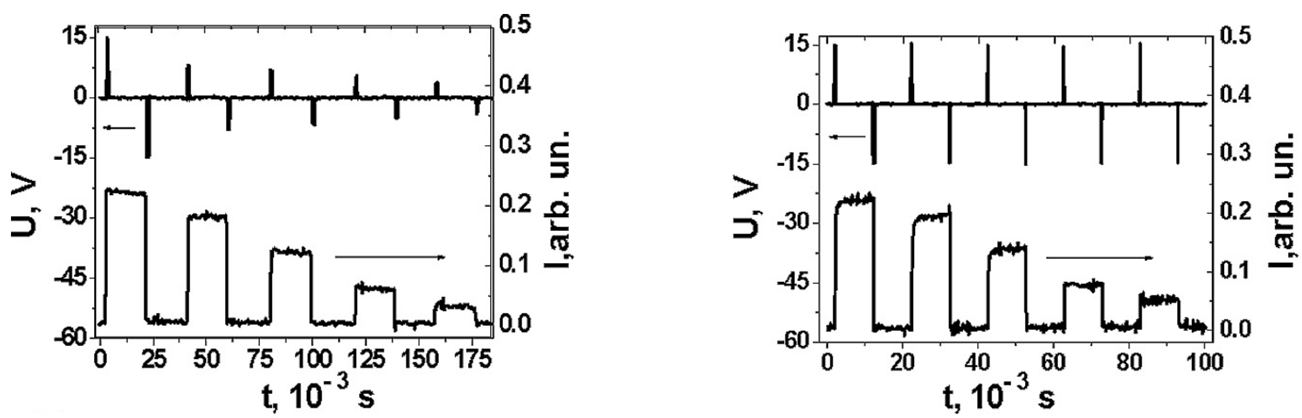
Abstract — Multistable electro-optical modes exist under certain conditions in ferroelectric liquid-crystal (FLC) cells, which means that any light-transmission level can be memorized after the driving voltage is switched off. The multistability is responsible for three new electro-optical modes with different shapes of the gray-scale curve that can be either S-shaped (double or single dependent upon the applied-voltage pulse sequence and boundary conditions) or V-shaped dependent upon boundary conditions and FLC cell parameters. The origin of these modes will be described.

Both the amplitude and the duration of the driving pulses can be varied to change the switching energy, which defines the memorized level of FLC-cell transmission in a multistable electro-optical response (Fig. 2). Therefore, any level of theFLC-cell transmission, intermediate between the maximum and the minimum transmissions, can be memorized after switching off the voltage pulses and short-circuiting of the cell electrodes.



(a) (b)

FIGURE 2 — Light transmission (bottom curves) memorized by the multistable FLC cell on (a) the amplitude of 1-msec alternating driving pulses and (b) the duration of alternating driving pulses ranging from 250 to 50 μsec.

Improvement of luminous efficiency using high helium content in full-HD plasma-display panels

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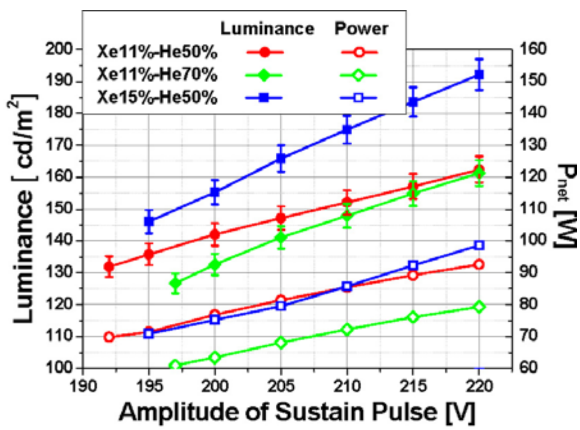
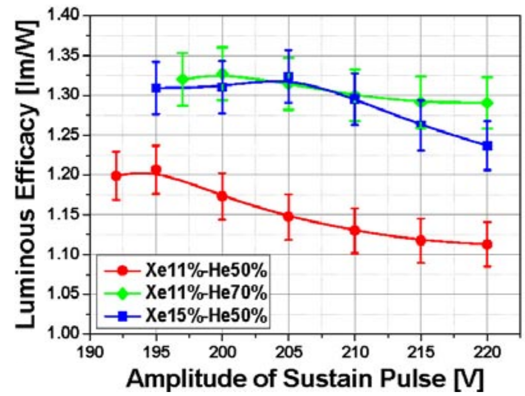
Heung-Sik Tae
Hyeong-Seol Jeong
Min Hur
Eun Gi Heo

Kyungpook University

Abstract — The influence of the Xe (15%) and He (70%) fractions on the discharge and driving characteristics was compared in 50-in. full-HD plasma-display panels. The same improvement in the luminous efficacy was obtained when increasing either the Xe or He fraction. However, the discharge current with a high He fraction was smaller than that with a high Xe fraction. While the breakdown voltage was hardly influenced by an increase in the He fraction, it was significantly changed when increasing the Xe fraction. The formative and statistical time lags were only slightly changed with a high He fraction, yet significantly increased with a high Xe fraction. In addition, the relatively low luminance and driving-margin characteristics with a high He fraction were compensated for by controlling the capacitance of the upper dielectric layer.



(a)



(b)

FIGURE 2 — (a) Changes in luminance and net power consumption and (b) corresponding luminous efficacy of 50-in. test panel relative to sustain voltage for three different gas conditions: Xe (11%) – He (50%) – Ne (case 1), Xe (11%) – He (70%) – Ne (case 2), and Xe (15%) – He (50%) – Ne (case 3).

editorial

continued from page 2

Few know this better than this issue's Guest Editor, Dr. Thomas Fiske, a respected contributor to the field and an ardent supporter of *ID* magazine for many years now. Tom is also past Technical Program Chair of the SID Symposium and currently chairs the Display Metrology sub-committee and will serve as General Chair of Display Week 2010.

Among the articles Tom solicited for this issue are two very illustrative articles from Nokia and UC Berkeley about the challenges of characterizing the performance of 3-D displays, one focused on metrology and the other on human perception. Together they contribute much to our understanding of 3-D displays and what characteristics will be important to focus on for future improvements.

Also this month, we get a better understanding of some of the subtle optical properties of high-dynamic-range (HDR) liquid-crystal displays and, as a result, will have a better appreciation of their unique characterization requirements thanks to the folks at Dolby Labs. And, of course, an issue on display metrology would not be complete without a contribution by Dr. Ed Kelley from NIST, this time furthering his work on replica masks to propose a more robust method for characterizing dark character contrast. You'll see and hear a lot more from Ed in the coming months as the International Committee on Display Metrology finally unveils its first official version of the new ICDM Standard.

I hope you enjoy this issue, and it is my sincere hope that you all have a safe, successful, and prosperous 2009.

– Stephen Atwood

guest editorial

continued from page 4

Finally, HDTV expert, writer, and speaker Pete Putman offers eminently practical advice about the need for HDTV calibration. He provides the definitive answer to the age-old question: "Do I need to spend the extra cash to have my HDTV professionally calibrated?"

We've presented articles here that provide guidance for characterizing some of today's newest and most exciting display technologies from some of the best experts in their fields. I hope that you find this year's display measurement issue lively, compelling, informative, and relevant.

Have a happy and healthy New Year. Play hard, work safe, do good, and be well. ■

__Thomas G. Fiske__ is a Principal Systems Engineer at Rockwell Collins Display Systems in San Jose, CA; e-mail: tgfiske@rockwellcollins.com. His primary interest is in display technology development and metrology.

president's corner

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to follow in charting the future of SID. For sure, the technology behind electronic display devices will remain the central focus of SID for some time, but it's fun to think about ways that things may evolve in the future.

For example, many companies that fabricate active-matrix backplanes have noticed that their technology is useful in fabricating photovoltaic panels. Similarly, technologies useful in fabricating displays and backlights, such as organic and inorganic LEDs, also have important roles to play in solid-state lighting. The companies manufacturing active-matrix backplanes and solar panels, and OLEDs and LEDs for display or solid-state lighting, take a more holistic view of their technology base. Could some of this thinking leak into SID? Time will tell.

Similarly, there are tremendous innovations ongoing in materials – organic semiconductors, organic light emitters, printable silicon and other semiconductors, and flexible-display devices. Some materials have had a long history at SID (think silicon), while other materials have only recently been an area of focus (think organic materials for OLEDs). SID organizing committees are stepping up their activities in these areas, so it's safe to say we may see a few more chemists and chemical engineers sitting alongside their electrical-engineering cousins in future conferences.

What about consumer devices? While SID will not be competing with mega-events such as CES, there is strong interest by consumers in obtaining honest evaluation of displays, and getting a heads-up on where display technology is heading. SID can play a role as a source of information useful to the people manufacturing the devices that incorporate displays, and to the people that buy them.

So what's in a name? For SID, the words "Society for Information Display" have transcended the individual components to represent something more. The SID "brand" stands as the premier source for authoritative information on topics associated with display technologies. The details of what SID organizes and presents depends in large part on the interests of its members, coupled with the requirements for high quality. So, as SID approaches 50 years of existence, it's safe to predict that it's not predictable where the next 50 years will lead.

Paul Drzaic
President
Society for Information Display

Remembering Chuck Pearson

Written by Dr. Peter Smith

On November 28, 2008, the SID community lost a much loved and respected colleague. Charles Arnold Pearson was born on January 10, 1952 in White Plains, New York. Chuck attended Stephanic High School in New York, graduated from King's College in Pennsylvania, and received his Masters degree from Merrill-Palmer Institute in Michigan. In 1976, he moved to Phoenix, Arizona, with his loving wife Debbie and built an executive recruiting business he called Murgence. Murgence operated for over 30 years with Chuck's leadership and helped a great many people further their careers, as well as helped build the leadership teams of many well-known display companies. However, Chuck's contributions to SID and the industry went way beyond his business activities.

Chuck freely and enthusiastically gave of his time and energy to make SID a better organization for its members. Chuck's contributions to SID included revitalization of the Southwest SID Chapter in the late 1990s, increasing membership in the Southwest Chapter and the Society as a whole, and navigating a complex legal situation related the SID's corporate status. For the latter accomplishment, Chuck was recognized in 2006 with an SID Presidential Citation. Chuck's energy and enthusiasm was contagious and resulted in getting many others on board to serve the Society also.

Chuck held several official titles in SID including Membership Chair, Audit Committee Chair, and Director of the Southwest SID Chapter, which he held from 2003 to his passing.

Chuck's stated profession was recruiting, or as Chuck would say, "Helping the members of SID achieve their career goals." Chuck built the premier boutique recruiting firm serving the Information Display industry. Chuck recruited for firms in North America, Asia, and Europe. Chuck's impact permitted members to advance their careers and hiring companies to find the best talent to achieve the unique challenges of the display industry. In this process, other companies would lose talent. Chuck would reply with humor that, "You are either a client or a source of talent." Chuck's clients were always pleased, the newly promoted human capital was happy, and the sending firm's human resource function often a bit puzzled.

While Chuck spent considerable time building his business and serving SID, he was, at heart, a family man. Chuck was most proud when his conversations turned to family and, in particular, his children. In the last few years, Chuck took up Irish Dancing with his wife, Debbie, moved to California to be closer to his children, and maintained his Arizona-based recruiting business through daily phone calls to his long time partner, Lawrence Liakos. He is survived by his wife, Debbie; children, Chuck, Michael, Robert, and Catherine; daughters-in-law Katie and Christine; granddaughter, Hannah Marie, and expected granddaughter, Maddyn Grace; brothers, Bill, Tom, John, and Chris; and his father, Andy.

A formal notice of Chuck's passing is also available on the SID website: www.sid.org. ■

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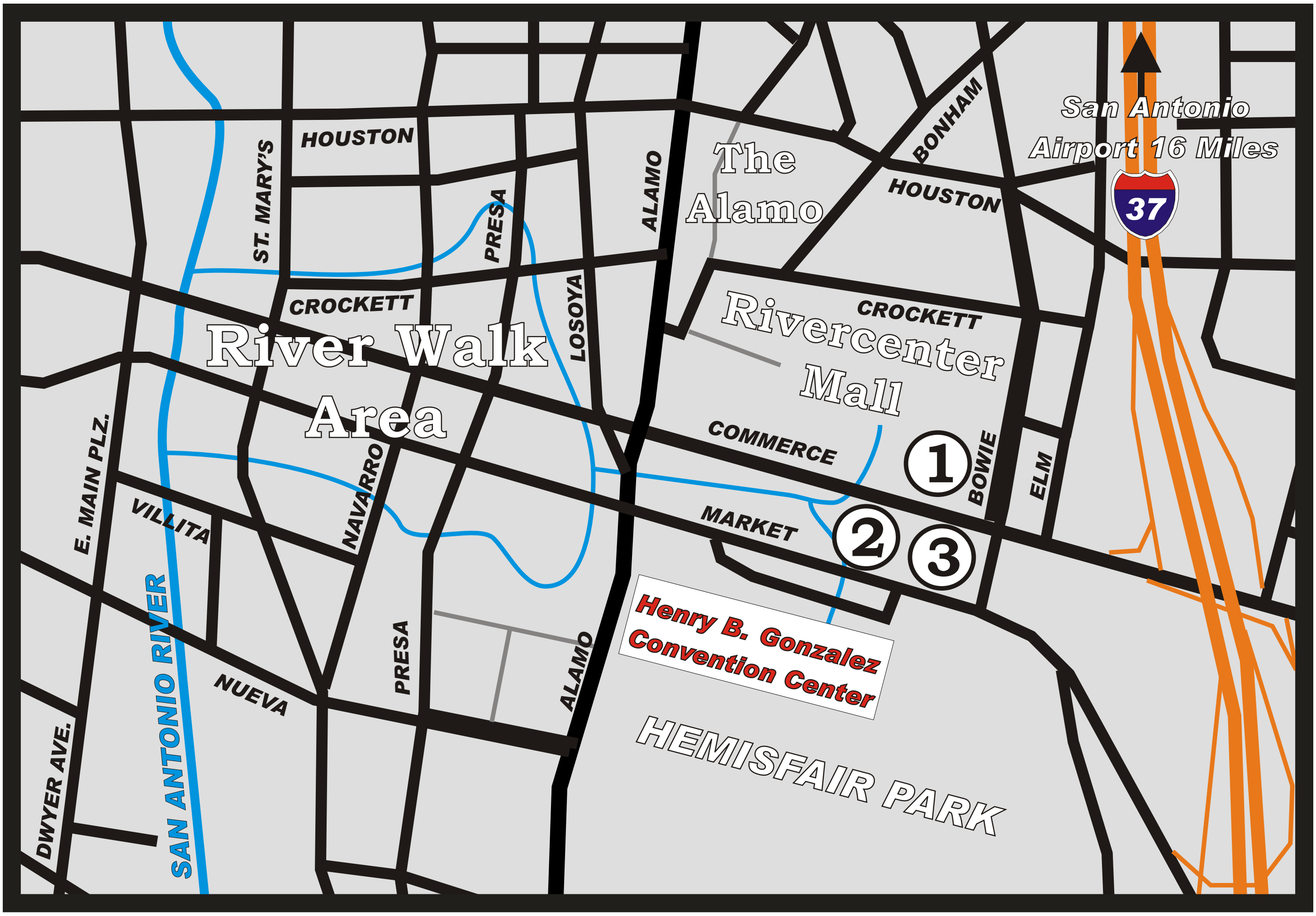

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