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The 3D-Color Rendering Map

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1. ABSTRACT

As a supplement of [1] the method of evaluating color rendering using a visual, graphical metric is presented. A Color Rendering Map (CRM) of a light source's color-rendering capabilities is explained and demonstrated. A technique to three-dimensional CRMs of objects under illumination is explained, including the method of introducing numerical indices in order to evaluate standards for specific applications in lighting. Three diverse applications, having a range from subtle to significant color variation, are shown with their respective CRMs. These three applications are also used to demonstrate how three differing light sources produce different maps. The results show a flexible, simple method to obtain a clear, visual determination of color rendering performance from differing sources used in differing illumination applications. The use of numeric indices in these applications shows how specific standards can be imposed in assessing the applicability of a light source.

2. INTRODUCTION

The CIE Color Rendering Index (CRI), first proposed in 1964, and later updated in 1974 [2], is the most common metric currently in use for assessment of artificial light sources in their ability to render visible colors. The Special CRI or Ri, as individual color difference index of 14 color test samples, and the General CRI, or Ra as the index averaging the color difference of the first eight of the Ri color-test samples (all taken from the Munsell Book of Color), involve an obsolete chromatic adaptation and use a color space which is not uniform. It has been shown that these metrics incorrectly estimate the color rendering capabilities of light sources, notably white Light-Emitting Diodes (LED) [3]. There is general consensus that the General CIE-CRI (Ra), and Special CRI (Ri), need a re-evaluation [4].

In recent years there have been several proposals for improving the CIE-CRI, or for establishing a different metric which evaluates a light source's color-rendering capabilities. All of these proposals can be categorized as either objective- or subjective-based measures. The majority are objective-based, using a reference illuminant for comparison and intended for improving the CIE-CRI. The subjective-measure proposals focus on color preference or memory colors. The following proposals are among the most recent and relevant.

The Gamut Area Index (GAI) [5] is an objective measure calculated as a percentage of the area of the polygon defined by the chromaticities in CIE-1964 coordinates of the eight CIE color test samples as specified in [2] when illuminated by a test light source, compared to the same polygon area when illuminated by a reference, equal energy white spectrum. The GAI is complementary to the CIE-CRI, and the test source is deemed both "natural" and "vivid" when both the CRI and GAI have values exceeding 80.

The Color Quality Scale (CQS) [6] is a method which mixes color fidelity and people's preference for chroma enhancement, by using more saturated test-color samples. The CQS does not penalize (nor reward) for increased chroma, includes improvements for chromatic adaptation, and uses a more homogeneous color space in evaluating color differences.

The Memory Color Rendering Index (MCRI) [7] MCRI evaluates a more subjective aspect of color rendition by calculating the degree of similarity between a set of familiar objects illuminated by the test source and their memory colors.

The proposed CRI-CAM02UCS [8] improves upon the CIE-CRI because it uses the CAM02-UCS that is not only a color appearance model but also a uniform color space, replacing the obsolete Von-Kries chromatic adaptation and the less uniform CIE 1964 (U*V*W*) space.

Because these approaches are general metrics, none of them take into account the specific color rendering requirements constrained by particular applications. We present here as it was disclosed in [1], a new approach, called the Color Rendering Map (CRM), which is used for evaluating and assessing light sources.

These 3-D representations provide immediate, intuitive information concerning the color-rendering capability that any light source has when used for that specific application. Several example applications are given to demonstrate that a lamp's color rendering can vary, according to each application. These results demonstrate an alternative to a single-number color-rendering metric.

3. THE 3D- CRM AND ITS APPLICATION

There are specific cases where color quality is of highest importance, and where the careful selection of a suitable spectral content is critical. In such specific situations, general indices are not a valid option.

We present in this section a methodology for assessment of the color quality of light sources under a particular application. As inputs, this method requires not only the spectrum of the light source, but also the chromaticity coordinates of all the illuminated elements (i.e. image pixels obtained with a luminance/color camera) under a reference illuminant (in our case, a D65 simulator). We use a Class B, (which is in the limit of being Class A since the measured Metameric Index is MIvis=0.268 (under CIE-L*a*b*) and MIvis=0.328 (under CIE-L*u*v*)), which has enough resemblance to the CIE Standard D65 for our purposes, since the minimum distance between consecutive samples of the Munsell set is ΔELab=4.86.
For a particular application (i.e. artwork, food, retail, etc…) we use a 3D representation of the color coordinates obtained with the luminance camera. This is performed by using different color spaces, such as CIE 1931 xyY [10], the CIE 1976 L*a*b* (CIELAB) [11], and the CIECAM02 [12], each of these having increasing complexity and computational power demands.
In order to evaluate how a light source renders the whole set of colors present in a particular application, the process followed is to first choose an ordered set of colors based on a color order system, resulting in what we call a Reference (color) Set. The color coordinates of the object of interest in the application are then measured with the luminance camera as illuminated by our D65 simulator, the resulting set of color coordinates being what is called the Observed Gamut. Again, although filters incorporated in these cameras are not perfect matches to the CIE 2º Observer matching functions, the x-y error is less than $\Delta E<2\cdot10^{-3}$ under reference illuminant A. Finally, a sub-set of the Reference Set is selected by finding minimum distances between the Observed Gamut and the Reference Set, resulting in the Test Set. This Test Set is then mapped in the 3-D color space chosen, creating the CRM. The flow chart in Fig. 1 depicts this process.

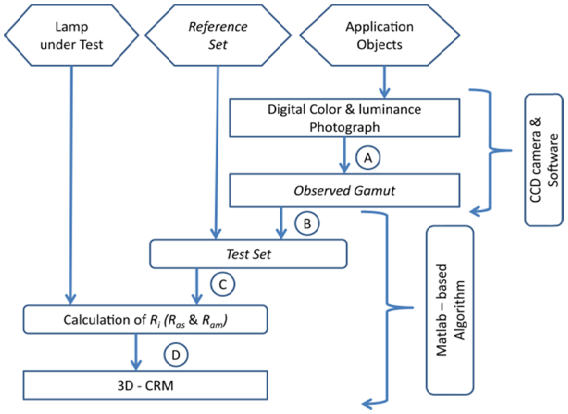

Fig. 1. Flow chart for the evaluation of the 3-D CRM. (A) A calibrated digital photograph measures all luminance and color coordinates of the application object, giving the Observed Gamut. (B) The Test Set is obtained by finding the closest Euclidian distance between each pixel in the Measured Set to the Colors of the Reference Set. (C) As before, the Ri values for the complete Test Set (as well as the Ras and Ram indices) are computed. (D) Finally, the 3-D CRM is plotted using the Ri values of the Test Sample.

The Reference Set requires a group of test colors of a sufficiently wide range of hue, chroma and lightness, such that the Set contains all the colors present in all the objects associated with application of interest. For purposes of the examples which follow, we use a reflectance database of the 1269 color samples corresponding to the Munsell color system, as was used in Section 2. This Reference Set is 90% of the color samples of the Munsell Book of Color (used for color assessment in industrial applications [13]), and although it demonstrates some metameric weaknesses, it suffices to demonstrate the CRM in the cases we tested. Other authors have demonstrated good color appearance modeling using 1000 reference colors [8], and reasonable improvement (as compared with Ra) with as few as 17 reference colors [14]. Test objects which have a very limited gamut, or require illumination at very-low CCT values may fall not be properly mapped using the Musell set. In such cases, a Reference Set drawn from a different color ordering system, such as the NCS or OSA Uniform Color Scale (depending on the objects and illumination conditions) will likely be needed to generate and accurate CRM.

Using a digital luminance camera, we obtain a picture of the test objects illuminated by our D65 simulator. It is necessary to calibrate the color and luminance of the camera using a standard illuminant, and include (during the test) a test card of a range of the reference colors to verify the accuracy. Editing the area(s) of interest of the picture, removing any test cards or surfaces of the experimental viewing booth from consideration in the data, the set of pixels that represent the chromaticity of the test objects are obtained (Observed Gamut). Subsets of these areas of interest can also be examined, which may give rise to a slightly different Observed Gamut, depending on the diversity of colors in the test objects of the application. While this variability might be seen as a weakness of the method, it actually emphasizes the high level of customization that it is able to provide, assessing color rendering aimed at each special case. In those applications where the diversity of colors is extremely broad, the benefits of our CRM are not so clearly seen, and other metrics that only depend on the spectrum of the light source but not on the input gamut might make more sense.

The Observed Gamut is compared to the Reference Set, resulting in a sub-set (of the Reference Set) which is the Test Set that represents the color gamut of the objects. This comparison is performed between each single pixel of the Observed Gamut to all samples of the Reference Set and assigning to the Test Set the nearest color within a uniform color space (such as CIELAB or CIECAM02.). Colors in the Observed Gamut can occur multiple times, which is noted using a multiplicity factor, mi, with a integer value mi ≥ 1, for each element in the Test Set. The Test Set, along with the respective mi values, allows us to create the 3-D Color Rendering Map and two associated numerical indices as seen in Eq. (1) and (2). These indices are used for color-rendering evaluation of the test light source; but are specific to the application being studied, and are not intended as a replacement or substitute for the CIE-Ra, It is evident that the value of multiplicity is highly dependent both on the diversity of color in the test objects, as well as to the size of the area of interest chosen from which to draw the Observed Gamut. The user of the CRM chooses, according to his requirements, the value of Ras and/or Ram which can be considered acceptable for the application being studied.

Once the Test Set is defined, and using the spectrum of the light source under test (see stage C in Fig. 1), the average of all Ri values, as defined in [2], of this set is the Index Ras. Considering that some samples have greater weight, if their mi >1 (a likely situation in most applications) in the gamut, the color rendering is also calculated as a Weighted Index, Ram. The sum of all pixels in the Observed Gamut, given their respective mi values is evaluated as:

$$\mathrm{R_{as}} = \frac{1}{\mathrm{s}}\sum_{\mathrm{i=1}}^{\mathrm{s}} \mathrm{R_i} \tag{1}$$

and the weighted average is:

$$\mathrm{R_{am}} = \frac{1}{\mathrm{u}}\sum_{\mathrm{i=1}}^{\mathrm{s}} \mathrm{m_i} * \mathrm{R_i} \tag{2}$$

$$\mathrm{u} = \sum_{\mathrm{i=1}}^{\mathrm{s}} \mathrm{m_i} \tag{3}$$

Where:

s : Number of elements in the Test Set

u : Number of elements (pixels) of the Observed Gamut

m_i : Multiplicity of the i-th element in the Test Set

Considering that human vision has adapted to natural daylight, an artificial light source is perceived as "natural" if it emulates a Planckian radiator [15]. By this standard, color quality can be objectively measured by considering parameters such as the Correlated Color Temperature (CCT) and the deviation of the chromaticity coordinates from the black body locus (Δuv) in addition to its Ra value. However, color quality assessment in general lighting sources has some subjective components such as color preference, memory colors and other issues varying with individuals [16]. The selection of areas of interest is already a subjective process reflected by the Observed Gamut; however, this is unique to each application, and defined by the user. Furthermore, although objective measurements can find the chromaticity of a source based on the spectral power distribution, the phenomena of metamerism, where two sources with the same chromatic coordinates (but different spectral content) generate different color perception of some objects [17], would have to be evaluated using a metamerism index for a more complete assessment of the color quality. Such subjective measures can be included in mapping an Observed Gamut by using methods which have been proposed by others who have described these phenomena, and how to evaluate them; but this is beyond the scope of this work which focuses on using the CRM for visual mapping of color rendering. Also, efficacy of a light source, which is of paramount importance, often has a significant, measureable tradeoff with color quality [15], and a user's threshold efficiency constraints can be incorporated into a CRM by plotting only the final data values which meet or exceed whatever value is chosen. The standards of how natural, efficient, metameric, or other qualities, as they would be incorporated in a CRM, are not addressed in the following application examples, and are reserved for future work.

1. Application Examples

The tools used to complete the measurement, shown in Fig. 2, include a viewing booth, both for calibration and for illumination of the objects by the chosen test sources, a CCD camera (calibrated for color and luminance), both color and gray checker cards, and software for data management and graphical representation. With these tools we are able to obtain an *Observed Gamut* for each application, and compute the *Test Set*, as well as portray the CRM.

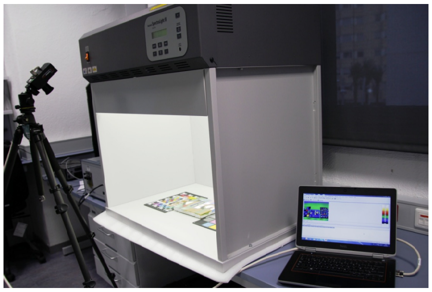

Fig. 2. (Color online) Experimental viewing booth, for generating Test Sets, with a simulator of the standard illuminant CIE-D65, calibrated CCD camera and a computer for editing and selecting the areas of interest. Also seen in the booth are color-checker patches. All measurements are performed with room lights dark.

Demonstrating the 1269 Munsell samples of our chosen Reference Set in 3-D is seen in Fig. 3, in (non-uniform) CIE-1931 xyY color space (a) as well as uniform CIELAB (b) color space.

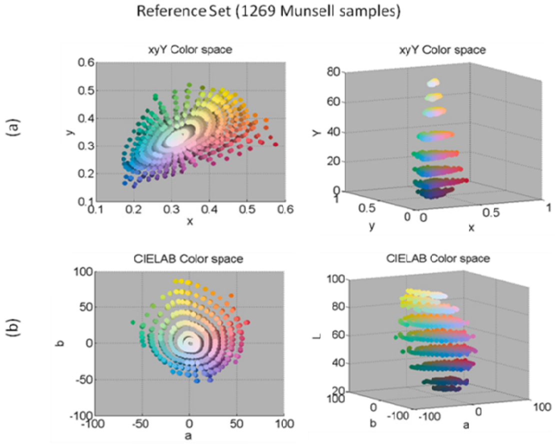

Fig. 3. (Color online) Volumetric color space depiction of the 1269 color Reference Set used in the application examples. The equivalent Reference Set is demonstrated in two versions of color space: (a) CIE-1931 xyY and (b) CIE-1976 CIEL*a*b*.

Three diverse, practical lighting applications here demonstrate the CRM, seen in Figures 4a-c using the reference D65 illuminant. The first case, lighting of meat in displays, seen in Figure 4a, examines a lighting application where the illuminated object has somewhat subtle color variations. The second, a collection of various fruits, Fig. 4b, looks at a broader range of colors. Finally, Fig. 4c, lighting of artwork, covers a most-diverse usage of colorfulness, saturation and lightness. For these three applications, we follow the method described in Section 3, determining the Test Set and evaluating Ras and Ram indices with differing light sources. Finally, we show the CRMs for each case. Table 1 shows some figures for Observed Gamut (pixels) and Test Set (selected Munsell samples) obtained for the three applications in Fig. 4.

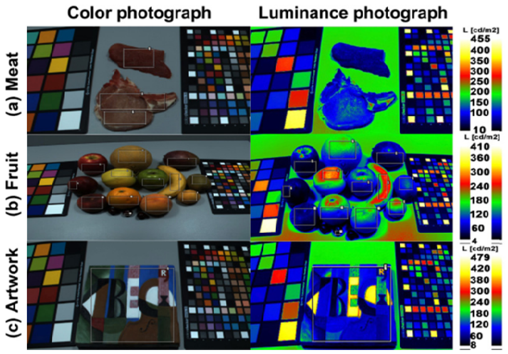

Fig. 4. (Color online) Color photograph (left column), taken under D65 reference illumination, of meat samples (a), assorted fruit (b) and artwork (c), along with corresponding luminance photographs of each scene (right column). The rectangles delineate the areas of interest to be analyzed. The color-checker cards are used to verify the calibration of the camera.

Table 1. Comparative results of calculated Observed Gamut and Test Set using CIELAB and CIECAM02 color systems for three different applications.

Application	**Color System**	**Observed Gamut**	**Test Set**
		(Size in pixels)	
Meat	CIELAB	29,401	231
	CIECAM02	29,401	232
Fruit	CIELAB	134,207	170
	CIECAM02	134,207	174
Artwork	CIELAB	194,208	611
	CIECAM02	194,208	610

Table 1 highlights that the difference (in our case, using the Munsell color samples) between Test Sets obtained using CIELAB and CIECAM02 for these three chosen applications is negligible.

The size of any Observed Gamut may comprise several mega-pixels, varying on how many, and how large, the selected areas of interest are. Therefore, an algorithm that extracts the volume surface of the Observed Gamut, is used to optimize data management for the CRM to be represented in a 3-D graphics.

The resulting Test Set (solely for the meat application), is shown in Figures 6a-c, as derived from the measurements of the application in Figure 4a. The Test Sets of Figures 6a-c show the two different angles of view for the CIE-1931 xyY.

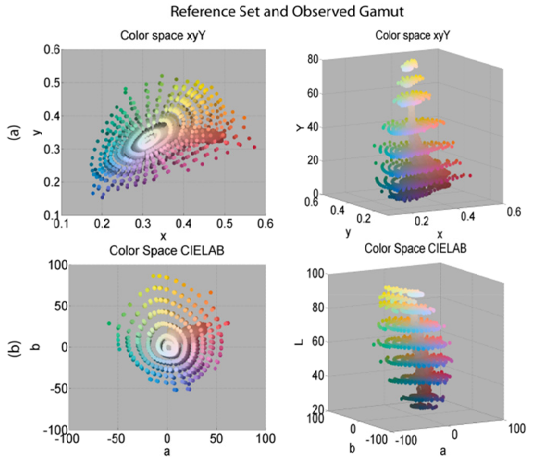

Fig. 5. (Color online) Observed Gamut data measured under a D65 simulator from the meat application shown in Fig. 4a, in two versions of color space: CIE-1931 xyY (a) and CIE-1976 CIEL*a*b* (b). These are seen in two views.

The Test Set for each application is obtained by evaluating the minimum Euclidean distances from each single pixel of the Observed Gamut to each element of the Reference Set, in these cases using the cylindrical coordinates in CIELAB and CIECAM02. Figures 6a-c shows the 3-D CIE 1935 xyY Test Set for the three example applications as seen in Figures 4a-c.

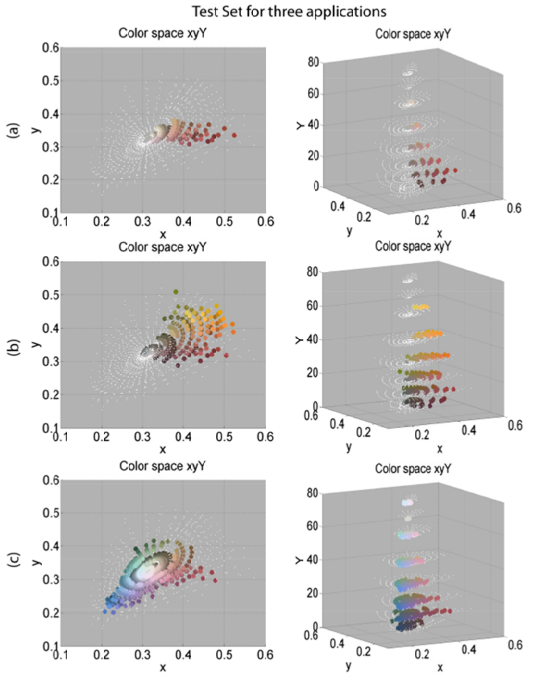

Fig. 6. (Color online) CIE 1935 xyY representation of the Test Set found for the meat (a), fruit (b) and artwork (c) applications of Fig. 4.

We now analyse three different light sources (with comparable CCT's and Ra's) as shown in Fig. 7 (left) by following the steps described above for the calculation of the Test Set and for the indices Ras and Ram. It can be seen (Fig. 7, left) that even though the Ra value remains essentially the same for each light source (and strictly the same for each application because it only depends on the spectral content of the light source), the Ras and Ram indices change from application to application. This demonstrates how the CRM and the derived indices constitute a useful tool for the lighting designer when personalizing scenes in specific applications. When high color rendering is of importance (i.e. retail, artwork, surgery, etc.), the use of customized indices such as Ras and Ram enables the user to establish specific threshold constraints which need to be met.

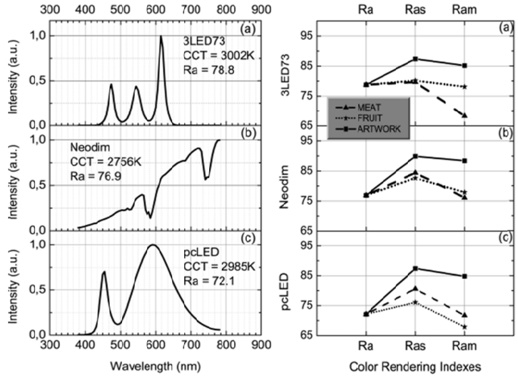

Fig. 7. Left column: Three differing light sources, CCT=3000K , (a) R-G-B LED, (b) incandescent Neodimium lamp, and (c) Phosphor-converted LED. Right column: Corresponding color rendering indices CIE-Ra, Ras and Ram, for the three applications (Test Set) Meat, Fruit and Artwork.

For the lamps studied in Fig. 7, the highest values of Ras and Ram are obtained for the artwork application, since artwork shows a Test Set with the widest range of hues.

Beyond the single-number indices Ras and Ram, a full description of the situation can be found in the Fig. 8 where one view of the 3D-CRM has been plotted. In the Figures 8(1-9), the Ri values of the Test Set evaluated is plotted by using a color scale from deep blue to deep red (representing 0 to 100). Hence, nine different visual representation are shown for three different applications, i.e. meat (left column), fruit (central column), and artwork (right column), likewise three different light sources, i.e. R-G-B LED (upper row), Neodimium (middle row) and phosphor-converted LED (lower row).

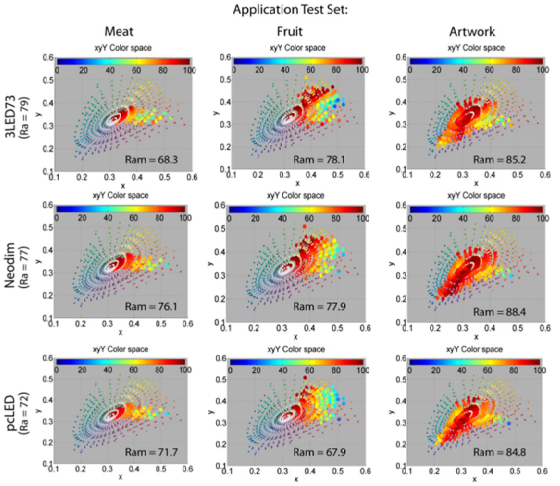

Fig. 8. (Color online) CRM representation in xyY color space of the Test Set for the three applications shown in Fig. 4, illuminated with light sources of Fig. 7. R-G-B LED (upper row), Neodimium (middle row) and phosphor-converted LED (lower row). Only one view is shown.

2. CONCLUSION

A method for evaluating light sources, and also for evaluating (and/or comparing) that source's desirability in specific applications using a graphical metric, the Color Rendering Map, has been described and demonstrated. A systematic method for evaluating light sources in specific applications of any source has been described by using the 3-D CRM.

Solid State Lighting and the forthcoming emerging technologies will allow spectral reproduction in the near future. At that point, the Lighting Designer will be challenged by a situation in which the spectral content of a light will have to be adapted to its intended final application or space location. With this perspective in mind, the CRM constitutes an excellent tool for expanding illuminance and luminance-based designs to include color-based designs in the future.

The value of these methods is seen in their visual, graphical depiction in a map, as opposed to less descriptive, and potentially ambiguous, numeric metrics.

4. ACKNOWLEDGMENTS

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6. BIOGRAPHY

Jesús M. Quintero received the degree of Specialist in Industrial Automation and Control from the National University of Colombia in 2007, a B.S.E.E. degree from the National University of Colombia in 1992 and a Specialist degree in Informatics and Communications Technology from Los Andes University, Colombia in 2002. Since 2004, he has been at the National University of Colombia in Bogotá, where he is a Senior Lecturer on Electrical and Electronics Engineering, with appointments in the Light and Lighting program. He is in his fourth year of a Ph.D. Program in Electrical Engineering studies at the Universitat Politecnica de Catalunya (UPC) in Barcelona, Spain and is doing a Ph.D. Fellowship at the Institute for Energy Research of Catalonia (IREC). His research centers on high-power light-emitting diodes, luminescent materials and color quality of light sources.

Charles E. Hunt received the B.S.E.E. and M.S.E.E. degree from the University of Utah and the Ph.D. degree in Electrical Engineering from Cornell University. From 1979 to 1983 he served as Staff Engineer to the VLSI Design Research Group at the Computer Science Department of the University of Utah,. Since 1986, he has been in the Electrical and Computer Engineering Department at the University of California at Davis, where is presently Professor. His major research emphasis has been in the areas of field-emission vacuum microelectronics, semiconductor wafer bonding, silicon on insulator (SOI) materials and devices, and CVD epitaxy. Professor Hunt is a Senior Member of the Institute of Electrical and Electronics Engineers, and is Author or Co-Author of over one hundred refereed publications, eight books, and holds eleven patents. Since 1997 he has served as Editor of the journal, Solid-State Electronics.

Josep Carreras received his B.S., M.S. and PhD. (Cum Laude, with Honours) in Physics from the University of Barcelona. He has published more than 30 articles in several SCI journals, has filed two patents, participated in more than 15 different projects at a national and international level. Since June 2009, he is working for IREC, where currently he is the Head of the Lighting Group, leading research in novel concepts for Energy Efficient Lighting, Colour Science and Technology, Simulations, Photometry, and Intelligent Lighting with advanced communication and computation functionalities. He also helped in the definition of the research strategies and infrastructures from the early stages of the Institute and is currently managing the group and supervising several projects in close collaboration with industrial partners.