6P COLOR

What is 6P Color, Inc. and how is Baylor University involved?

The Full Color Range (FCR) System, formerly dubbed 6P, is the result of a sponsored research project funded by 6P Color, Inc. and conducted at Baylor University by researchers Corey Carbonara Ph.D., Michael Korpi Ph.D. and Gary Mandle of the Film and Digital Media Department, along with a team of creatives, scientists and engineers including Steven Poster, ASC, Mitch Bogdanowicz Ph.D., Jim DeFilippis and Gary Feather who are working with 6P Color, Inc.

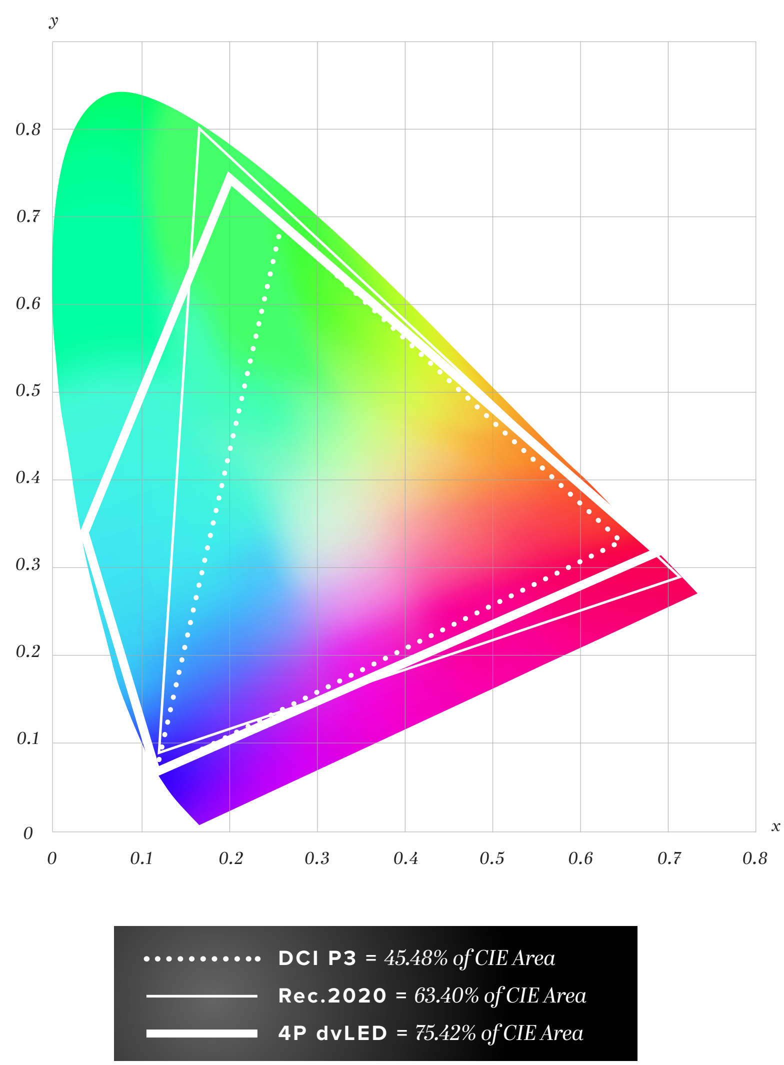
WHAT IS THE **FULL COLOR RANGE SYSTEM?**

FCR means "all the colors humans can see." FCR is an end-to-end color system starting with the RAW data captured by a camera imager, created electronically (e.g., animations, visual effects), or scanned (e.g., film). The system allows for color processing and transport of all available colors to displays using existing formats and standards. (FCR is the only current system we know of that can do this.) Each display then transforms the data to take maximum advantage of its own display characteristics: color gamut, dynamic range, white point, number of primaries, and *xy* positions of primaries. Thus, the system can coexist with legacy RGB displays, in addition to enabling a variety of future multi-primary displays.

"Full Color Range is not just Bit-Depth or Gamut, it's not just Chromaticity and Luminosity. FCR is ...a compendium of neurologic cues that allow our audience to really feel the emotional message that true and complete color can impart."

STEVEN POSTER, ASC

CIE 1931 **STANDARD OBSERVER AREA**



Why Multi-Primary?

Displays employing four or more color primaries (multi-primary) are necessary to expand color gamut beyond that of the largest possible RGB triangle. There is an industry trend toward extending color gamut, however, attempts to do this in RGB have encountered significant problems. Multi-primary can significantly reduce or eliminate these problems. It also provides a promising upgrade path for both display manufacturers and their retail outlets. Many believe the competition for better images will inevitably lead to multi-primary displays. To generate the greatest audience impact with FCR, multi-primary displays are highly desirable.

Do we need to shoot all new material for multi-primary displays?

No. FCR uses the out-of-gamut colors already captured by digital cinema cameras and maintains them throughout post-production and transport to displays. Productions that used color film for acquisition can rescan the negative—the original negative contains a wider gamut of color than could ever be carried forward to film prints. New productions can be shot with wider color gamut in mind—thus, taking full advantage of the expanded palette from the start.

The FCR System uses *Yxy*. What is *Yxy*?

Limiting the available colors to a particular RGB display space (e.g., Rec.709, Rec.2020, P3) excludes some colors that are not only visible to humans but are also well within the capture ability of modern digital cameras. The *xy* coordinates from the CIE 1931 color model (a model of human color vision, often called the "standard observer"), can be used to define all human visible colors. In the CIE 1931 color model, the full three-dimensional color space is represented as a triplet, *XYZ*,[1] and this is used in digital cinema for distribution.

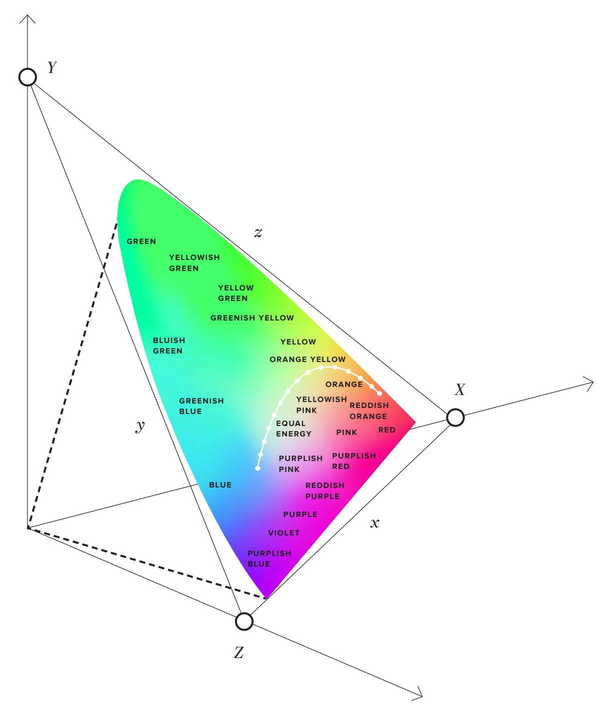
The FCR System uses an alternative representation of the same CIE 1931 color space, *Yxy*, that is an extension of *XYZ*—color scientists call this a "projection" from *XYZ*. *Y* in *Yxy* represents only luminance, and the *xy* coordinates represent each specific color. *Yxy* has compatibility and data rate advantages over *XYZ*, in terms of its use over the wide range of current workflows and transport standards.

What changes to current methods and standards are required to implement the FCR System?

(1) Add *Yxy* and *XYZ* as options in standard workflow and transport streams. There is no bandwidth increase over RGB, and FCR supports 8-bit, 10-bit, and 12-bit. (2) Displays must be able to accept a 3-component signal or stream consisting of *Yxy* or *XYZ* data and transcode it to the display color gamut. This may be achieved in the display's internal processor or with a dongle attached to the display input. With this transcode capability, FCR is backward compatible with all RGB displays.

What are the benefits of the FCR System?

- FCR enables consumers to see near-full spectrum color. FCR delivers a significantly enhanced viewer experience: increased attention, greater sense of presence, intensified engagement, more complete suspension of disbelief, and the ability to really feel the emotional message. There is an "awe" factor.
- FCR provides expanded creative color choices to content producers. When using a display with four or more primaries, FCR can show colors not reproducible in any RGB system.
- FCR leverages existing technology and standards, with only minimal changes needed to any workflow. FCR operates at the same data rates as RGB systems, and it simplifies the future upgrade path to multi-primary displays.



1 – Note that values can be upper or lower case, and this identifies greatly different meanings. As an example, *xyz* is not the same as *XYZ*.

Why is the FCR System superior to Rec.2020?

Rec.2020 provides a greater volume and chromaticity area than both Rec.709 and P3. However, significant colors are outside the Rec.2020 gamut. Furthermore, due to the narrow bandwidth of the Rec.2020 primaries (close to the spectral locus curve of the CIE chromaticity diagram) it is difficult to achieve these primaries in practical real-world displays. Lasers, narrow-band LEDs, and quantum dots have been tried. The main problem is that these narrow-band light sources exacerbate metameric error, that is, different people viewing the same thing but perceiving different colors.

FCR multi-primary displays use primaries that are wider than those required for Rec.2020, but still narrow enough to achieve a high color saturation. The additional primaries fill in the gaps that would otherwise be left by narrowing the bandwidth of the RGB primaries.

When comparing the area of CIE chromaticity coverage, adding just a fourth primary (4P) over Rec.2020's three primaries includes up to 75% of the full CIE color spectrum, whereas Rec.2020 P3 includes only 67%. Adding a fifth or sixth primary expands the color spectrum even more over Rec.2020.

How does FCR enable multi-primary displays?

With the FCR System, display manufacturers are not constrained by a specific display standard. They can implement as many primaries with whatever positions they need for their requirements and target markets. Beyond the consumer entertainment space, multi-primary displays can be optimized for medical, agricultural, surveillance, and other specialized markets. In conjunction with Baylor University, 6P Color, Inc. is evaluating several display technologies that can be adapted to use four, five, six and more color primaries. Because the *Yxy* signal transport system can support displays with any number of primaries and with the full color spectrum, we see a future with a great variety of displays reproducing colors that viewers have never seen before.

Do you actually get more colors with multi-primaries compared to RGB systems such as Rec.709, DCI P3, and Rec.2020?

Yes, the additional color primary channels convey colors not reproducible in an RGB system. Not only are there colors beyond the RGB gamut triangle, but there are more gradations of colors, many of which are "colors between the colors" residing inside the RGB gamut. To put this into perspective, here is the effect of adding primaries and how this adds to more gradations of color in an 8-bit, 10-bit or 12-bit color system:

- **RGB 8 bit = $(2^8)^3$ = 16.8 million colors vs RGBC 8 bit = $(2^8)^4$ =**
  4.3 BILLION COLORS
- **RGB 10 bit = $(2^{10})^3$ = 1.1 billion colors vs RGBC 10 bit = $(2^{10})^4$ =**
  1.1 TRILLION COLORS
- **RGB 12 bit = $(2^{12})^3$= 68.7 trillion colors vs RGBC 12bit = $(2^{12})^4$ =**
  281.5 TRILLION COLORS
- **RGBCMY 12 bit = $(2^{12})^6$ =**
  4.7 SEXTILLION COLORS!

Modern color systems have 16-bit specifications that make these numbers even more dramatic!

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Has anyone ever made a multi-primary display?

Yes, multi-primary displays are not a new idea. Many have been built and demonstrated over the past 30 years. The summary accomplishment of these experiments has been to verify that multi-primary displays can show more and better color. The main reason these projects went no further than demonstrations is that the displays required an entirely new system of image acquisition, manipulation, and transport to deliver content to the display. In other words, the displays were not compatible with existing industry methods, standards, and equipment. The assumption was that multi-primary displays would require an overhaul of methods and infrastructure. The FCR system demonstrates that this assumption is false.

Sharp Corporation took a dramatically different approach to multi-primary displays and succeeded in mass production and distribution of Quattron™ displays with four primaries (RGB+Yellow), but ultimately, this attempt failed. The input to Quattron™ displays was standard Rec.709 RGB. There was no additional data for yellow, and the RGB input signal contained no color information outside of the RGB triangle. To take advantage of the yellow primary, Sharp processed the image to accentuate yellow and push it out of the RGB gamut. Creating more intense yellows like this was marginally successful, but in the end, more intense yellows by themselves were not enough to impress consumers.

Until now, the common assumption has been that the success of multi-primary displays would necessarily involve: A) new cameras and workflow for capturing more colors and/or (B) the need to make fake colors. In contrast, the FCR system provides methods and technology that maintain current acquisition methods to collect all of the image information, to format it into data paths in common use today, and to extract the correct image data for an accurate representation of the content maximized to the limits of any display.

How can colorists deal with multi-primary color space?

The same way they work with RGB now. Many colorists already use extended color spaces, such as *XYZ* or ACES or a camera RAW format. Colorists can continue to work as they do now, and then output the result as *Yxy*, or they can work in *Yxy* directly. Transcoding to/from *Yxy* is simple and fast.

How does the FCR System address the challenges of converting SDR to/from HDR?

With advancements in high dynamic range (HDR) imaging, including wider color gamuts (such as P3), conversions become even more complicated and often show dramatic differences when converted to standard dynamic range (SDR) or when SDR images are converted to HDR. Attempting to keep both hue and chroma consistent and acceptable is a major challenge. The FCR System allows for separation of the luminance and color coordinates, which provides for more consistent hue and chroma.

Will the industry accept a colorimetric approach?

A colorimetric approach is already in use. Digital Cinema uses an *XYZ* colorimetric image encoding method, which has proven to be an effective and practical method for processing and distribution of movies for theatrical exhibition. The Digital Cinema Initiative (DCI) published the first specifications for this system in 2005.

How does the FCR System work with archiving?

By encoding the image information as full human vision colorimetric data, the archived version is future-proofed. Capturing and storing all the colors today preserves the value of the content for future exploitation as displays improve.

How does the FCR System work?

Instead of using RGB (or YCbCr data), within the signal structure, the FCR System inserts a colorimetric set of image signals, *Yxy*, formatted with 3 components: *Y* containing the luminance of the pixel along with *x* and *y* representing the color coordinates. The *x* and *y* channels contain no luminance information and, therefore, may be subsampled (like YCbCr image formats, where the Cb and Cr components are subsampled using 4:2:2, 4:2:0). The *Yxy* data values are derived from linear light values in 16-bit float numbers. A non-linear function is applied to those 16-bit float values for data efficiency when transporting or storing as 12-, 10-, or 8-bit integer values (this should not be confused with the optical gamma used in conventional image coding). The major impact to the image processing workflows is the modification of the source output format and the receiving input. Ideally *XYZ* or *Yxy* is directly sourced from the camera (although existing camera RAW formats can also be used), and *XYZ* or *Yxy* is applied to the input of the display (which transforms this input data into the display color space). The infrastructure in-between does not require significant changes. Also, *Yxy* can be used within any Academy Color Encoding System (ACES) workflow.

Why not use *XYZ*?

The FCR System uses *Yxy*, which includes the luminance of the image in "Y," whereas *XYZ* has luminance in all three channels. Separating luminance from chrominance allows for "subsampling," which is widely used in broadcasting and streaming. Therefore, *Yxy* processing can be done for a variety of conditions (e.g., 4:4:4:4, 4:4:4, 4:2:2, 4:2:0, 3:1:1, etc.). This reduces latency along with the complexity of image processing and manipulation. Furthermore, because *Yxy* is like YCbCr, the images can be efficiently compressed using current video and image compression tools (e.g., JPEG2k, MPEG-4, JPEG).

Digital cinema uses *XYZ* for theatrical exhibition, which is a very high bandwidth application. FCR can also use *XYZ* when appropriate but doing so precludes applications requiring high levels of compression. *Yxy* is more generally applicable.

What about scene-referred vs. device-referred color processing, does the FCR System support one or the other or both?

The FCR System supports both scene-referred, and device-referred color processing. Scene-referred is generally the preferred approach for color grading. When doing scene-referred color grading, many colorists prefer to use a camera RAW format with the camera manufacturer's log function applied. It is also possible to grade in *XYZ*, *Yxy*, or ACES. Camera RAW, *XYZ*, *Yxy* and ACES AP0 can preserve all the colors captured by the camera. No matter which of these approaches is used in color grading, it is a simple conversion to output Yxy for transport and delivery to displays.

Display-referred color grading is constrained by the gamut limitations of the target display; that is, no out-of-gamut colors allowed. The FRC system does not preclude the display-referred color grading approach, since the result can be exported as *Yxy*, just as easily as in the scene-referred approach. However, the display-referred method does have the distinct disadvantage of not maintaining all of the original colors.

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Why does the FCR System apply a non-linear function to the *Yxy* data?

To preserve the linear light values, the FCR System employs a non-linear function to the *Yxy* data—we call this Data Rate Reduction (DRR)—which minimizes the error (i.e., maximizes the peak signal-to-noise ratio [PSNR]) of the encoded image. DRR is applied to the linear image data prior to signal transport or storage and can be reversed using the inverse to recover the linear image data. An additional benefit of DRR is that if the display uses a simple gamma function, the conversion from *Yxy* to display image data—DRR and gamma—can be combined in one conversion step.

Ideally all color image processing should occur in linear light space. In order to process color imagery in linear space, a minimum of 16-bit (integer or float) numerical encoding is required in order to avoid severe truncation errors. Unfortunately, most electronic image transport and storage standards are based on 8/10/12 bit integer numbers, which do not provide enough code values to ensure that there are no image artifacts (e.g., contouring). This is dealt with in current image encoding for transport and storage by applying a power type function (i.e., gamma) or a more complex curve (e.g., PQ or HLG).

How does the FCR System solve problems associated with color processing and displays today?

Current electronic digital image coding standards are generally based on a three-color primary method (RGB) of encoding a literal image representation. (Digital Cinema Initiative (DCI), which uses *XYZ* encoding, is the notable exception.) Image data within any serial stream is typically an integer-based representation of each primary color with an optical gamma applied. The balance between the colors represents the white point. Depending on the intended display, conversions are required to deliver content for each unique image display format. These conversions are costly, complicated, and require considerable planning and oversight to ensure the creative intent is preserved. What does the FCR System approach do for the processing of color?

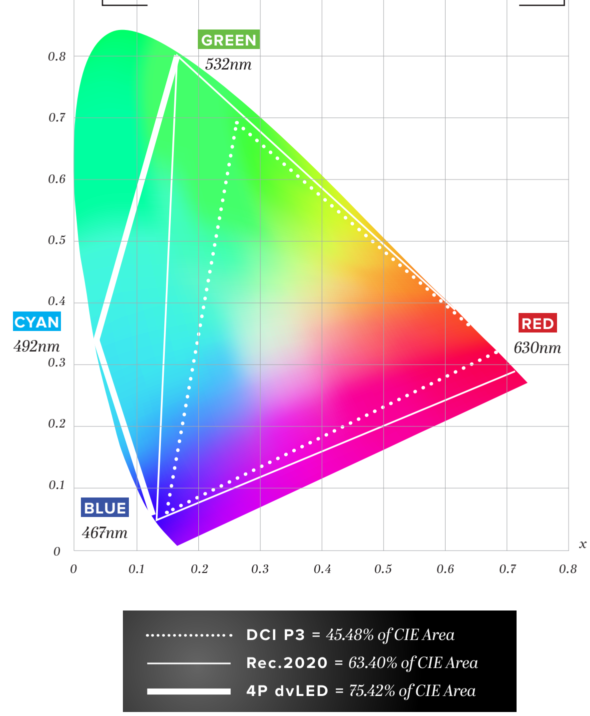
The *Yxy* approach used by the FCR System allows the source to conform the image to a colorimetric description of *x* and *y*—color is defined as a coordinate. Because *x* and *y* have no luminance information, color processing is simplified for streaming and display, as well as for production and post-production stages. Chromatic information expressed as *xy* is useful in production, post-production, and visual effects, and can be subsampled for distribution to streaming devices, laptops, tablets, or cell phones. The *Yxy* format enables simpler conversions to other image formats while preserving the full color gamut when authoring content (media conforming) and not restricted to any particular display color gamut that RGB formats adhere to. Any camera native color capture (i.e., full color spectral response) can be encoded to *Yxy*. All color manipulation in either *XYZ* or ACES, for example, can be transformed to or from *Yxy* using a simple matrix with negligible processing or overhead. The transport and storage of images in *Yxy* supports all visible color possibilities to be presented to the display and thus is only constrained by the display device itself.

How would you sum up the technical advantages of the FCR System?

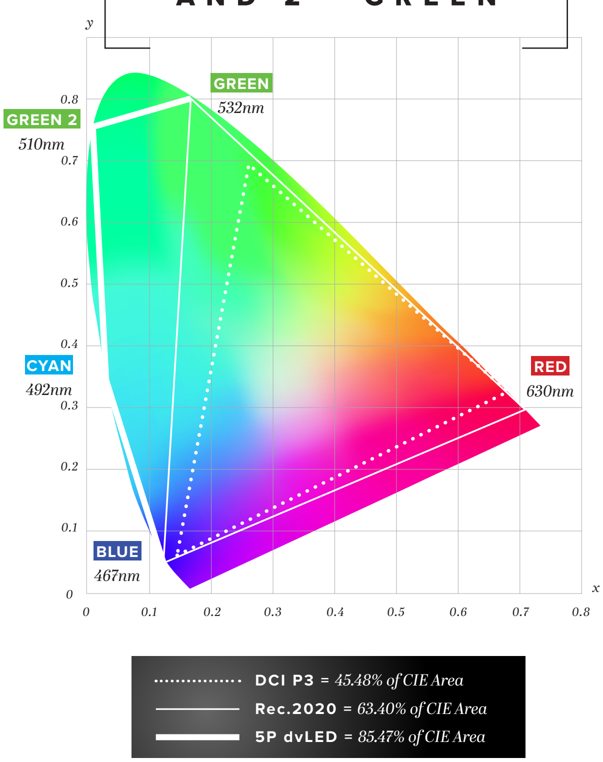
- All color possibilities are available to the display for movies, TV, recorded media, video games and streaming.
- Perceptual problems such as metameric error are minimized.
- FCR is independent of both camera colorimetry and display color gamut and primaries.
- Current digital image cameras may be used for wide color gamut acquisition with minimal or no processing modifications.
- Mastering of content is not constrained to display limits.
- There is no increase in data requirements. The bandwidth used for RGB is the same for *Yxy*.
- RGB to *Yxy* conversion uses simple, efficient techniques with low-process latency and overhead.
- Displays with different colorimetry will express the same color provided the color is within the gamut of the display. Out-of-gamut colors can be scaled to fit in the display gamut.
- Conversion between SDR and HDR is simplified.
- Archival content is future-proofed.

Can you give some examples of possible multi-primary systems?

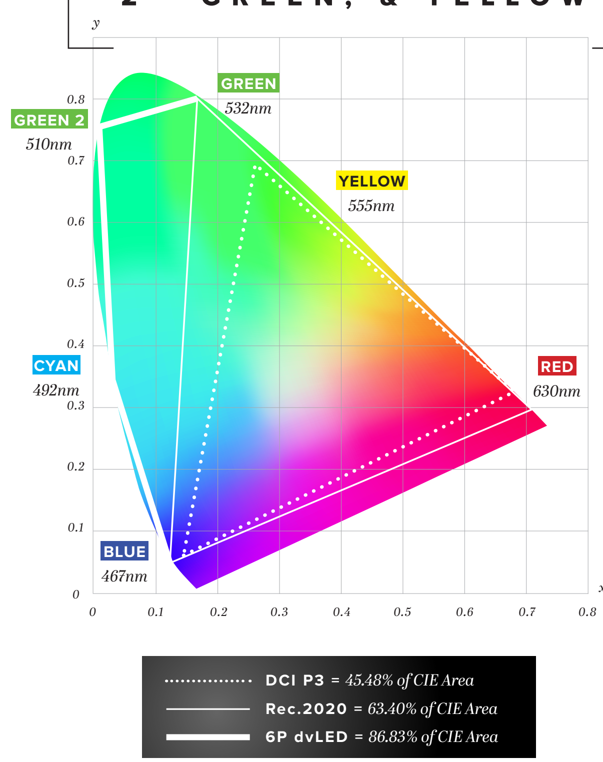
4 PRIMARIES
RGB PLUS CYAN



5 PRIMARIES
RGB PLUS CYAN AND 2ND GREEN



6 PRIMARIES
RGB PLUS CYAN, 2ND GREEN, & YELLOW



APPENDIX A
DATA RATE REDUCTION (DRR)

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EVALUATION OF DRR (TAU)
BIT DEPTH & RANGE IN F-STOPS

Bit Depth	f-stop	DRR (τ)	PSNR
12	14	0.8571	63.3
12	16	0.75	67.4
12	20	0.6	68.8
10	14	0.7143	53.8
10	16	0.625	51.5
10	20	0.5	51.5
8	14	0.5714	40
8	16	0.5	39.8
8	20	0.4	43.6

EVALUATION OF DRR (TAU) BY
BIT DEPTH VS 16 BIT FLOAT (EQUIVALENT TO 24 F-STOPS)

Bit Depth	DRR (τ)	PSNR
12	0.5	76
10	0.417	63.7
8	0.333	49.7

RECOMMENDED APPLICATION OF DRR
(EQUIVALENT TO 20 F-STOPS)

Bit Depth	f-stop	DRR (τ)	PSNR (test image)	PSNR (Image gradient)
12	20	0.6	68.8	80.3
10	20	0.5	51.5	73.6
8	20	0.4	43.6	56.2

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APPENDIX B

INTELLECTUAL PROPERTY

All Patent Office entries are titled either:

SYSTEM AND METHOD FOR A SIX-PRIMARY WIDE GAMUT COLOR SYSTEM, or

SYSTEM AND METHOD FOR A MULTI-PRIMARY WIDE GAMUT COLOR SYSTEM.

Additional patents may be pending in the United States or elsewhere.

PATENT OR PUBLICATION NUMBER	APPLICATION NUMBER
US10607527	16/659307
US10950160	16/831157
US10997896	16/853203
US10950161	16/860769
US10950162	16/887807
US11043157	17/009408
US11011098	17/060869
US11030934	17/060917
US11062638	17/060959
US11037480	17/076365
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