# Analog Video 101 and 102 for All

**By Wayne McLachlan**

*Analog video is on the way out, so why study it at all? Many digital television standards evolved from analog video standards. To have a complete understanding of standards, it is necessary to understand why the choices were made to create standards for today's digital video. Why do we have interlace in the first place and why should it be considered in digital video; what problem did the color difference signal (R-Y and B-Y) solve, and why was it chosen for today's digital system? These and other concepts are briefly discussed in this paper.*

Scanning pictures is a method of time multiplexing over a single transmission path (coax cable or single television channel). By sending a varying voltage over a time interval, a single line of video is transmitted. Sending line after line of time-varying voltage makes up the picture. The horizontal sync pulse signals the end of the line, and the vertical sync pulse signals the end of the picture. Sync pulses are used to properly frame the receiver to the original picture being sent. This approach is straightforward, but orbits around bandwidth and picture flicker, causing a problem.

The phosphor on the picture tube has a carefully selected persistence. Persistence represents the length of time the phosphor will continue to emit light after the passing electron beam has exited. If persistence is too long, moving objects will experience a trailing smear; if too short, the picture will have a visible flicker, particularly if the scene is bright. Therefore, as the top half of the screen is being rescanned, the bottom half begins to fade, and as the bottom half is being refreshed, the top half begins to fade. This combination of persistence of the eye and that of the phosphor can cause a very noticeable flicker problem.

As a result, a picture rate of 30 frames/sec was chosen because it is at least as good as motion picture (24 frames/sec) and is also a multiple of the power frequency (60 Hz). (Europe's television system is at 25 frames/sec because the power line frequency is 50 Hz.)

Chemists and circuit design engineers tried to solve the flicker/smear problem and discovered that it was possible to get a unique value of phosphor so that 30 frames/sec (progressive scan) and 525 lines per frame could result in smear and flicker. It soon became obvious that working with phosphor does not fix the problem. Instead, it is necessary to increase the sweep rate (doubling it) so that the picture can be scanned in half the time and be refreshed before it starts to fade by any noticeable amount (avoiding flicker), when using a phosphor that is quick enough to avoid smear. Increasing from 30 frames/sec to 60 frames/sec causes another problem because doubling the line scanning rate also doubles the required bandwidth of the system. This is explained below.

## Frequency Rate of the Varying Analog Waveform

Doubling the scan rate doubles the frequency rate of the varying analog waveform. This is best illustrated in Fig. 1(a), which shows a scene of vertical lines, scanned by the system horizontally from left to right. (The lines of resolution of the scene will remain the same throughout this discussion. The number of lines per unit interval will remain constant but the scan rate will affect the required bandwidth needed to send the analog waveform representation of the line.)

Figure 1(b) shows the analog waveform of a portion of the line being scanned. In order to fill the picture with 525 lines and have it refreshed at 30 frames/sec, it is necessary to sweep it at a horizontal scan rate of 15,750 Hz or 63.5µ per line. To give the desired lines of resolution (about 350 lines per picture height, which gets 3/4 of the picture width—a topic outside of the context of this paper) a bandwidth of about 4 MHz is needed.

When scanning the same picture with 525 lines, but double the frame rate, at 60 frames/sec (to avoid the flicker/smear problem), it is also necessary to double the horizontal scan per line. Look again at Fig. 1. The waveform in Fig. 1(b) shows a certain cycle per second as it is being scanned. If the horizontal scan rate is doubled across the image the cycles per second of the waveform is also doubled, doubling the requirements of the frequency response of the delivery system. A bandwidth of 8 MHz is now needed for the baseband signal.

Greater bandwidth of the baseband signal gobbles up the number of television channels that are permitted on the air given the frequency allocations from the FCC. Therefore, this is not a very desirable solution to the flicker/smear problem either.

## Interlace to the Rescue—or the Stealth Flicker

Designers of modern television system are faced with a dilemma: Flicker is objectionable at 30 frames/sec, if the phosphor is quick enough to avoid smear. It is also not practical to double channel space by increasing the frame rate to 60 frames/sec. So what do you do? The solution is to hide the flicker.

The human visual system (HVS) is much more sensitive to flicker in large areas than in small ones. In fact, it will integrate small flicker areas (seen as motion) into an average value. When the vertical scan rate is doubled from 30 to 60, the picture tends to stretch

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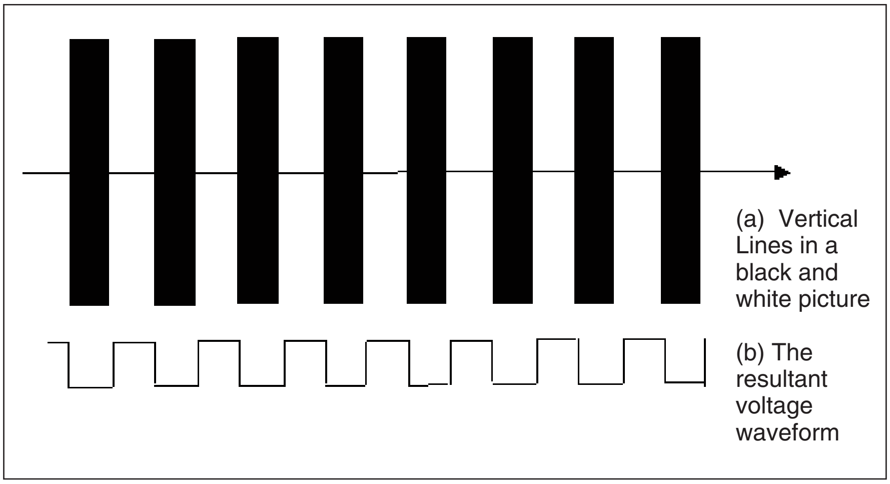


*Figure 1. The cycles per second of an analog waveform is directly proportional to the rate that the picture is scanned. (a) Vertical lines in a black-and-white picture. (b) The resultant voltage waveform.*

(vertically) leaving one-line gaps between the scan lines. This results in only 262.5 lines per picture (called field 1), although there is time to rescan the picture from top to bottom filling in between the lines (field 2). At the conclusion of the two quick scans, there are 525 lines total at 30 frames/sec.

The flicker is still present, but it is not visible (stealth). Every other line is fading away from the phosphor's persistence, not the picture halves, as in the progressive scan method. This technique is called interlace scanning, where the frame is divided into two fields and the lines of each are interlaced together as seen in Fig. 2. Interlace has become a very clever solution for solving the flicker problem without having to increase the frame rate to 60 frames/sec. It is also considered one of the first techniques for bandwidth conservation.

Interlace does have motion artifacts due to the fact that the fields differ in time by 1/30 of a second. Moving objects in one field will be located elsewhere in the other field. This tends to smooth the motion to a 60 frames/sec type of rate but at 1/2 the vertical resolution. The vertical edges of moving objects are feathered by the images of both fields. There are also vertical motion artifacts where scrolling texts tends to skip to every other line some of the time, then to the adjacent line at other times. Vertical scrolling does not appear as smooth with interlace as it does with progressive scanning. However, in spite of the motion problems caused by interlacing, it is a very clever method for reducing the bandwidth by half.

## Adding Color

Red, blue, and green are the only colors that most people see; all other colors are fabrications of the HVS. A very simple proof of this is as follows: White is the presence of all colors that can be seen. Therefore, if equal lumens of red, blue, and green light are taken and their projections are overlapped on a screen, white is seen. Additionally, if red, blue, and green filters are placed on the viewing surface of a white light source, such as that from an overhead projector, black is seen where these three filters overlap showing that removing the three color sources leaves nothing to see.

When looking at an object that has a wavelength of yellow light, the red- and green-sensitive cones in the eye are stimulated. This simultaneous stimulus of red and green is interpreted in the brain, not as reddish-green, but as a totally different color, yellow, which can be synthetically produced by playing a trick on the brain.

Red and green can be projected onto a screen at the same location. This simultaneously stimulates the red and green cones, causing the brain to interpret the response as yellow. Although the actual wavelength of yellow light is not there, it appears to be. To make orange, simply dim the green light source. A mixture of these three primary colors can produce all other colors that are seen in nature. For some people, particularly males who are color impaired, this trick does not work. For instance, color television is not very "natural" looking because the synthetic color system works on some assumptions of the HVS. These assumptions are based on average responses from several hundred individuals during an evaluation test.

CBS had a mechanical method of adding color: a wheel of transparent red, blue, and green filters would simultaneously rotate in front of a

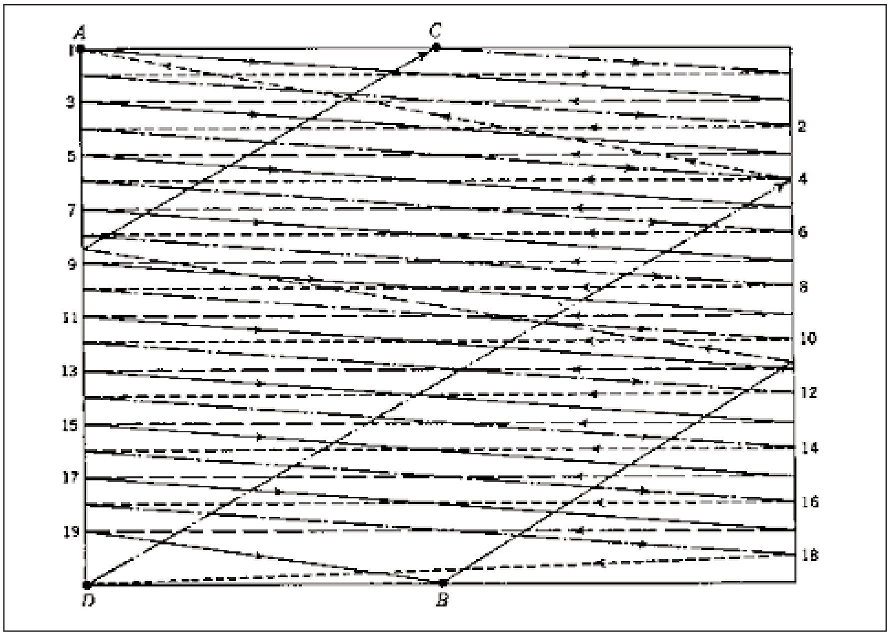


*Figure 2. Interlace scanning.*

camera (and in color sync) and a television receiver, where each field scan would produce one of the color components. The results were very good, and this was a very inexpensive method for adding color to the existing system. However, the transmitted picture intended for a color receiver was not compatible with a black-and-white television receiver, unless it was retrofitted with the color option. There was also a slight amount of color flicker. The worst offender was that moving objects tended to separate back into three colors. For example, if a white disk was moved onto a black background, the disk would be scanned as a red component in one field, green in the next field, and blue in the other. The disk would move in each field, showing three disks that would appear white only in the place where they all overlapped.

The CBS system was not fully in place by the time the war effort (WW2) led to the suspension of all developments. During this time, RCA flooded the market with millions of noncompatible (to the CBS color system) black-and-white television sets. After the war, CBS submitted to RCA's color method, which was compatible with existing black-and-white receivers.

RCA's color system was not complete until the mid 1950s and did not really catch on until ten years later. The reason was that television sets were very expensive, because of expensive cameras and the necessity for studios to replace most of their existing equipment. There was also the problem of color "timing" a studio, something that was new and foreign to engineers.

NBC (owned by RCA) was the only broadcaster sending color signals. CBS was not about to start using RCA's method, supporting its competitors, and ABC had no reason to adopt NBC's method either. As a result, NBC transmitted only two shows a week, *The Wonderful World of Color* (Disney show) followed by *Bonanza*, both in beautiful color but to a very small population of viewers.

This was a great system, but difficult to get going. There were not enough programs to get the public interested in paying for a television set that was equivalent to the purchase of a new car. Television station affiliates were also not willing to invest in equipment that would not provide increased revenue due to increase in market share. Most stations were simply going to "passthrough" the color feed from the networks.

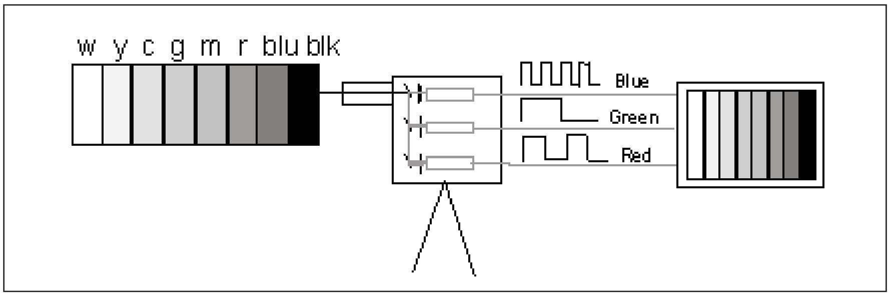


*Figure 3. RCA's simultaneous color system.*

To get started, RCA invested in the production of color television receivers at a loss, with thousands of unsold sets in warehouses and on showroom floors. NBC had to make investments in color studios with no increase in revenue until it gradually added more productions in color. Eventually market share for NBC began to grow, because more people started purchasing television sets. As a result, CBS and ABC conceded and added RCA's color system to their studios (circa mid-1960). Then color took off!

## Color Compatibility

This is familiar to today's entry into digital and high-definition television (HDTV). Digital is already in place with satellite due to the economics gained by compressing several channels into one channel space, and cable television is doing the same for simular reasons. Terrestrial broadcasting is required to make the change by 2002 because the government wants to sell half the existing channel space to mobile-land communications. However, HDTV is not a requirement; it is a downward-compatible enhancement to the existing digital system. But again, it is a major investment for both the viewer and the content provider. Stations will most likely transmit the HDTV signal from the network feed.

The public is much more interested in high-tech entertainment today than in the 1960s when color started becoming popular. In addition, the cost of an HDTV television receiver is only about 1/10 the cost of a car as opposed to the same price as a car purchased in the 60s. The transition to HDTV will be slow but should not be a ten-year process as the introduction to color was.

RCA's color system was a simultaneous system whereby the screen was split into its three color components (red, blue, and green) as the scene was being scanned by the camera. Figure 3 shows this process. To make the system compatible with the millions of existing black-and-white systems already delivered, the three color signals were mixed to form the black-and-white signal or the luminance portion of the signal. The luminance signal is referred to as y.

$y$ = luminance

A luminance signal (derived from the color signal) for black-and-white television receiver compatibility is sent. Inherent with the color system, there are red, blue, and green signals. That is, four signals to represent three colors. Mathematics tells us that you need only three equations to solve three unknowns, but this would suggest sending luminance and two colors. The third color is then derived at the television receiver by using the luminance value and the value of the other two colors.

Let us see how this might work. If green is not sent, can the television receiver extract green given the luminance, red, and blue values?

We start with $y = 0.59g + 0.30r + 0.11b$

Solving for green

$$0.59g = y - 0.30r - 0.11b$$
$$g = 1.69y - 0.51r - 0.19b$$

The television receiver will take about half of the red signals received, mixed with about 19% of the blue, add these values together and invert the result (the minus sign), then take 1.69 (a voltage gain) of the luminance signal, and mix that signal with the earlier resultant. Green is then solved.

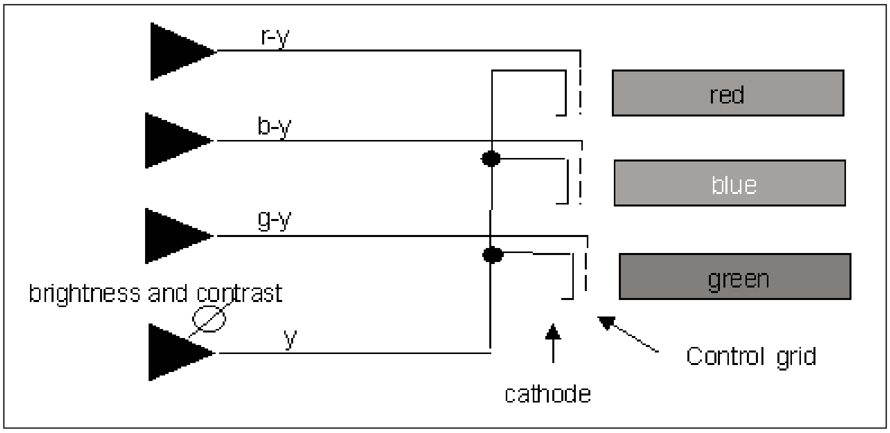


*Figure 4. Picture tube.*

Does it work? We should test this concept by sending yellow. Yellow is made up of red and green (no blue). We are sending only luminance, and red at the source, which requires the receiver to synthesize green.

Restating the luminance equation again,

$$y = 0.59g + 0.030r + 0.11b$$

Yellow is comprised of green and red with no blue, so replacing the symbols with the values yields

$$\begin{aligned} y &= 0.59(1) + .3(1) + 0.11(0) \\ y &= 0.59 + 0.3 \\ y &= 0.89 \end{aligned}$$

The television receiver receives a luminance signal that is 0.89 units of brightness and with a full red signal encoded with it (more later on how color is encoded onto a luminance signal). If everything works correctly, then the receiver should be able to take this information and synthesize green.

Substituting the values from the transmitter into the receiver's equation,

$$\begin{aligned} g &= 1.69y - 0.51r - 0.19b \\ g &= 1.69(0.89) - 0.51(1) - 0.19(0) \\ g &= 1.51 - 0.51 \\ g &= 1.0 \end{aligned}$$

The system will work for all colors and all levels of gray sent from a color television transmitter. Because *y* (luminance) is also being sent the systems will work with the millions of existing black-and-white systems (downwards compatible). But, suppose this new color television receiver receives a signal from one of the thousands of black-and-white television transmitters. Will this new color receiver be compatible with a signal being sent from any of the existing black and white television transmitters? The answer is no. None of the existing black-and-white transmitters have the circuitry to encode the red and blue color signals. They send just luminance. So all the receiver will receive is a luminance signal. Plugging the value of a full white luminance signal (*y*=1) into the equation of the receiver gives,

$$\begin{aligned} g &= 1.69y - 0.51r - 0.19b \\ g &= 1.69(1) - 0.51(0) - 0.19(0) \\ g &= 1.69 \end{aligned}$$

What we would want is for all three color guns to be the same value (white is equal amounts of red, blue, and green), but what we get is a very green picture. A normal black-and-white transmission would yield a high contrast green-and-white display on the color receiver. It would be similar to looking at a television picture on an oscilloscope.

## Color Difference Signal to the Rescue: (R-Y) and (B-Y)

As seen above, a color television receiver will work with a new color television transmitter, but fails to work with a signal from a black-and-white transmitter. Engineers attempted to resolve this matter and decided to have the color television receiver receive the black-and-white signal just as a black-and-white receiver would. The luminance signal was driven into all three color guns as shown in Fig. 4.

Now an unwanted term has been added to the color pictures, luminance (y). The eyes inherently see blue darker than yellow, the help of the y signal is not necessary to further enhance that attribute. So, how do we get rid of it when a color signal is transmitted?

To get rid of the luminance term (y) in a color receiver when a color signal is sent, a negative y term is placed in the color signal itself. Instead of sending just r, r-y is sent. Instead of just sending b, b-y is sent. Now when y is combined with r-y, the y terms vanish leaving just r, and when y is combined with b-y, only b is left, as shown below.

$$(r-y) + y = r$$

and

$$(b-y) + y = b$$

Now when a signal from a black-and-white facility is being transmitted, there will be no color terms, just luminance. If a black-and-white signal is sent from a color facility, there will be no color terms, just luminance. And if a color signal is being sent from a color facility, the black-and-white receiver will respond only to the luminance term (y) and the color receiver will remove the y term by combining it with the color-difference terms.

A new problem emerged with the color-difference signal. Mixing in the wrong amount of brightness (y) with the color-difference signal (color intensity) can disturb the saturation of the resultant signal. If there is too much brightness the colors will be pastel and with too little brightness the colors will look too intense. A control for adjusting the color is provided so that a reasonable picture can be obtained.

g-y is made by combining the following value of y, r-b, and b-y.

$$\begin{array}{r} y = 0.59g + 0.3r + 0.11b \\ \underline{-y = 0.59y + 0.3y + 0.11y} \end{array}$$

$$\begin{aligned} 0 &= 0.59\,(g-y) + 0.3\,(r-y) + 0.11\,(b-y) \\ -0.59\,(g-y) &= 0.3\,(r-y) + 0.11\,(b-y) \\ g-y &= \frac{-\,0.3\,(r-y) + 0.11\,(b-y)}{0.59} \\ g-y &= -[0.508\,(r-y) + 0.186\,(b-y)] \end{aligned}$$

The circuit for this equation is shown in Fig. 5.

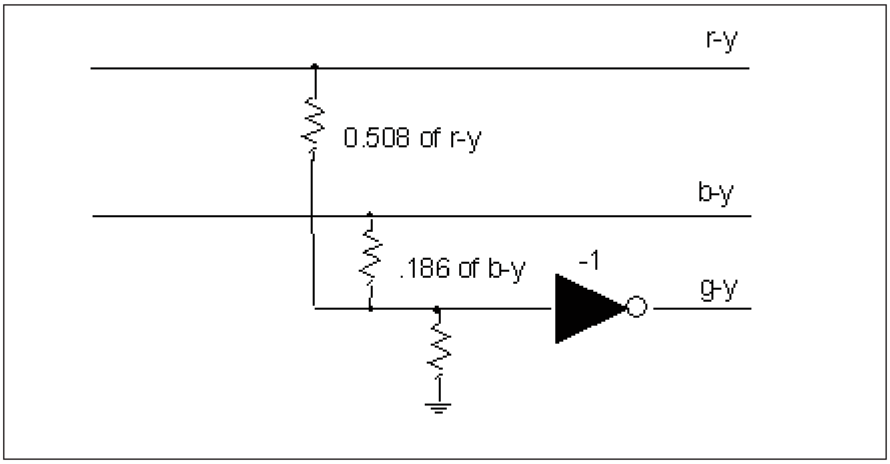


*Figure 5. Deriving g-y from r-y and b-y.*

Two types of component color have been developed, using red, green, and blue as the color signals. They are known as r,g,b component video. Four new terms, luminance y, the color difference signals r-y, b-y, and g-y have also been introduced.

The r-y and b-y terms are given new names v and u.

$v = (r-y)$

and

$u = (b-y)$

An example of the YUV equations at work in the receiver to decode yellow is shown below.

$y = 0.89$

$r-y = 0.11$

$b-y = -0.89$

$g-y = -[0.508\,(r-y) + 0.186\,(b-y)]$

$g-y = -[0.508\,(0.11) + 0.186\,(-0.89)]$

$= 0.11$

$(r-y) + y = 0.11 + 0.89 = 1.0$

$(b-y) + y = -0.89 + 0.89 = 0$

$(g-y) + y = 0.11 + 0.89 = 1.0$

## Color modulation—Encoded Subcarrier (Composite Color)

The topic on how the u and v signals are placed on the y signal is not part of this paper and is mentioned only to complete the discussion.

Composite color, also known as NTSC (in Japan and the U.S.), PAL (for much of the rest of the world), and SECAM for the remainder (France and Russia), has given way to digital broadcasting and is quickly becoming obsolete. In composite coloring, the u and v signals are fed to a pair of modulators, which are set 90° apart from each other, driven with a subcarrier frequency of 3.579545 MHz (Fig. 6).

The resultant signal is a phase- and amplitude-modulated sinewave. The phase (to a reference signal) will decode to a particular hue of the picture (the color itself) and the amplitude will give the intensity. Information containing the value for each of the r-y and b-y signals is encoded in the amplitude and phase of the carrier. When extracted and added to the y signal, the result is a full red, blue, and green signal, just as it started in the color camera.

Of course (as expected), even this new method caused problems: there was a beat between the sound carrier and the color carrier; the sound would modulate the color in the picture; the sound carrier could not be moved from its 4.5-MHz position above the picture carrier; and the relation of the color carrier is precisely set to exactly 1/2 of an odd multiple of the horizontal line rate to reduce chroma interference in the picture. The only practical solution to this was to adjust the horizontal frequency by a small amount so that the color subcarrier is an even multiple of both the line rate and sound carrier. If the horizontal (line) frequency is adjusted, the vertical (picture) frequency is also adjusted to preserve the 525 lines per picture relation. The new frequencies are shown in Table 1.

## Going Digital

The transition to digital started with videotape recorders. Recording in analog formats results in a rapid degradation of picture quality when making multiple passes needed for editing a production. However, when the signal is digitally sampled and converted to numbers, these numbers can be recorded repeatedly without degradation or error. As a result, other equipment such as routers, distribution amplifiers, and switchers have become capable of processing the digital tape formats directly without having to first convert the signals to analog. The prevailing digital tape format used to interconnect equipment is D-1 (digital component).

## Digital Component—Which One to Use

As discussed earlier, there are two types of component color. RGB (red, green, and blue) and YUV (luminance, b-y, r-y). RGB is used for computer graphics and YUV, for television video.

RGB is used as the component standard in high-resolution graphics systems. Red, green, and blue all need to be high resolution because the operator sits within 2 ft of the viewing

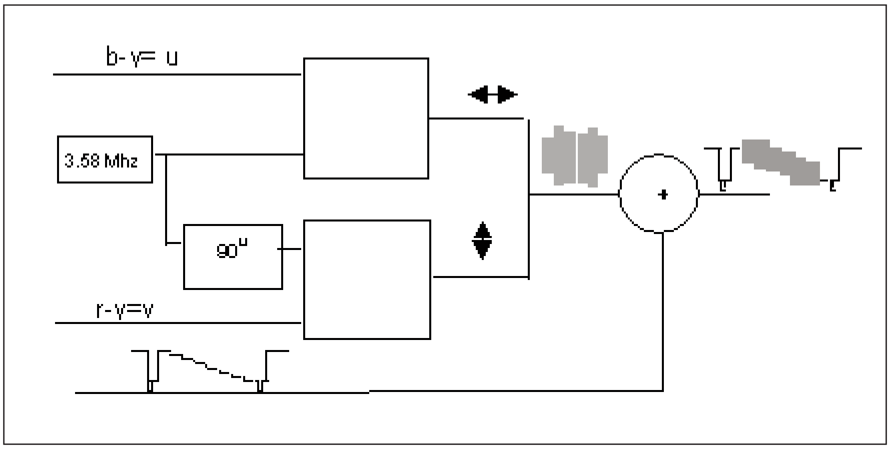


*Figure 6. Composite color.*

Table 1—Black and White Line and Field Rates and Color Rates

| | Black-and-White Standard | Color Standard |
|---|---|---|
| Horizontal (line) frequency | 15,750 Hz | 15,734.264 Hz<br>(15,750 ÷ 1.001) |
| Vertical (picture) frequency | 60 Hz | 59.94 Hz<br>(60 ÷ 1.001) |
| Color Subcarrier frequency | N/A | 3.579545 MHz |

screen. Fine lines in any color need to be clearly visible at close inspection.

NTSC and PAL color systems were designed with a little twist in mind. A viewer is not expected to sit within 2 ft of the screen because doing so blocks the view of others trying to watch a program. In addition, the viewer(s) must sit at six times the picture height from the screen for optimal viewing quality. This distance allows for the design of a system with some changes due to the HVS. Color resolution is not seen as clearly as luminance resolution. For example, finely spaced vertical lines of black and white may not be distinguishable as lines when moving the picture away from the viewer. The picture may also appear to have a gray background. However with color, if red and yellow vertical lines spaced the same as before, are moved away from the viewer, the individual lines might not be distinguishable at about a quarter to half the distance as with the black-and-white lines. The lines would blend into an orange background.

Therefore, taking into account that color is not seen with the same detail as luminance, and that the viewer is sitting some distance from the screen, color is sent with resolution reduced of that of luminance. This is indeed the case with NTSC and in PAL. Chroma bandwidth is reduced to about one-quarter that of the luminance bandwidth without any visual impairment.

This concept of reduced chroma bandwidth migrates into digital video as well. If r, g, and b are used as the color components, then full resolution would be needed on each to create full bandwidth luminance. However, if YUV is used, then U and V (the color terms) can be sent with less resolution while Y is sent with full resolution.

For digital, reduced resolution means reduced bandwidth, and reduced bandwidth means less data is being sent for the chroma as compared to the luminance. This is a form of compression (avoid sending irrelevant data).

## Component Digital Color Structure

YUV signal components are sent down the same data cable, one after the other in a time multiplex method (Fig. 7).

The first pixel in the line of video has Y, U, and V components to 8 or 10 bits of the U; color component is sent first, then Y, then V. On the next pixel, only the Y term is sent, excluding any color information. This is because changing color cannot be seen from the designed viewing distance (five times the picture height), so it is not sent. The third pixel has all the terms, the fourth is Y only, and so on. This structure is known as 4:2:2 where 4 represents full luminance resolution and the 2:2 represents half the resolution for U and V. The color terms are subsampled at half the rate.

A clock rate of 13.5 MHz is the standard for clocking the Y signal. The bandwidth for the U and V terms are half that of Y, which means half the data rate. As shown in Fig. 8, the clock rate for U and V are 6.75 MHz, respectively. The clock rate required to move YUV successively through the multiplexed path is 27 MHz and would be higher if the chroma was not subsampled at a lower data rate.

## Going to Serial Digital Data Streams

Sending 8 or 10 bits of data (in parallel) down a cable at a clock rate of 27 MHz has its problems. Among the greatest contributors is crosstalk in the cable between the signal carrying pairs of wires. Fifty meters is the practical maximum length of parallel cable before sparkles begin to appear in the picture; however, if the bits of data are

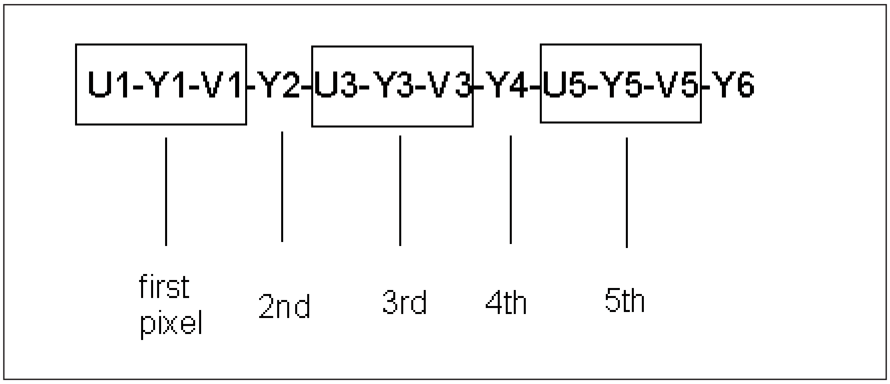


*Figure 7. YUV sent down the same wire with this structure.*

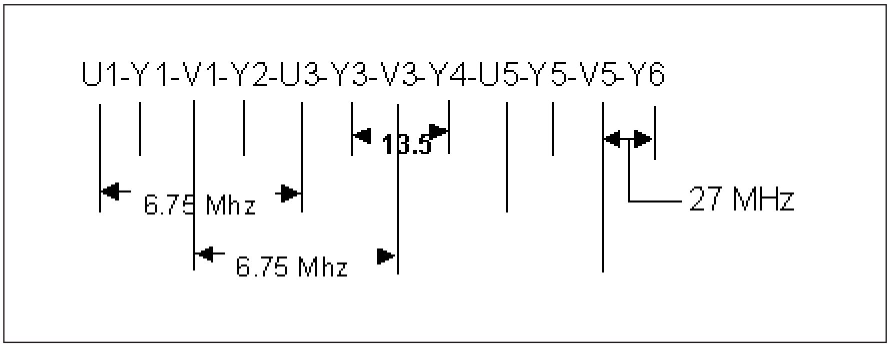


*Figure 8. Clock rates for the chroma, luminance, and data streams.*

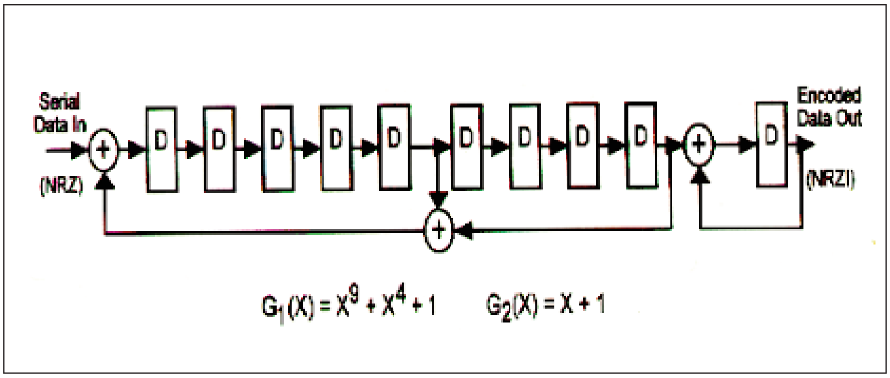


*Figure 9. Serial data scrambler.*

sent one at a time down a single wire, there is no chance that they will interfere with each other. In order to assemble the bits back into a 10-bit word, the data rate needs to increase by ten (270 MHz). This technique allows the cable length to extend several hundred meters. By placing the serial data stream as a payload on other types of data carriers such as ATM the length is unlimited.

Again, this new technique has its faults. In the parallel cable, a clock signal was also sent that would signal when the data was valid to the equipment at the receiving end of the cable. There is no clock in the serial cable, therefore the receiving equipment needs to fabricate a clock by guessing where it should be, based on the placement of the data bits. This is done with stable phase lock loop (PLL) oscillators acting as clock generators. The edges of the incoming data keep the PLL in phase.

The stability of the PLL oscillators, at the receiving end of the cable, depends on the number of transitional edges of the incoming data stream. Some video signals (such as certain matte values) may not have enough edges to keep the PLL in proper phase. To improve this situation, the signal is scrambled, not to hide or disguise the data, but to statistically increase the number of edges. Of course, the scrambling is completely reversible (Fig. 9).

## Data Compression

To reduce the cost of storing and transporting, video data is compressed. Compression has two purposes: it removes redundancy and irrelevance. Removing redundancy is most often a completely reversible process, but this form of compression alone gives only about a 2:1 reduction in data. The removal of irrelevant data, (things in the picture that if removed, one would not notice or care about) is not reversible without introducing some error. It is based on the HVS system. Compression ratios of 20:1 are obtainable with excellent results. Further compression is obtainable, but compression artifacts begin to get obvious.

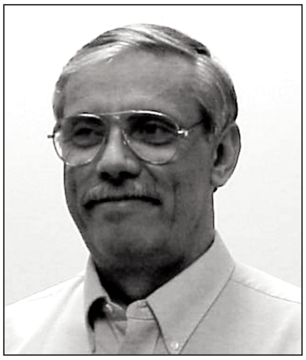
## Conclusion

Several choices were made when putting together the original analog and the NTSC color systems, which carried over as practical solutions to our current digital systems of today. We are fortunate that these decisions were based on good sound principles involving studies in the human visual system (HVS), else we would have had much more to do with regards to specifying and designing today's digital systems.

For the most part, the conversion from the analog picture to the digital picture is a rather straightforward process of filtering, sampling, and filtering again. The field rates, line rates, resolution, interlace, and YUV color choices all prevailed throughout this conversion. There are, however, significant changes to those regions out side of the active picture area (vertical and horizontal blanking), but the choices of the picture itself are still practical and used.

## THE AUTHOR

**Wayne McLachlan** has been with Grass Valley Group (Tektronix) in a number of different capacities for the past 25 1/2 years. He is co-author of "Applied Electronic Instrumentation and Measurement" and has authored several application booklets on video testing methods, including "Comprehensive Video Test Methods," a guide used by Grass Valley Group and Tektronix for 20 years. He is an active member of SMPTE and is Past Chairman of the Sacramento Section.



McLachlan has taught a two-seminar course in advanced communications technology at Yuba College with emphasis on video broadcasting. Since 1980, he has taught Introduction to Broadcast Video—Principles and Measurment, a very popular course from which he has compiled a 12-volume videotape series. He is currently teaching a short course series in Digital Video Compression, at UCLA.