Conforming to SD, RGB, and Composite Colorimetry in High-Definition Serial Digital Video Systems

By Dave Guerrero

Conforming the color space of high-definition (HD) video is a challenge that requires an awareness of other digital and analog video formats into which the HD content may be distributed. The range of color space of any format also describes its color "gamut." Color space "errors" are a product of the conversion of video signals originally produced for one video format into another. Broadcasters and post-production facilities accept programming from a myriad of sources that may or may not meet "over-the-air" standards. In today's digital world, the only standard is that there is no standard; HD post-production and ATSC broadcast add many new standards and challenges to the marketplace.

In every step of the production process, not only must caution be taken to ensure that the distributed program material maintain the "look" that the producer created and paid for, but also the finished material cannot be rejected because of technical flaws. The awareness of image legalization is essential, especially when distributing video in formats down-converted from high-definition (HD). Legalization will not generally cause color shifts to the video; color correction will almost always result in a change to the image's color balance. Tools such as color correctors and legalizers are employed to convert digital video from one color space to another. This paper will discuss the reasons and demonstrate the methods required to legalize, color-correct, and process HD digital video in any subsequent format.

Color Characteristics

In nature, all colors may be described by their hue and saturation. One difference between a rose and a carnation is that the color of the rose is a deeper, purer red. The carnation is less saturated (depth of color), lighter in color, and not purely red. Capturing these colors into an electronic medium requires some interpretation.

Video Acquisition

A video camera must first capture the hue and saturation characteristics of an image, then translate it into an electronic signal representative of the original scene. The camera's image sensor is the first limitation of the scene as a video representation. The color spectrum of the raw RGB signal found at the image pick-up of a video camera is unlimited and contains 15 to 16 million color combinations. The translation from the natural scene to the electronic representation is the first in a series of processes that define the color space for a video signal format.

The many color combinations available are the product of three image receptors, each capable of detecting one of red, green, or blue hues from a scene. RGB are the primary colors, and yellow, magenta, and cyan are the secondary colors, each being a combination of at least two primary colors. White is the equal sum of all colors, while black is the absence of color.

For example, when an object of pure magenta is detected by the red and blue image sensors, both will have nearly equal output, while the green sensor has no output. Because of this interaction, electronically adjusting the amount of red in the camera's output to reduce the saturation of a pure rose will change the color of the rose; however, it will also directly alter objects in the scene colored magenta. Also, white and black objects (equal amounts of all colors) will also be affected by changing the value of red. Therefore, reducing red in an image will cause white and black objects to become slightly blue-green in hue.

Stated simply, color correction (color matching) is usually a compromise that begins as soon as an image is created electronically, and most colors are a product of varying amounts of the three primary colors. Making a change to correct one color problem usually results in a change to another seemingly unrelated hue.

Professional camera base stations usually provide RGB, YPbPr, SDI (HD or SD), and even composite analog outputs. Each of them may have an entirely different color space; the program producer will decide which format is used for acquisition (recording) while leaving the others unused.

"Professional camera base stations usually provide RGB, YPbPr, SDI (HD or SD), and even composite analog outputs. Each of them may have an entirely different color space; the program producer will decide which format is used for acquisition (recording) while leaving the others unused."

To derive native color space for any format, a color matrix is used, employing a mathematical relationship between the linear RGB produced by a camera or graphics generator and that of the native video. High-definition serial digital signals use International Specification Rec. ITU-R BT.709-4 to define the color matrix for luma and chroma samples. The HD color matrix differs from the analog (SMPTE 170M) and SD-SDI (Rec. ITU-R BT.601-5 or SMPTE 259M) matrices.

An additional step in the process of defining color space is the requirement that the output electronic signal must conform to interface standards in order to be transferred (routed), displayed, broadcast, and recorded. Therefore, the gamut of a video signal produced by a professional camera is also limited by the physical electronic interface that allows connectivity to the outside world to the camera's electronics. This is also considered an element of the acquisition format of the video signal.

Editing, Finishing, and Distribution

The acquired program is usually edited before broadcast. In a post-production facility, a telecine transfer may have been used to create the original video and it is usually edited or finished before distribution. Finishing may include adding graphics, animations, effects, audio sweetening, and so on. In any case, the acquired material is used to create a master for distribution. At this point, the engineer must be sure that the master conforms to the technical specifications of distribution format. Any program produced today may be broadcast or distributed in any one of a multitude of analog or digital formats.

It is at this critical step of the production process that caution must be taken to ensure that the distributed program material not only maintains the look that the producer created and paid for, but also that the finished material cannot be rejected because of technical flaws.

The awareness of image legalization is essential, especially when distributing in formats down-converted from HD. Legalization will not generally cause color shifts to the video; color correction will almost always result in a change to the image's color balance.

Why Legalization?

In the ITU-R BT.709-4 recommendation, luma is defined as:

Y' = .2126R' + .7152G' + .0722B'

For NTSC (SMPTE 170M) and SD-SDI (ITU-R BT.601-5 or SMPTE 259M), the luma matrix is defined as:

Y' = .299R' + .587G' + .114B'

Chroma samples can be derived algebraically from these equations as well.

From these equations we can see that the HD luma will contain a different mixture of color than the standard-definition equivalents; the result is a slightly different overall image colorimetry. This change was made to compensate HD video for the inevitable display on flat panel monitors instead of CRTs. Standard-definition video was designed to be viewed on monitors using CRT technology with phosphor dots splattered on the screen.

One function of a color matrix is to make monochrome video (luma only) appear black-and-white—void of any color—when displayed on a monitor. If HD video is simply down-converted and not color-compensated, the HD signal will appear on a CRT to have a higher green content and not purely monochromatic. This becomes problematic when viewing color as well. As the Cb and Cr components are added to the luma, the resulting display will not be of the correct hue.

As mentioned earlier, linear RGB allows for as many as 16 million colors. Accounting for system headroom (the limiting factor is the interface, the electrical output of the camera), linear RGB video is reduced to approximately 10 million colors. The native YCbCr system is capable of nearly 100 times this value; however, current technology of standard-definition production equipment cannot take advantage of its full range. RGB transcoded into YCbCr (nonlinear—limited to 700 mV—8 bits) and composite video, are capable of about 2.5 million colors. Color limiting is always necessary when down-converting from HD.

The design of any video processing equipment should not allow operators to adjust video levels beyond the protected sampling range of native digital video formats. With the introduction of digital video to the "pro-sumer" market, hardware designed for non-broadcast applications is finding its way into some broadcast facilities. It may be possible that some products produce invalid digital video data. If video sample values infringe on reserved values, the signal may become incompatible with recording, transmission, or switching medium and therefore technically useless. A legalizer can correct for improper data sample values by reinserting the reserved timing data.

"If video sample values infringe on reserved values, the signal may become incompatible with recording, transmission, or switching medium and therefore technically useless. A legalizer can correct for improper data sample values by reinserting the reserved timing data."

Applying Legalization to an Image

Care must be taken when applying legalization to an HD signal. Legalizing a digital signal is similar though not exactly the same as clipping an analog signal. The analog equivalent of a legalizer is essentially a reverse biased diode in a signal path that allows a normal signal to pass unaffected. When the amplitude of the video signal exceeds the reverse bias of the diode, it conducts and clips the signal at that point—no ifs, ands or buts! Some designs added hysteresis for "soft clipping;" however, amplitude clipping is clipping, no matter what terminology describes it.

High-definition legalization is somewhat different. The legalizer looks at data sample values from the input video data. The legalizer also has a LUT (look-up table) that reflects user settings for limiting. These settings define substitution in a logical scheme. If the input

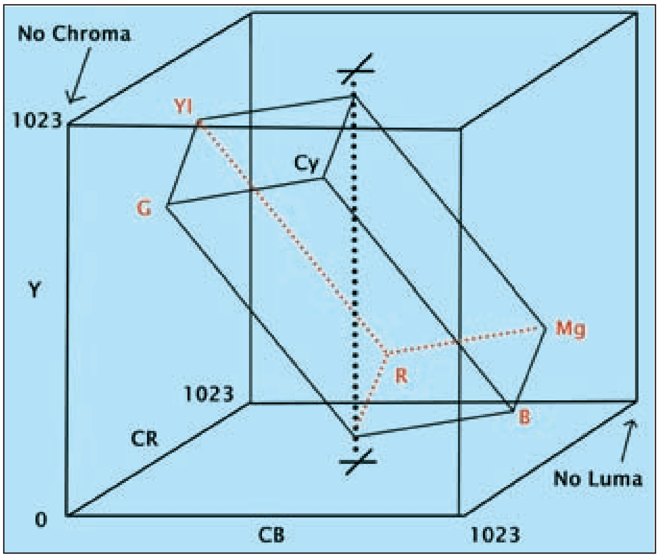

Figure 1. RGB vs. SDI color space—nonlinear RGB transcoded to 700 mV limits (8 bits, 255 samples) approximately 4.0 million colors.

value is 1000, then output 1000, if the user input is 1010 or 1011, then output 1010, if the user input is 1012, also output 1010, and so on. The LUT is used to resolve the output values of the data samples. It defines the output values for any specific input value. As video data passes through the legalizer, it is analyzed. When values exceeding the user setting threshold are detected, a new data value is substituted per the LUT.

Conforming RGB

Conforming HD to nonlinear RGB or composite video is complex. The color space of these formats is much smaller than that of HD, and precise adjustment of the HD video is required to ensure that the output HD video signal meets industry specifications. The transcoded RGB color space is usually defined as all RGB colors that can be produced in 8 bits, 0 to 700 mV.

Figure 1 demonstrates that the color space of RGB transcoded to YCbCr is a subset of the native SDI format. Because of its limitation of 700 mV per color component (effectively 8-bit chroma resolution), RGB gamut is limited to approximately 2.5 million colors.

Limiting HD video to RGB specifications requires the application of an algorithm that reduces the minimum and maximum sample levels to a range of 0 to 700 mV. The HD active video sample range is 1,019 samples, which equates to 746.1 mV of video. The conversion of the HD YCbCr component into RGB is the simplest form of legalization.

In this form of legalization, the algorithm transcodes sample numeric values of one format to another (HD native YCbCr to nonlinear RGB). Any value seen above the equivalent of 700 mV is set to 700 mV; any value seen under 0 mV is set to 0 mV. In peak component limiting, limiting an individual color component may affect other colors. For example, if the amount of blue is reduced, other colors may be affected, such as magenta and cyan.

Conforming to Composite Color Space

The color space of composite video is representative of broadcast standards and specifications for the analog equipment passing or processing composite signals. Some operators clip luma at 100 ire (714 mV) and overall composite at 105 ire (749 mV), whereas others may elect to clip at 110 ire (785 mV). The composite color space as it relates to SDI is plotted in Fig. 2.

Figure 2 demonstrates that the color space of composite video is a subset of the native HD SDI format. Because of its broadcast limitations composite gamut is

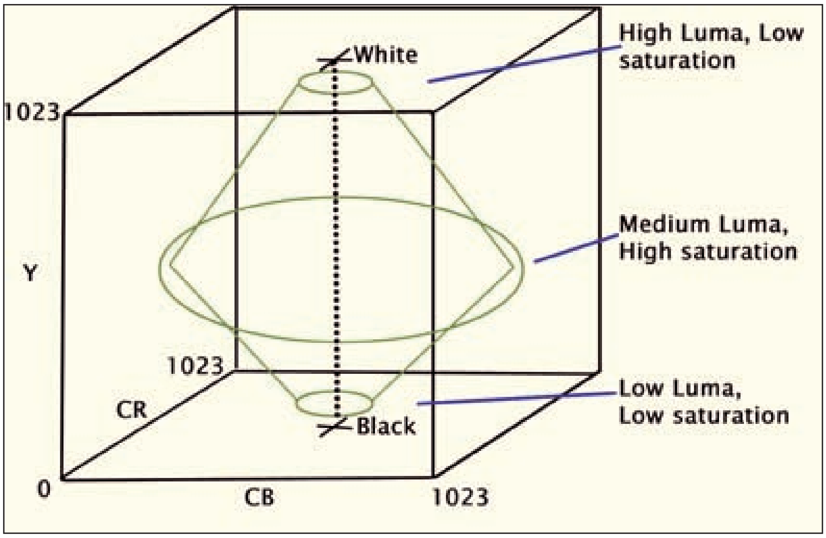

Figure 2. Composite vs. SDI color space—composite color space is a sub-set of SDI color space approximately 2.5 million colors. Not all colors are allowed equal saturation.

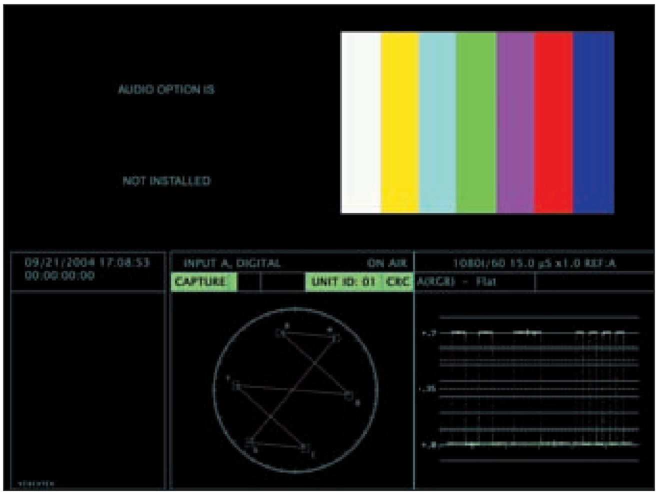

Figure 3. Test signal with normal saturation.

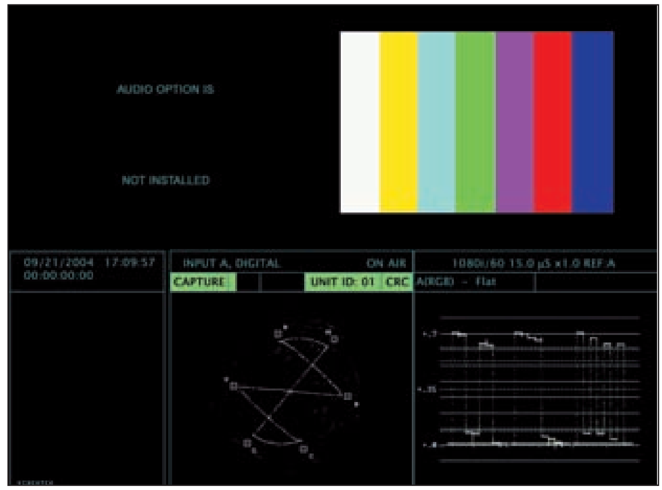

Figure 4. Test signal, vector limited.

limited to approximately 2.5 million colors. Notice that the limitations of composite video are a function of luma versus chroma saturation. The higher or lower the luma, the less allowable is chroma saturation. Colors with medium luma are allowed the highest color saturation.

Conforming HD video to composite (NTSC and PAL) standards becomes more complex because of the nature of composite video. In composite video, a matrix determines the proportion of each color component. All composite components contain some proportion of red, green, and blue (Y,I,Q or YUV).

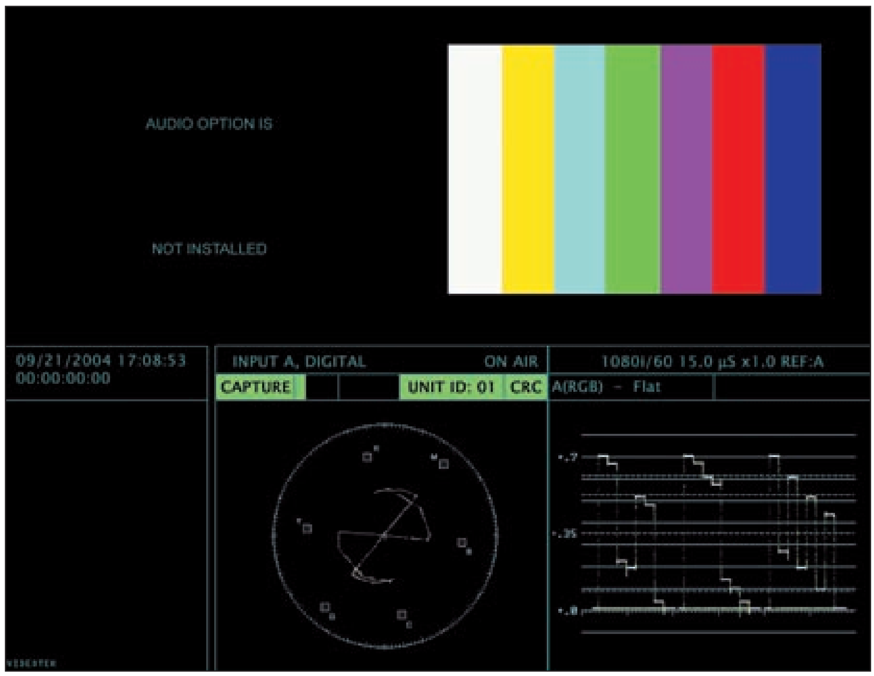

Figure 5. Test signal, vector limited—no degradation of hue.

Adjusting the overall peak excursion of the signal can modify a single color's saturation. If a color with a high luma value approaches the maximum value for peak limiting, the peak limiter will compress the luma and chroma, resulting in a lower saturation of the bright color. Vector limiting maintains the original hue of the image, while reducing overall chroma saturation. Peak limiting may desaturate an individual color, leaving all others with normal saturation.

Vector Limiting

Figure 3 shows a normal test signal. Figure 4 depicts approximately 7% vector limiting. Notice that all colors are reduced by the same amount. Vector limiting sets the maximum excursion of the chroma information to an outer diameter. Any color in excess of the maximum vector setting will be limited. With the application of vector limiting, as in Fig. 4, the operator can ensure that colors will not exceed a set maximum, and that their hue will not change.

Severe vector limiting, nearly 50%, is shown in Fig. 5; there is no noticeable degradation of the image hue. This sort of legalization, in realtime, is much more efficient than color correcting an image. Changing any

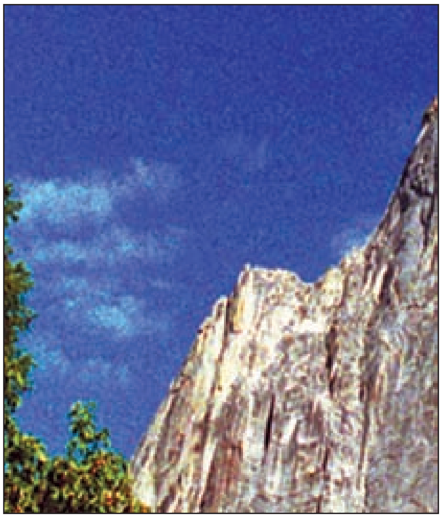

Figure 6 (a). Normal exposure.

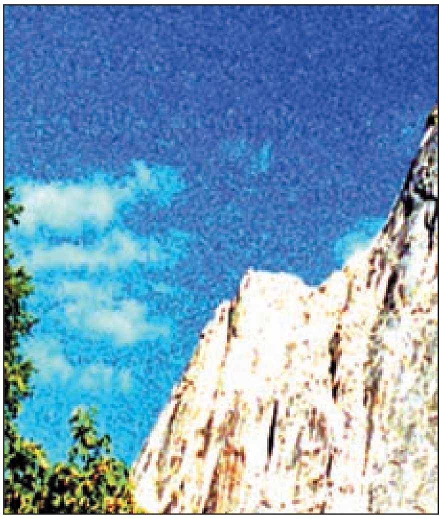

Figure 6 (b). 2x over-exposure.

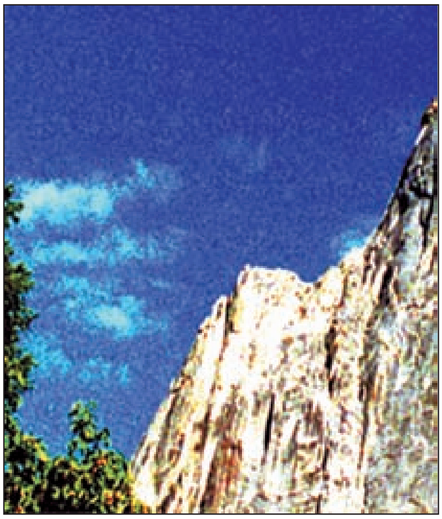

Figure 6 (c). Image legalized.

individual color component will change other vector limiting, ensuring that there is no change to images' color balance, while making it legal for broadcast.

Adding a knee (or softness) to the composite conformance allows the operator to make artistic decisions in low light or high light areas of the image. A hard clip will cause all voltages above a certain point to become the same. Therefore, when viewing the image, a bright area of the scene, such as billowy clouds, will become splotches of white in the sky; the image loses any high light latitude.

In Figs. 6 (a), (b), and (c), the sky and rock formation contain areas brighter than other portions of the picture. Figure 6 (a) is a normally exposed image. Figure 6 (b) is an overly exposed image with severe clipping. By adding softness to the clipping process, the image in 6 (b) can regain its highlight latitude, as in Fig. 6 (c), and still be broadcast legal.

Conclusion

It becomes quite obvious that legalizing HD video to another color space may severely limit the range of color latitude available. Conforming HD video using peak and vector limiting, and clip softness in place of hard clipping is invaluable, not just for the capability of repairing the HD video, but also to maintain the look of the unlegalized image created by the program producer. Legalization can be a "set-and-forget" tool, or a resource that the editor, colorist, or engineer uses to make subjective content decisions. A legalizer must provide the flexibility to select the optimum method of color limiting, based on the image content and distribution format.

Presented at the 146th SMPTE Technical Conference and Exhibition in Pasadena, CA, October 20-23, 2004.

THE AUTHOR

Dave Guerrero is vice-president and general manager of Videotek, a division of Leitch Technology Corp. Guerrero's long, diverse career includes extensive hands-on experience in live studio audio and video productions. Before joining Videotek in 2002, Guerrero held progressively responsible positions with various broadcast radio and television stations, culminating in the prestigious role of engineer in charge of network-level remote productions for all U.S. broadcast networks.

A highly respected authority in the area of television production, Guerrero has supervised the engineering for coverage of numerous high-profile events including the Macy's Thanksgiving Day Parade, the State of the Union Address, multiple Super Bowls, and the 1988, 1996, and 2002 Olympics. He is an active member of SMPTE, AES, SBE, and IEEE and has earned two Emmy Awards for his contributions in the area of engineering expertise.