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LIMITING OF *YUV* DIGITAL VIDEO SIGNALS

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Summary

The Report discusses methods of limiting excessive YUV component video signals so that the corresponding RGB components lie within specified limits. In the proposed methods, YUV limits derived from the RGB limits are applied directly to YUV component signals without any intermediate conversion of the signals into RGB form. Tests have shown that a very satisfactory basis for YUV limitation is to arrange that both hue and luminance remain unaltered by the process. Software techniques for processing stored video data and hardware techniques for processing real-time video signals are both described.

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Section Page

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LIMITING OF *YUV* DIGITAL VIDEO SIGNALS

V.G. Devereux, M.A.

1. INTRODUCTION

During development work on television processing equipment handling digital *YUV* component video signals, a need has arisen for limiting these signals to eliminate combinations of *Y*, *U* and *V* which would give invalid *RGB* components. The term 'invalid' refers to *RGB* components lying outside specified *RGB* limits. The specification of suitable limits for *YUV* components is difficult because the range of valid magnitudes for one of these components is dependent on the current magnitudes of the other two components. For example, if the luminance (*Y*) component is at its maximum (white) or minimum (black) level, then any non-zero values of the colour-difference (*U* and *V*) components will give invalid values of *R*, *G* or *B*.

If the *YUV* component video signals are to be eventually converted into *RGB* components, it is possible to avoid the problems associated with the interdependence of components in *YUV* limiting by only applying limiting to the final *RGB* components. However, this solution can obviously give unsatisfactory results if an invalid *YUV* signal is combined with other *YUV* signals before the conversion to *RGB* components and would require an unnecessary conversion to *RGB* if the *YUV* components are to be converted into a composite video signal (e.g. a PAL colour video signal). Furthermore, the subjective appearance of pictures which have undergone *RGB* limiting can be less satisfactory than if the limiting has been applied in the *YUV* domain. The improved appearance of the type of *YUV* limiting described in this Report was found to be very desirable in the still-picture composition system known as 'Art File'[1]*. A comparison between *RGB* and *YUV* limiting is given in Section 6.

Typical processes in which invalid *YUV* components can be obtained are (a) electronic picture generation in which the *Y* component can be specified independently of the *U* and *V* components and (b) video mixing where the sum of the gains applied to the two video signals being mixed can be greater than unity.

The Report first gives a theoretical discussion of the nature of *YUV* limits derived from *RGB* limits, and it then goes on to describe practical techniques for applying these limits to *YUV* component video signals. Both software and hardware techniques are described; the software is applicable to computer processing of stored *YUV* data and the hardware is intended for real-time processing of digital *YUV* video signals and, in particular, signals encoded according to CCIR Recommendation 601.

* Art File is manufactured and marketed by Rank Cintel

2. CONVERSION OF *RGB* LIMITS TO *YUV* DOMAIN

For analogue video signals, the luminance and colour-difference signal magnitudes Y, $B - Y$ and $R - Y$ are related to R, G and B signals by the equations[2]:

$$Y = 0.299R + 0.587G + 0.114B \qquad (1)$$

$$B - Y = 0.886B - 0.587G - 0.299R \qquad (2)$$

$$R - Y = 0.701R - 0.587G - 0.114B \qquad (3)$$

where Eqns. 2 and 3 are derived from Eqn. 1.

By a common convention, the colour-difference signals given, $B - Y$ and $R - Y$, are often referred to as U and V signals respectively. This convention is used in this Report particularly where digital signals are concerned.

For normalised *RGB* signals whose minimum and maximum values are 0 and 1 respectively, it follows from Eqns. 1 to 3 that the minimum and maximum values of Y, $B - Y$ and $R - Y$ are given by:

$$0 \leqslant Y \leqslant 1 \qquad (4)$$

$$-0.886 \leqslant B - Y \leqslant 0.886 \qquad (5)$$

$$-0.701 \leqslant R - Y \leqslant 0.701 \qquad (6)$$

These maximum and minimum values will be used for relating digital *YUV* limiting values to analogue *RGB* limits. The following discussions concern digital rather than analogue *YUV* video signals because the proposed limiting method has so far only been applied to digital signals although analogue signals could be limited in a similar manner.

Note that analogue *RGB* signal magnitudes have been expressed in normalised units throughout this Report. In order to obtain *RGB* values expressed in volts for standard level *RGB* signals, the normalised values should be multiplied by 0.7. The use of normalised *RGB* values does not affect the digital *YUV* limits which are derived below.

When Y, U and V component signals are digitally encoded according to CCIR Rec. 601[3], the maximum and minimum 8-bit values of the Y component are defined as being 235 (white level) and 16 (black level) while those of the U and V signals are defined as being +112 and −112. Thus, since the maximum and minimum analogue values of $B - Y$ as given by Eqn. 5 are +0.886 and −0.886, it follows that 8-bit digital values of U (or $B - Y$) are given by multiplying the analogue $B - Y$ values given in Eqn. 2 by the factor 112/0.886. By applying similar reasoning to Y and V values, it can be seen that 8-bit values of Y, U and V are related to normalised RGB voltages by the expressions:

$$Y = 16 + 219 \times (0.299R + 0.587G + 0.114B) \quad (7)$$

$$U = 112 \times (0.886B - 0.587G - 0.299R) / 0.886 \quad (8)$$

$$V = 112 \times (0.701R - 0.587G - 0.114B) / 0.701 \quad (9)$$

The resulting YUV values for the colours in a 100% saturated colour bar signal are shown in Table 1.

Table 1

8-bit YUV quantum levels for 100% saturated colours

Colour	*R*	*G*	*B*	*Y*	*U*	*V*
White (w)	1	1	1	235.0	0	0
Yellow (y)	1	1	0	210.0	−112.0	18.2
Cyan (c)	0	1	1	169.5	37.8	−112.0
Green (g)	0	1	0	144.5	− 74.2	− 93.8
Magenta (m)	1	0	1	106.5	74.2	93.8
Red (r)	1	0	0	81.5	− 37.8	112.0
Blue (b)	0	0	1	41.0	112.0	− 18.2
Black (bk)	0	0	0	16.0	0	0

In three-dimensional (3-D) RGB space, the R, G and B values of the colours in Table 1 give the co-ordinates of the corners of a rectangular block as illustrated in Fig. 1. The six faces of this block are planes given by $R = 0$, $G = 0$, $B = 0$, $R = 1$, $G = 1$ and $B = 1$ and they enclose all the points in RGB space which have 'valid' combinations of R, G and B.

By transforming the RGB points on the surface of this block into YUV values, a block can be constructed in 3-D YUV space which encloses all YUV values corresponding to valid RGB values. This block will be referred to as the 'YUV valid-colour' block and its shape is illustrated in Fig. 2. Since the RGB to YUV transformation is a linear process, the corners of the YUV valid-colour block are, like the RGB block of Fig. 1, given by the co-ordinates of the colours in Table 1 and the surfaces are flat planes corresponding to $R = G = B = 0$ and $R = G = B = 1$. Further details of the shape of this YUV block can be conveniently illustrated by three, mutually perpendicular, views or projections obtained by viewing along the Y, U and V axes. These views are obtained by plotting U versus V, Y versus V and Y versus U as shown in Fig. 3. Further useful information is obtained from cross-sections of the YUV block at different constant values of Y as shown in Fig 4.

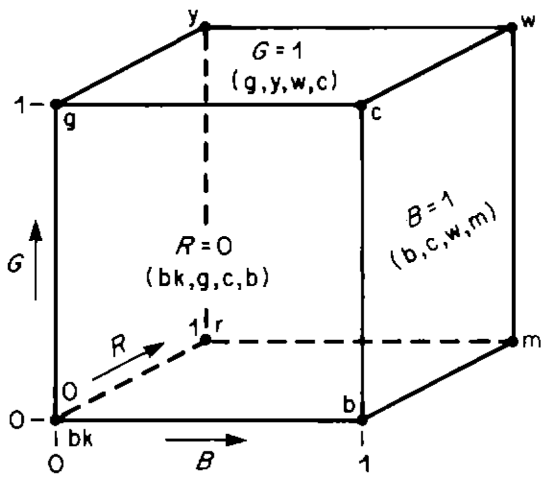


Fig. 1 - Limits of valid colours in 3-D RGB space.

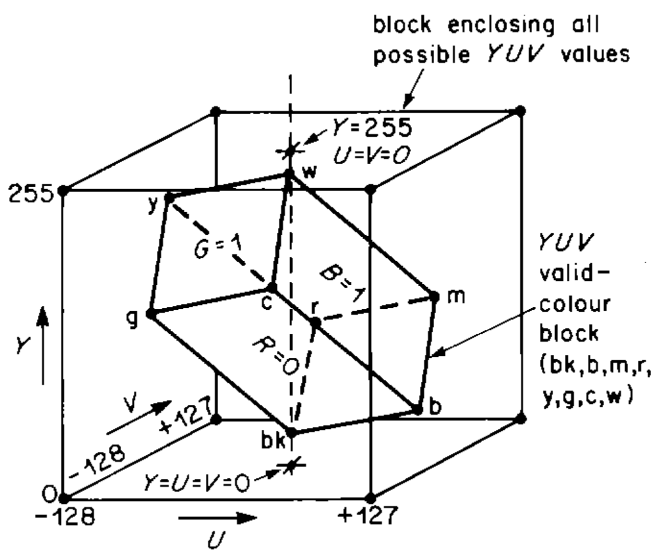


Fig. 2 - RGB limits transformed into 3-D YUV space.

It should be noted that the four saturated colours having $B = 0$ (black, red, green and yellow) and the four having $B = 1$ (blue, magenta, cyan and white) lie along straight lines in the $Y - U$ plane of Fig. 3(b). This means that the faces of the valid-colour block given by $B = 0$ and $B = 1$ are perpendicular to the $Y - U$ plane. Similarly, the faces given by $R = 0$ and $R = 1$ are perpendicular to the $Y - V$ plane. As a result the edges of the cross-sections of the valid-colour block as shown in Fig.4 are predominantly parallel to the U or V axes; the slanting edges occur where the cross-sections meet the $G = 0$ and $G = 1$ planes of the block. Note that all slanting edges have the same slope.

Other workers have also discussed these 3-D plots of *YUV* signals[4]; this work was concerned with displaying the information in *YUV* signals and did not consider *YUV* limiting.

3. PRINCIPLES OF PROPOSED *YUV* LIMITING TECHNIQUES

3.1 General

The limiting techniques described in this Section have the effect of moving any invalid combination of Y, U and V to a point on the surface of the *YUV* valid-colour block. The direction of movement defined in Section 3.2 gives very satisfactory visual results and, in the author's opinion, it is unlikely that a more suitable definition can be devised. The technique described in Section 3.3 is a possible alternative if simpler signal processing is required.

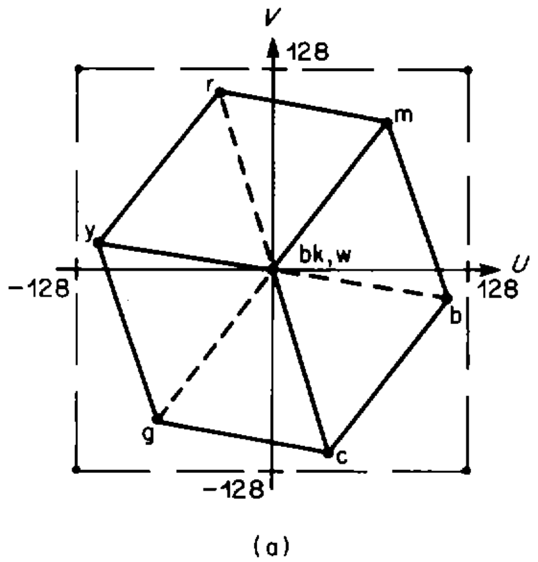
3.2 Constant hue and luminance technique

The direction of movement in YUV space caused by this limiting technique can be defined as the direction which maintains:

(a) constant hue; this corresponds to moving directly towards the origin in the $U - V$ plane of Fig.3(a).

(b) constant luminance; this corresponds to moving horizontally towards the Y axis in the $U - Y$ and $V - Y$ planes of Figs. 3(b) and 3(c).

Using these rules of constant hue and luminance, the video components *Y*out, *U*out and *V*out



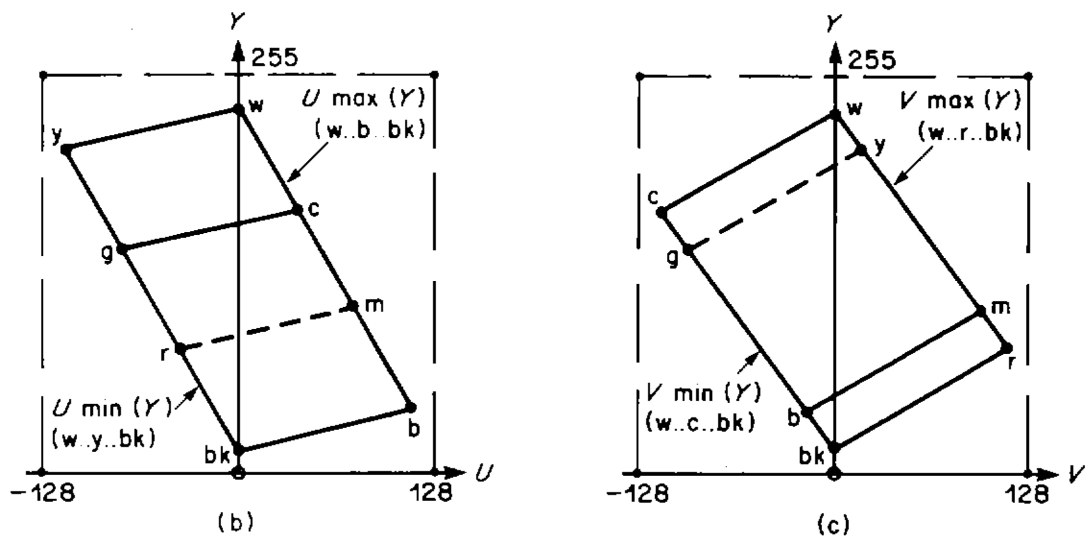


Fig. 3 - Three mutually perpendicular views of the YUV valid-colour block.
(a) Top view looking down Y axis
(b) Side view looking along V axis
(c) Side view looking along U axis

given out by the limiter are related to the input components Yin, Uin and Vin by:

$$Y\text{out} = Y\text{in} \tag{10}$$

$$U\text{out} = \text{K} \times U\text{in} \tag{11}$$

$$V\text{out} = \text{K} \times V\text{in} \tag{12}$$

where K $= 1$ for valid colours and $0 \leqslant \text{K} < 1$ for invalid colours. In the following discussions, K will be referred to as the 'UV limiting factor'.

To obtain the value of the UV limiting factor K for any combination of Y, U and V, mathematical details of the edges of the cross-section of the valid-colour block for the given Y are required. These details can be defined in terms of five parameters which are dependent on Y; in addition, a constant giving the slope of the slanting edges is required. These parameters are illustrated in Fig. 5 for a value of Y lying between that of 100% red and magenta and are defined as follows:

(a) Umax(Y) = maximum positive valid U for given Y

(b) Umin(Y) = maximum negative valid U for given Y

(c) Vmax(Y) = maximum positive valid V for given Y

(d) Vmin(Y) = maximum negative valid V for given Y

(e) Vo(Y) = value of V at the point where a slanting edge of a cross-section (caused by the $G = 0$ limit for $Y<128$ or $G = 1$ limit for $Y>128$), or an extension of this edge, crosses the V axis.

(f) Slope, dV/dU, of slanting edge $= -0.482$ for the definitions of digital YUV magnitudes given in Section 2.

From the above definitions, the equation of a slanting edge is:

$$V = -0.482U + \text{Vo(Y)} \tag{13}$$

The value of Vo(Y) for a given Y and the slope of the slanting edges can be calculated by setting $U = 0$ and $G = 0$ or $G = 1$ in the equations for Y, U and V given in Section 2 (see Appendix Eqn.40). Note that, as indicated in Fig. 4, the slanting edge given by the $G = 0$ limit encroaches on the rectangular limits given by Umax(Y), Umin(Y), Vmax(Y) and Vmin(Y) only if Y is less than that for 100% saturated magenta, Ymag. Thus the $G = 0$ limit need be considered only if $Y<Y$mag. Similarly, the $G = 1$ limit need be considered only if $Y>Y$cyan. However, the instrumentation of a limiter may be more convenient if the $G = 0$ and $G = 1$ limits are determined for the wider range of Y values given by $Y<128$ and $Y\geqslant128$ respectively.

For values of Y between black level ($Y = 16$) and white level ($Y = 235$), values of Umax(Y) and Umin(Y) can be derived from the $Y - U$ projection of the valid-colour block shown in Fig. 3(b). Similarly, Vmax(Y) and Vmin(Y) can be derived from the $Y - V$ projection shown in Fig.3(b). For all Y values below black level and above white level, the values of Umax(Y), Umin(Y), Vmax(Y), Vmin(Y) and Vo(Y) are all made equal to zero.

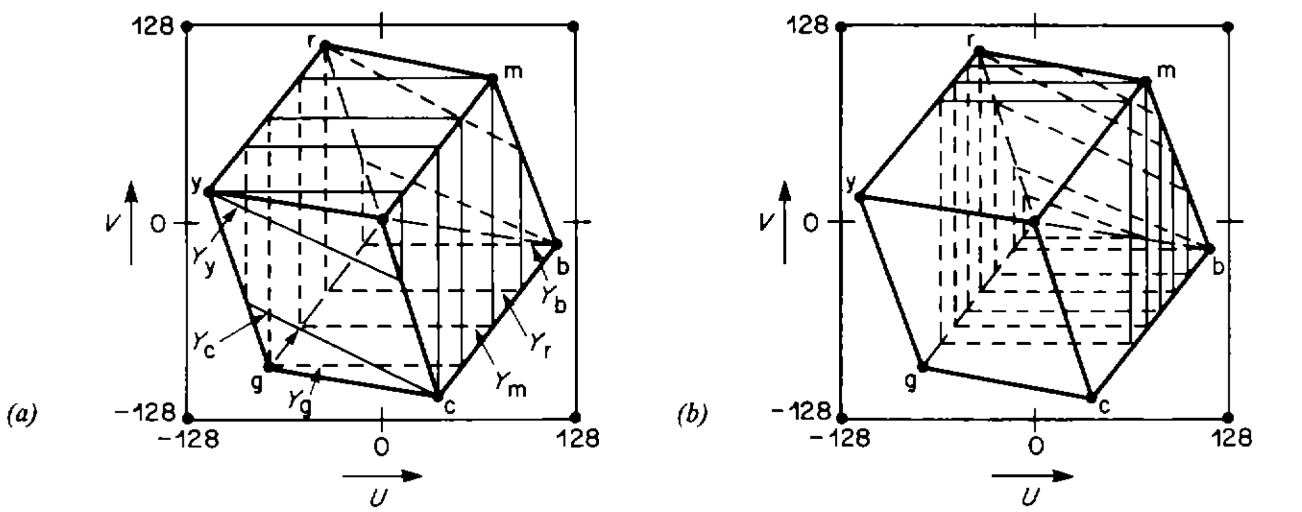


Fig. 4 - Cross-sections of YUV valid-colour block with Y constant for each cross-section.
(a) Y values given by colours in 100% colour bars (b) Further intermediate cross-sectiions for Y<128

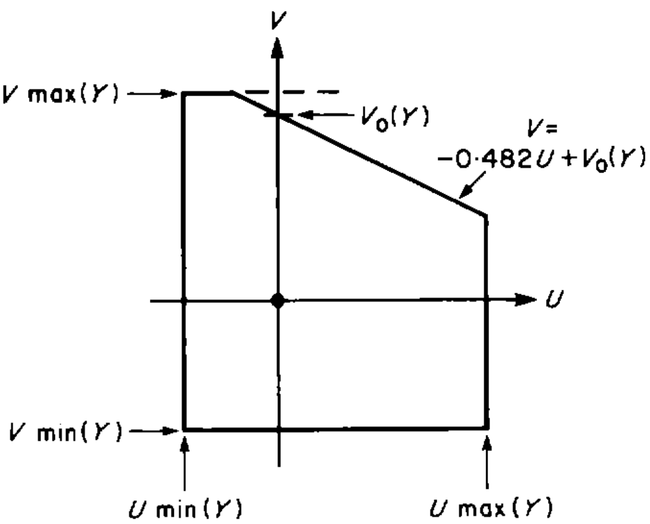


Fig. 5 - Diagram indicating paramters which define the edges of a constant-Y cross-section of the valid YUV block.

A procedure which employs these parameters for calculating the value of the UV limiting factor K may be explained as follows*. Suppose that the cross-section of the valid YUV block at Yin is as shown in Fig. 6 and that Uin and Vin correspond to point A in this figure. Points B, C and D correspond to three possible values of Uout and Vout, i.e. they are the points where the line joining point A to the origin O crosses the limits given by $U = U\text{max}(Y)$, $V = V\text{max}(Y)$ and $V = -0.482U + V\text{o}(Y)$. Point F is the intersection of the V-axis with a line passing through point A and drawn parallel to the slanting edge of the cross-section. As a result, $V = V\text{in} + 0.482U\text{in}$ at point F.

Remembering that K is the ratio Uout/Uin or Vout/Vin, it can be seen that points B, C and D correspond to three different values of K given by:

$$\text{Kb} = \text{OB/OA} = V\text{max}(Y)/V\text{in} \quad (14)$$

$$\text{Kc} = \text{OC/OA} = U\text{max}(Y)/U\text{in} \quad (15)$$

$$\text{Kd} = \text{OD/OA} = \text{OE/OF} = V\text{o}(Y)/(V\text{in} + 0.482U\text{in}) \quad (16)$$

For invalid colours, the required value of K is the lowest of these three values. Let this value be Kmin. If Kmin>1, point A must lie inside the valid cross-section and therefore no limiting is required; this is achieved by setting K = 1 if Kmin>1.

A method of handling all possible combinations of Y, U and V will be explained using the following psuedo computer program. It is assumed that the

* This procedure was devised by colleagues of the author, M. Weston and J.E. Easterbrook.

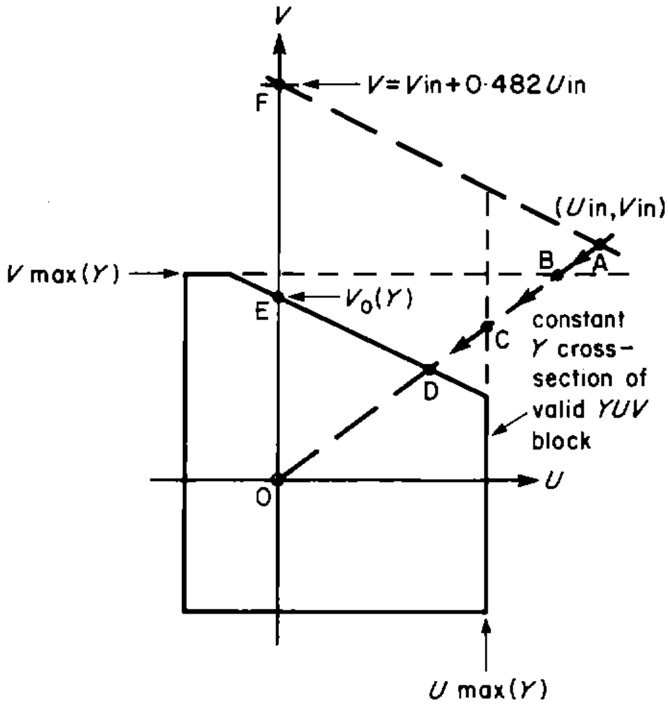


Fig. 6 - Diagram illustrating method of determining the limiting factor K for constant hue and luminance limiter.

values of Umax(Yin), Umin(Yin), Vmax(Yin), Vmin(Yin) and Vo(Yin) required by this programme would be calculated first and stored in look-up tables.

Psuedo computer program 1.

```
input Yin, Uin, Vin,

if Vin > Vmax(Yin)
      Kb = Vmax(Yin)/Vin
else if Vin < Vmin(Yin)
      Kb = Vmin(Yin)/Vin
else
      Kb = 1

if Uin > Umax(Yin)
      Kc = Umax(Yin)/Uin
else if Uin < Umin(Yin)
      Kc = Umin(Yin)/Uin
else
      Kc = 1

if Yin<128 AND (Vin + 0.482Uin) > Vo(Yin)
      Kd = Vo(Y)/(Vin+0.482Uin)
else if Yin ≥ 128 AND (Vin + 0.482Uin) < Vo(Yin)
      Kd = Vo(Y)/(Vin + 0.482Uin)
else
      Kd = 1

Kmin = lowest(Kb,Kc,Kd)

Uout = Kmin × Uin
Vout = Kmin × Vin
```

An alternative procedure is described in the Appendix. Its use would probably not significantly affect the complexity of practical hardware or software but it has been included because the explanation of how it was derived avoids the introduction of the parameters *U*max(*Y*), *U*min(*Y*) etc., and may be helpful to the reader.

3.3 Independent *U* and *V* limitation technique

A simpler method of ensuring valid *U* and *V* values is provided by a routine in which *U* and *V* are limited independently of one another in much the same way that *R*, *G* and *B* signals are normally individually limited. Like *RGB* limitation, this routine has the disadvantage of altering hue but does not change luminance. The technique is conveniently explained by the following psuedo computer program.

Psuedo computer program 2.

```
input Yin,Uin,Vin

Uout = Uin
Vout = Vin

if Uin > Umax(Yin)
      Uout = Umax(Yin)
if Uin < Umin(Yin)
      Uout = Umin(Yin)

if Vin > Vmax(Yin)
      Vout = Vmax(Yin)
else if Vin < Vmin(Yin)
      Vout = Vmin(Yin)

if Y < 128 AND Vout > Vo(Yin)−0.482Uout
      Vout = Vo(Yin)−0.482Uout
else if Yin ≥ 128 AND Vout < Vo(Yin)−0.482Uout
      Vout = Vo(Yin)−0.482Uout
```

The effect of the above routine is illustrated in Fig. 7. In this figure, the arrowed lines show the direction of movement of *UV* co-ordinates caused by the limiting process. Thus invalid *UV* values given by point A would be changed to valid values at point D via points B, where $U = U\text{max}(Y)$, and C where $V = V\text{max}(Y)$.

Note that, in this routine, only the *V* component has been altered when the $G = 0$ or $G = 1$ limits given by the slanting edges of the cross-section have been exceeded i.e. the line CD in Fig. 7 is parallel to the V-axis. Slightly improved results, at the expense of more complex processing, would be obtained if both *U* and *V* were altered when the $G = 0$ or $G = 1$ limits have been exceeded so that *UV* co-ordinates are moved in a direction perpendicular to the slanting edges, i.e. point D would be replaced by a point D′ such that CD′ was at right angles to the slanting edge. The extra processing would involve replacing both occurrences of the expression:

$$V\text{out} = V\text{o}(Y\text{in}) - 0.482U\text{out}$$

in the above program, by expressions of the form:

$$V\text{out} = \text{a}.V\text{o}(Y\text{in}) + \text{b}.U\text{out} + \text{c}.V\text{out}$$
$$U\text{out} = \text{d}.V\text{o}(Y\text{in}) + \text{e}.U\text{out} + \text{f}.V\text{out}$$

where a, b, c, d, e and f are constants depending on the slope of the slanting edge.

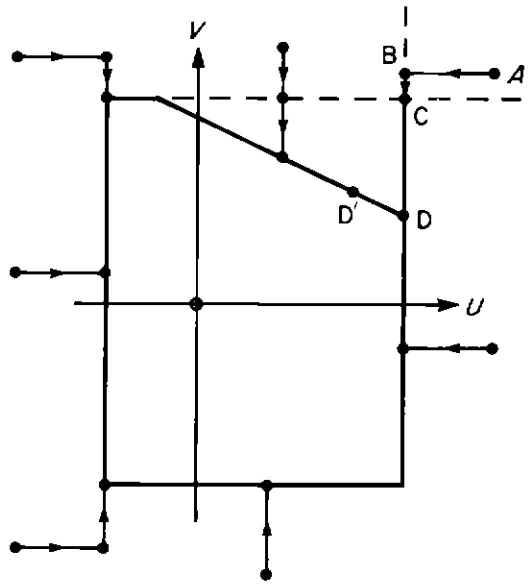


Fig. 7 - Diagram illustrating independent limiting of U and V.

4. SOFTWARE IMPLEMENTATION

4.1 Constant hue limiter

A software program similar to the psuedo program given in Section 3.2 has been tested in a computer-controlled still-picture composition system known as Art File[1]. This system stores pictures in *YUV* form digitally encoded according to CCIR Rec. 601. The microprocessor (type 6809) employed in this system operates at a clock rate of 2 MHz and contains a hardware multiplier giving fast generation of the products required by the program. The total time to apply the *YUV* limiting process to one complete picture varied between about 30 and 60 seconds depending on the amount of invalid colours in the picture, being fastest when no invalid colours were present. The processing was in general carried out to 8-bit accuracy except that intermediate values of K were calculated to 16-bit accuracy. At this accuracy, no quantising errors were noticeable in the final limited picture.

If necessary, faster results using the same computer could be achieved by means of a look-up table containing pre-calculated values of the limiting factor K for each possible combination of *Y*in, *U*in and *V*in. This technique has the disadvantages of requiring a very large look-up table and/or of giving coarsely quantised values of *U*out and *V*out. As an example, for 8-bit input *YUV* values, this table would have 17 million 24-bit *YUV* input addresses, giving a total storage requirement of 17 Mbytes for 8-bit values of K. Simulation tests showed that the quantising errors given by this processing accuracy are imperceptible but the size of table is too large to be acceptable. More realistically, the use of 6, 5 and 5 bits for *YUV* input addresses and 8 bits for K might give an acceptable compromise between storage capacity (65 Kbytes) and quantising errors; in tests using this coding accuracy, perceptible contouring effects were obtained in large plain areas of limited colours in critical test patterns but these errors were very difficult to detect on normal picture material.

It should be noted, however, that a limiter using a look-up table with only 13-bit input addresses derived from 5, 4 and 4 bits for *Y*, *U* and *V* has been found to provide a useful function in equipment now in use in the Television Service[5] despite its giving obvious quantising errors. The main purpose of this limiter is to prevent problems in recording the composite PAL output of the equipment when invalid signals are generated by the internal *YUV* processing circuitry. Its value in this respect is considered to be more important than the fact that picture areas subjected to limiting are coarsely quantised. This limiter was constructed in hardware using circuitry similar to that discussed in Section 5 but employed the same principles as the software look-up table techniques discussed above. Its circuitry was necessarily simple because it was added at a late stage in the development of the equipment when very little board space was available for its inclusion.

In the processes discussed above, the output *U* and *V* values would be obtained by multiplying 8-bit values of *U*in and *V*in by the K factor so that the only source of processing error would be that resulting from inaccuracies in the K factor. This K factor can easily be made precisely equal to unity in areas of valid colours thus avoiding processing errors in these areas.

A halving of the storage required for a look-up table could be achieved by making use of the fact that the *YUV* valid colour block is skew-symmetrical about the cross-section for mid-grey luminance, *Y*grey, where *Y*grey lies midway between the luminance levels for black and white. This means that the value of K for components (*Y*grey + X), *U*, *V* is the same as the value of K for (*Y*grey − X), −*U*, −*V* and therefore the K factor for any *YUV* combination with a luminance level above *Y*grey can be found from stored values with luminance levels below *Y*grey.

4.2 Independent *U* and *V* technique.

This technique was investigated using the Art File system and, while it gave quicker results than the constant hue technique and no perceptible quantising errors were introduced, it was found that quite noticeable hue errors were introduced on critical test pictures of the type illustrated in Figs. 11 and 12 which are discussed in Section 6.

5. HARDWARE

This Section discusses hardware instrumentation of the software described in Section 4. For any of the possible techniques, it is convenient to make extensive use of PROMs (Programmable Read Only Memories) to store parameters such as *U*max(*Y*) and to perform various processing operations. MOS PROMs are now available at a reasonable cost which have capacities up to 128K x 8 bits i.e. they can have 17-bit input addresses and give 8-bit outputs. Somewhat unfortunately, the access time of currently available large MOS PROMs, which is typically 150 to 250 ns, is slightly greater than the 148 ns sampling interval of the 6.75 Mhz clock specified for *U* and *V* signals in CCIR Rec. 601. This problem can be overcome by demultiplexing the *U* and *V* signals by a factor of two and by doubling the number of PROMs but results in increased circuit components. For storage capacities up to about 8K x 8 bits, bipolar PROMs with access times of only about 60 ns can be employed.

Diagrams indicating possible circuitry are shown in Figs. 8, 9 and 10. The number of bits shown for signal paths in these figures are suggested compromises for good performance without undue circuit complexity. For simplicity, no demultiplexing of *U* and *V* signals to allow for practical access times has been shown. It has also been assumed that, where necessary, the *Y* signals have been subsampled to the same rate as that of the *U* and *V* signals; alternatives to simple subsampling are discussed in Section 7.

Fig. 8 shows a method of determining the three possible K factors individually and selecting the lowest of these as in the psuedo computer program given in Section 3.2. A desirable feature of this circuit is that good quantising accuracy can be obtained without the need for excessively large ROMs. The main disadvantage is circuit complexity.

Fig. 9(a) shows a circuit arrangement based on a single, large look-up table. The main advantage of this circuit is its basic simplicity. The main disadvantage is the very large storage capacity required for good quantising accuracy. Improvements in quantising performance for a given size of PROM can be obtained using the additional circuitry shown in Fig. 9(b). The purpose of the inverters and switches shown in this figure is to take advantage of the skew-symmetry of the valid *YUV* block about mid-grey

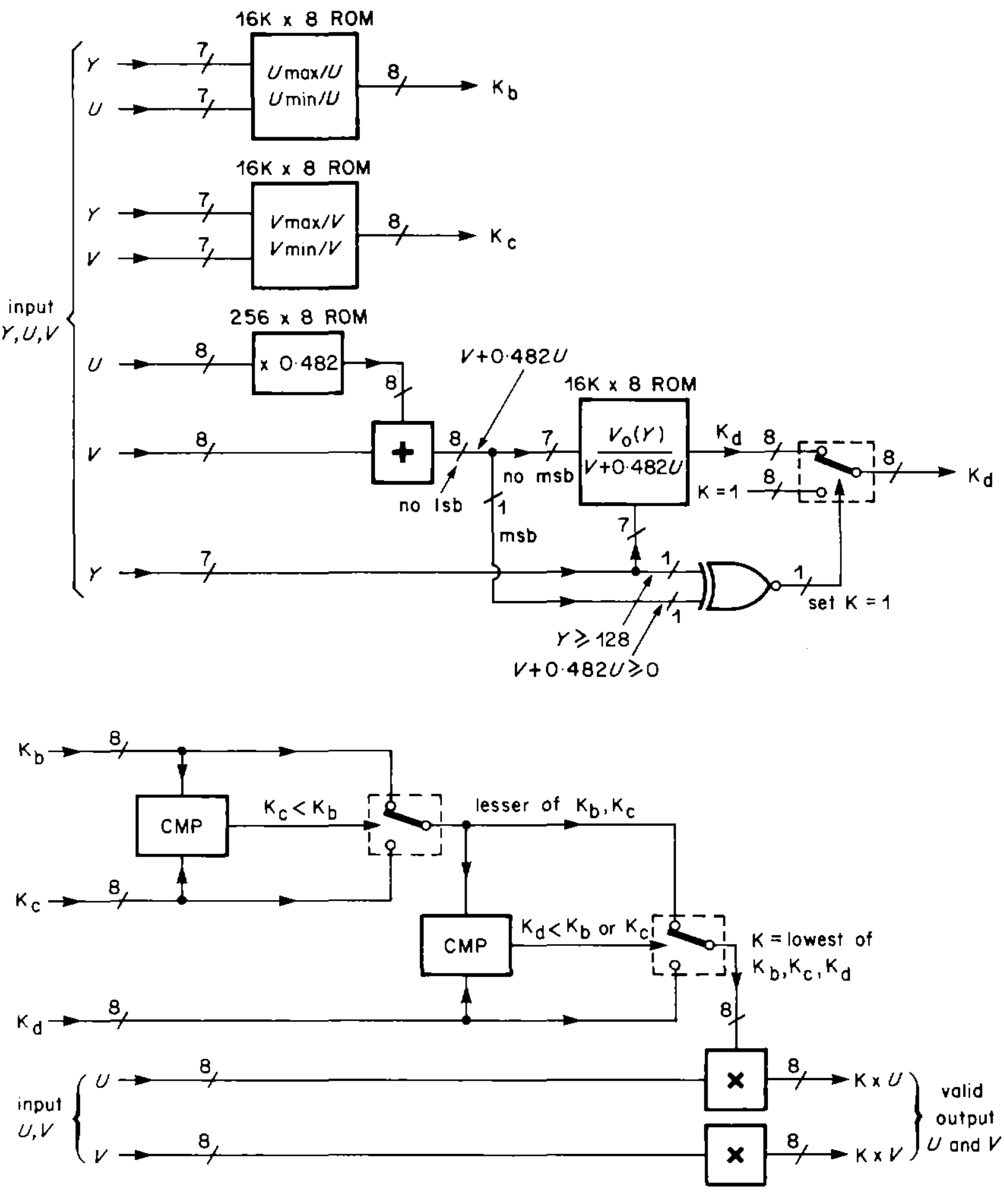
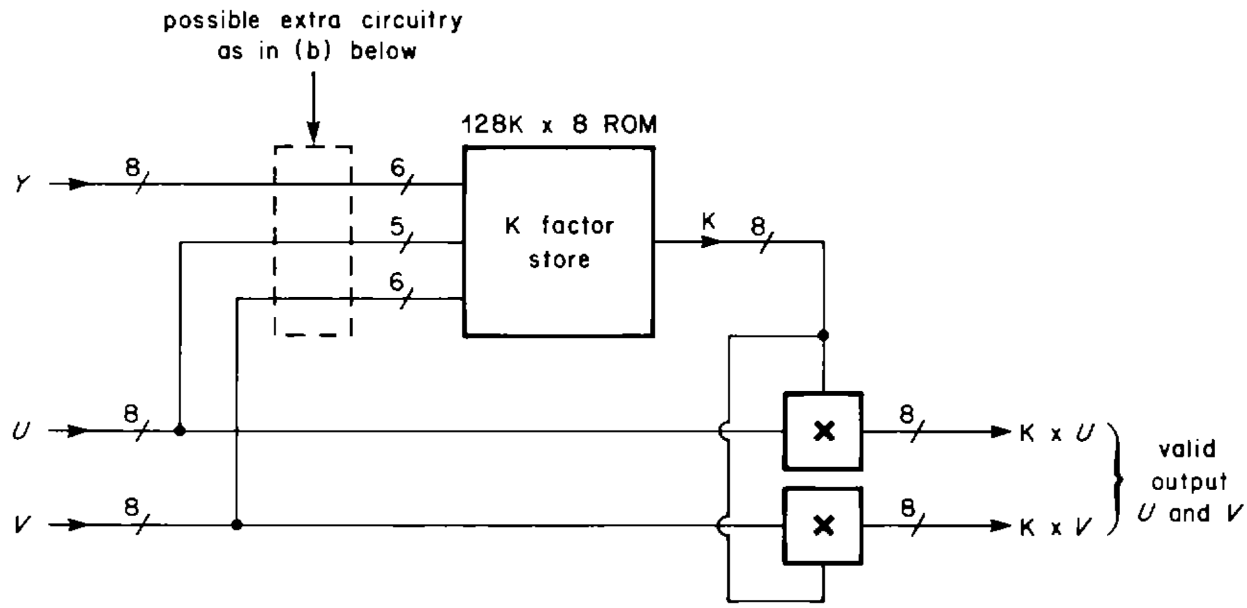


Fig. 8 - Constant hue limiter. Hardware implementation of pseudo computer program 1.

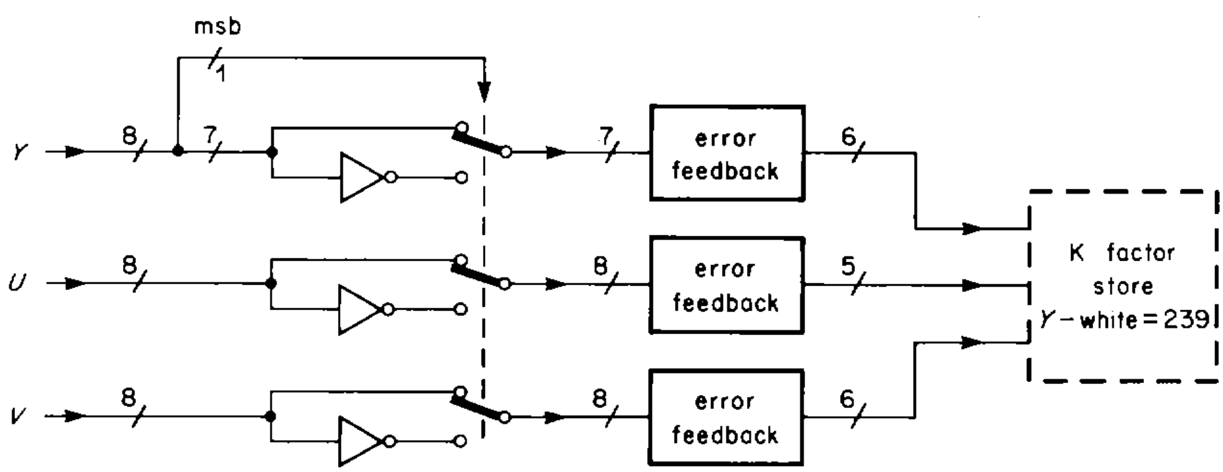
$\overset{n}{\text{—/—}}$ *indicates n bits in parallel* level, *Y*grey, as discussed in Section 4.1. This processing is based on a redefined valid *YUV* block for which the luminance of white level, *Y*white, is quantum level 239 rather than 235. With this value of *Y*white, the resulting value of *Y*grey (= 255/2) is such that (*Y*grey+X) can be converted to (*Y*grey−X) by simply inverting its binary code. Note that this change of Ywhite to level 239 does not affect the CCIR Rec. 601 specification that the luminance signal should not normally exceed level 235; it merely defines the luminance level above which the *U* and *V* components should be suppressed to zero when overloading has already occurred.

The purpose of the error feedback circuits in Fig. 9(b) is to minimise the visibility of quantising errors resulting from the reduced number of bits in the *YUV* signals fed to the PROM. In these circuits, discarded lower significant bits are added to the following input sample.

A further possible approach to implementing constant-hue limiting would be to first determine the hue angle corresponding to the input *U* and *V* values. Note that a 10-bit hue angle indicates the hue to a slightly greater accuracy than the 16-bits corresponding to 8-bit values of *U* and *V*. This hue angle would then



(a)



(b)

Fig. 9 - Constant hue limiter using single look-up table.
(a) Basic circuit (b) Additions for reduced quantising errors

n/ *indicates n bits in parallel*

be used in conjunction with the value of Y to determine the maximum valid values of U and V for the given YUV input values. All the above processes could be performed by means of ROM look-up tables. Finally the maximum valid U and V values would be compared with the input values and if either limit were exceeded then both input values would be replaced by the limited values. For a given accuracy of limiting, the required storage capacity would be similar to that needed for the method shown in Fig. 8 but the amount of other circuitry would be less; in particular, no multipliers would be required.

A circuit for limiting U and V independently as described in Section 3.3 is shown in Fig. 10. With currently available components, this type of circuit would provide a relatively inexpensive means of working to 8-bit accuracy thus avoiding visible quantising errors but has the disadvantage of altering hues. The relative advantages of independent U and V limiting compared to constant hue limiting are discussed further in Section 6.

6. COMPARISON OF *RGB* AND *YUV* LIMITING

Photographs illustrating the difference between *RGB* limiting and *YUV* limiting, using the constant hue and luminance principle, are shown in Figs. 11 and 12.

For the displays shown in Fig. 11(a) and 11(b), the *YUV* components before any limiting was applied were arranged to vary in the same manner as in Figs. 3(b) and 3(c), the left- and right-hand halves of each display corresponding to Fig. 3(b) and 3(c) respectively. In other words, for both halves inside the grey border, the luminance component consisted of a field sawtooth waveform changing from the digital level 255 at the top of the display to level 0 at the bottom of the display. The U and V components changed linearly from digital levels -128 to $+127$ across each half-line in the left- and right-hand halves respectively and were set to zero in the opposite halves. Thus the original *YUV* components were valid for areas corresponding to the inside of the parallelo

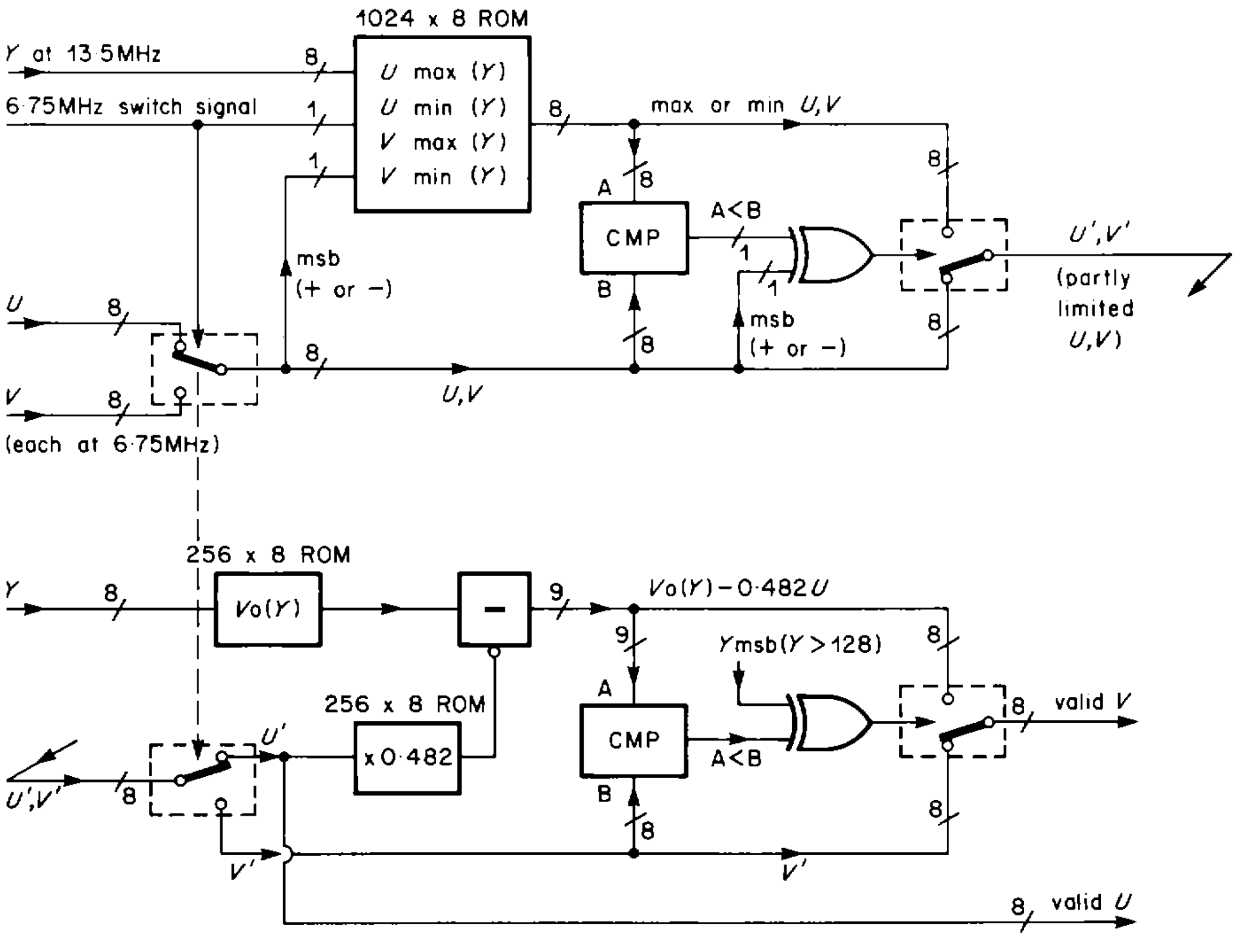


Fig. 10 - Independent limiting of U and V. Hardware implementation of pseudo computer program 2.

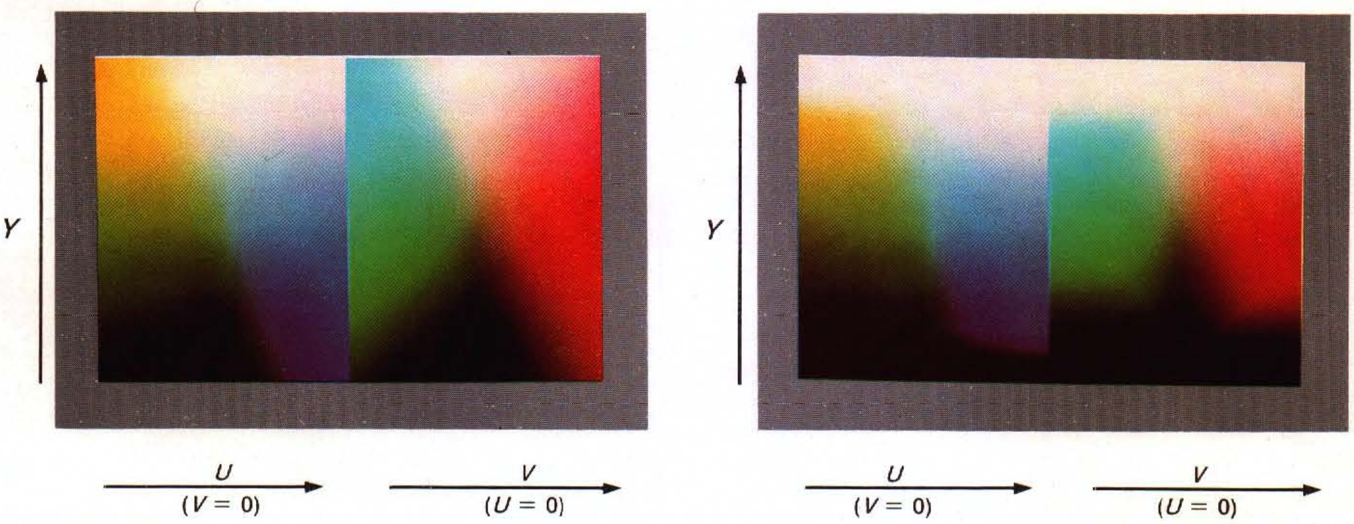
indicates n bits in parallel

grams w, b, bk, y and w, r, bk, c in Figs.3(b) and 3(c) and therefore only the areas outside these parallelograms were affected by limiting.

For Fig. 12, the *U* and *V* components before limiting was applied were constant over the entire picture area inside the grey border and their magnitudes were equal to the maximum valid values for a colour midway between blue and magenta in 100% colour bars. The *Y* component was provided by a normal picture. As a result, valid components were obtained only when the luminance level happened to be equal to one particular grey level, being obviously invalid for black and white levels in the picture. *RGB* limiting was then applied to the left-hand side of the display and *YUV* limiting was applied to the right-hand side. This 'colour-wash' effect was requested by the Television Service as a picture processing facility to be provided by Art File.

These pictures show that *RGB* limiting reduces the luminance contrast range compared to constant hue and luminance *YUV* limiting; this can be seen by the absence of black and white in the left-hand half of Fig. 12 and by the very limited amount of black and white at the bottom and top of Fig. 11(a) compared to Fig. 11(b). This is because clipping of individual *RGB* components at their maximum level reduces the luminance level while clipping at their minimum level increases luminance. Black and white areas in the *RGB* limited picture are obtained only if all three of the *RGB* components before limiting are equal to, or exceed, their limiting levels.

Another less important defect of *RGB* limiting which is avoided by the constant hue *YUV* limiting process is that it introduces a change of hue varying between 0 degrees, for the six hues given by a colour bar signal, and about 30 degrees for hues mid-way



(a) *RGB* limited (b) *YUV* limited

Fig. 11 - Effect of limiting a video signal with Y given by a field sawtooth and U and V increasing linearly across the two halves of the display.

Fig. 12 - Effect of RGB and YUV limiting of a 'colour-washed' picture. Before limiting, the U and V components were constant over the entire picture area and their values corresponded to a colour mid-way between blue and magenta in 100% colour bars.

between those in a colour bar signal. This is illustrated by the difference in hue of the left- and right-hand halves of Fig. 12, the right-hand half having the same hue as the original unlimited signal. A further example is the change in hue from red to magenta along the right-hand vertical edge of Fig. 11(a); this does not occur along the right-hand edge of Fig. 11(b). It should be noted, however, that this advantage of *YUV* limiting does not apply to the independent *U* and *V* limiting technique discussed in Section 3.3; this technique can give larger hue changes than *RGB* limiting.

Fig. 12 shows that the wider luminance contrast range obtained with *YUV* limiting can give much more satisfactory results than *RGB* limiting in picture composition systems where *Y*, *U* and *V* can be generated electronically independently of one another and where limiting is used for artistic effects. For such very critical applications, it is also important that a high accuracy limiting process is used and that hue errors should not be noticeable; the independent *U* and *V* limiting technique was rejected as unsuitable for providing the 'colour-wash' effect shown in Fig. 12 because of the hue errors it introduced.

However, if the reason for applying limiting is purely to ensure that the video signal conforms to existing specifications and limiting is intended only to prevent unintentional invalid signals, then the subjective differences between *RGB* limiting and *YUV* limiting may not be an important consideration. Nevertheless, it is desirable that all *YUV* processing equipment which can internally generate invalid components, e.g. video mixers, should give out valid *YUV* components so that these signals may be freely combined with other *YUV* signals before any conversion to *RGB* components. Under these circumstances, the cost advantage of the hardware for independent *U* and *V* limiting compared to constant hue *YUV* limiting may be considered to be more important than the disadvantage of the hue changes that it introduces.

7. PROBLEMS RELATED TO SAMPLING FREQUENCIES

Limiting of digitally encoded video signals cannot be performed entirely as satisfactorily as limiting of analogue signals because the non-linear nature of limiting causes intermodulation of the sampling and video frequency components in the spectrum of the digital signal. The resulting intermodulation products become most noticeable with hard limiting of high-frequency video components.

In the limiting of *YUV* video signals digitally encoded according to CCIR Rec. 601, there is the additional sampling problem that the *U* and *V* components are sampled at one half the rate used for the *Y* component, whereas the processes discussed above assume that all three components are available at the same sampling rate. The simplest solution to this problem is to send alternate samples only of the *Y* component to the *YUV* limiter. This solution has been adopted in all the practical investigations carried out so far. The results obtained have been generally very satisfactory but unwanted effects resulting from the sampled nature of digital signals are definitely noticeable on critical high-frequency picture material. Possible improvements are as follows:

The least complex alternative to simple subsampling of the *Y* component would be to pre-filter this component prior to subsampling using a digital filter in which a given output sample Y_{out} is given by:

$$Y_{out} = Y_{n-1}/4 + Y_n/2 + Y_{n+1}/4$$

where Y_{n-1}, Y_n and Y_{n+1} represent three successive input samples.

This filter would cause a substantial reduction in *Y* components above one quarter sampling frequency (i.e. above 3 MHz for CCIR Rec. 601 signals) and it would thus reduce intermodulation products caused by high-frequency *Y* components. It is difficult to forecast the subjective effect of this filtering and no tests have been carried out to see if the extra complexity would be worthwhile.

Probably the most satisfactory results would be obtained by increasing the *U* and *V* sampling rates to that of the *Y* component via an interpolating filter prior to limiting and then reducing them back to their original rate via a second filter after limiting. However, the extra complexity of software or hardware would be considerable and is unlikely to be worthwhile.

8. TOLERANCES FOR LIMITS ON *U* AND *V*

So far, it has been assumed that *U* and *V* should be clipped at limits corresponding to *R*, *G* and *B* equal to their nominal minimum and maximum values of 0 volts and 0.7 volts, denoted by normalised values 0 and 1 in this Report.

Experience with electronic picture generators has indicated that these limits are appropriate in equipment which is acting as a source of *YUV* video signals. For example, the limiting applied to the right-hand half of Fig. 12 had the desired effect particularly with regard to the complete removal of the *U* and *V* components in black and white areas of the picture.

Further experience, however, with a digital *YUV* mixer has indicated that the *U* and *V* components should be allowed to exceed their nominal limits by a small amount in equipment which is processing signals not generated in that equipment. It is important that such equipment is transparent to video signals which are nominally correct rather than, for instance, clipping wanted high-frequency overshoots in the *U* and *V* components. Another disadvantage of limiting at the nominal limits set by *R*, *G* and *B* equal to 0 and 1 arises where an incoming signal has wanted colour components associated with a luminance level, which through misalignment or noise, is slightly above white level (i.e. level 235). The result of removing these colour components can be more undesirable than allowing slightly invalid colours.

One possible basis for increasing the *U* and *V* limits is to arrange that *YUV* values are clipped only if the corresponding *RGB* values are greater than '1+x' or less than '−x', where x is a constant whose value is discussed below and the *RGB* signals have nominal limits of 1 and 0.

Increasing the value of x increases the size of the valid colour block shown in Fig. 2. Assuming this valid colour block is to remain entirely within the larger block containing all possible *YUV* values, the maximum value of x is approximately 0.06. With this value of x, the 8-bit *YUV* values for all combinations of maximum and minimum *RGB* values are as shown in Table 2. These *YUV* values were calculated using Eqns. 7 to 9.

Table 2

8-bit YUV quantum levels for RGB limits of 1.06 and −0.06

Colour	*R*	*G*	*B*	*Y*	*U*	*V*
White (w)	1.06	1.06	1.06	248.1	0	0
Yellow (y)	1.06	1.06	−0.06	220.2	−125.4	20.4
Cyan (c)	−0.06	1.06	1.06	174.8	42.3	−125.4
Green (g)	−0.06	1.06	−0.06	146.8	−83.1	−105.1
Magenta (m)	1.06	−0.06	1.06	104.2	83.1	105.1
Red (r)	1.06	−0.06	−0.06	76.2	−42.3	125.4
Blue (b)	−0.06	−0.06	1.06	30.8	125.4	−20.4
Black (bk)	−0.06	−0.06	−0.06	2.9	0	0

The eight sets of *YUV* values in Table 2 give the co-ordinates of the corners of the enlarged *YUV* valid colour block. All the *U* and *V* values are '1 + 2x', i.e 1.12, times the corresponding values in Table 1. It can be seen that the maximum and minimum *U* and *V* values are just within the range of −127 (binary code 00000001) to +126 (binary code 11111110) specified in CCIR Rec. 601 as being available for video usage.

Note that the difference between the *Y* value of the 'white' corner (248.1) and the maximum available *Y* value of 254 is greater than the difference between the *Y* value of the 'black' corner (2.9) and the minimum *Y* value of 1. This is undesirable because the probability of white level being unintentionally exceeded is greater than the probability of unintentional signals below black level. This problem can be overcome by introducing asymmetry into the *RGB* limits such that *YUV* signals are limited only if the corresponding *RGB* values are greater than '1+x+y' or less than '−x+y'. With these *RGB* limits, all the *Y* values of the corners of the *YUV* valid-colour block are changed by an amount equal to 219 × y but the U and V values of the corners are not affected by y. For example, if x = 0.06 as in Table 2 and y = 0.02, the *RGB* limits are 1.08 and −0.04 and the resulting *YUV* values of the corners of the valid colour block are as shown in Table 2 but with 4.4 added to all the *Y* values. Thus the *Y* value for the black and white corners would be 7.3 and 252.5 respectively. It is suggested that these represent suitable *YUV* values for the corners of an enlarged valid colour block applicable to *YUV* video mixers and other down-stream processing operations.

The only effect of using an enlarged valid-colour block on the software and hardware discussed earlier is that the values of *U*max(*Y*), *U*min(*Y*), *V*max(*Y*), *V*min(*Y*) and *V*o(*Y*) need to be altered to suit the new maximum and minimum values of *R*, *G* and *B*. The slope of diagonal edges of the constant *Y* cross-sections (= 0.482) shown in Fig. 4 is not altered (see Eqn. 40 in the Appendix).

9. CONCLUSIONS

The Report has described both software and hardware methods of limiting *YUV* component video signals so that the corresponding *RGB* components do not excurse beyond specified limits. Before a *YUV* limiter can be designed, a set of rules is required for defining the limited *Y*, *U* and *V* values which best represent any given combination of invalid *Y*, *U* and *V* values. The proposed rules, which have been found to give very satisfactory results, are that the *Y* value should not be altered and the *U* and *V* values should be limited to the maximium valid values having the same hue as the invalid *U* and *V* values prior to limiting.

In principle, the simplest method of instrumenting a *YUV* limiter is to employ a look-up table which gives limited values of *U* and *V* values for any *YUV* input (see Fig. 9). However, this table would require an excessively large storage capacity if it were to contain output *U* and *V* values for all the 17 million 24-bit possible combinations of 8-bit *Y*, *U* and

V values. Tests to investigate the effect of reducing the storage capacity by decreasing the number of bits used for the *YUV* input to the table showed that quantising errors in picture areas subjected to limiting became perceptible with less than 7, 6 and 6 bits for *Y, U* and *V* respectively. However, a hardware limiter using a look-up table with 13-bit input addresses derived from 5, 4 and 4 bits for *Y, U* and *V* has been found to fulfill a useful function in a mixer incorporated in equipment now in use by the Television Service[5].

Alternative techniques involving a number of separate operations can provide a more satisfactory means of constant hue *YUV* limiting than a single look-up table if good performance is the main objective. The disadvantages are more complex circuitry for hardware (see Fig.8) or longer processing times for software. Software based on one such technique (see Section 3.2) has been installed in the still-picture composition system known as Art File[1].

A different compromise between performance and complexity of hardware or software is given by the independent *U* and *V* limiting technique described in Section 3.3. As indicated in Fig. 10, this technique requires very little ROM storage capacity for full 8-bit coding accuracy and the hardware required is thus much less expensive than that required for the constant hue technique. Its disadvantage is that it can cause hue changes which can be quite significant for limiting of *YUV* values well outside the *YUV* limits. This technique is therefore useful where limiting is intended only to prevent unintentional invalid signals and where artistic effects are not an important consideration.

Limiting of digital signals cannot be performed as satisfactorily as limiting of analogue signals because the non-linear nature of limiting causes intermodulation between the digital sampling frequency and video frequency components. The effects are most noticeable when high-frequency video components are being limited. Methods of minimising the resulting beat patterns are discussed in Section 7.

It is proposed that the amount by which the *U* and *V* signal levels should be allowed to exceed their nominal maximum and minimum levels should depend on the type of equipment in which a limiter is installed. Tests on the Art File picture composition system indicated that the actual limits should be set precisely at the nominal limits; this may be applicable to other equipment acting as a source of video signals. On the other hand, tests on a digital mixer indicated that a limiter inserted in equipment handling signals not generated in that equipment should allow about 6% overload before limiting is applied.

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APPENDIX

Alternative procedure for constant hue and luminance limiting

This appendix describes an alternative procedure to that given in Section 3.2 for finding the values of the limited U and V components given by the principles of constant hue and luminance. This alternative procedure was devised after the remainder of the Report had been completed; although it does not lead to improved software or hardware, it has the advantage of avoiding the use of the functions $U\mathrm{max}(Y)$, $U\mathrm{min}(Y)$, $V\mathrm{max}(Y)$, $V\mathrm{min}(Y)$ and $V\mathrm{o}(Y)$ and hence it provides a more direct explanation of the limiting process. For simplicity, the procedure is described in terms of analogue YUV components to be denoted by $Y\mathrm{a}$, $U\mathrm{a}$ and $V\mathrm{a}$. These components are related to RGB component values by:

$$Y\mathrm{a} = 0.299R + 0.587G + 0.114B \quad (17)$$
$$U\mathrm{a} = B - Y\mathrm{a} \quad (18)$$
$$V\mathrm{a} = R - Y\mathrm{a} \quad (19)$$

Rearranging these equations to give R, G and B in terms of $Y\mathrm{a}$, $U\mathrm{a}$ and $V\mathrm{a}$:

$$B = Y\mathrm{a} + U\mathrm{a} \quad (20)$$
$$R = Y\mathrm{a} + V\mathrm{a} \quad (21)$$
$$G = Y\mathrm{a} - (0.299V\mathrm{a} + 0.114U\mathrm{a})/0.587 \quad (22)$$

If $U\mathrm{aout}$ and $V\mathrm{aout}$ represent output components from a limiter which maintains the same hue as that given by the components $U\mathrm{ain}$ and $V\mathrm{ain}$ at the input of a limiter, then:

$$U\mathrm{aout} = \mathrm{K} \times U\mathrm{ain} \quad (23)$$
$$V\mathrm{aout} = \mathrm{K} \times V\mathrm{ain} \quad (24)$$

where K is the UV limiting factor as used in Section 3.2.

From the principle of constant luminance, the output luminance given by the limiter is equal to the input luminance $Y\mathrm{ain}$.

Assuming that limiting has been applied, $Y\mathrm{ain}$, $U\mathrm{aout}$ and $V\mathrm{aout}$ correspond to a point on the surface of the valid colour block bounded by the planes given by $R = G = B = 1$ and $R = G = B = 0$ and it therefore follows from Eqns. 20 to 22 that $Y\mathrm{ain}$, $U\mathrm{aout}$ and $V\mathrm{aout}$ must be related by one of the following expressions:

$$\text{for } B = 1, \quad 1 = Y\mathrm{ain} + U\mathrm{aout} \quad (25)$$
$$\text{for } B = 0, \quad 0 = Y\mathrm{ain} + U\mathrm{aout} \quad (26)$$
$$\text{for } R = 1, \quad 1 = Y\mathrm{ain} + V\mathrm{aout} \quad (27)$$
$$\text{for } R = 0, \quad 0 = Y\mathrm{ain} + V\mathrm{aout} \quad (28)$$
$$\text{for } G = 1, \quad 1 = Y\mathrm{ain} - (0.299V\mathrm{aout} + 0.114U\mathrm{aout})/0.587 \quad (29)$$
$$\text{for } G = 0, \quad 0 = Y\mathrm{ain} - (0.299V\mathrm{aout} + 0.114U\mathrm{aout})/0.587 \quad (30)$$

Substituting for $U\mathrm{aout}$ and $V\mathrm{aout}$ from Eqns. 23 and 24, the following values of the limiting factor K are obtained:

$$\text{for } B = 1, \quad \mathrm{K} = (1 - Y\mathrm{ain})/U\mathrm{ain} \quad (31)$$
$$\text{for } B = 0, \quad \mathrm{K} = -Y\mathrm{ain}/U\mathrm{ain} \quad (32)$$
$$\text{for } R = 1, \quad \mathrm{K} = (1 - Y\mathrm{ain})/V\mathrm{ain} \quad (33)$$
$$\text{for } R = 0, \quad \mathrm{K} = -Y\mathrm{ain}/V\mathrm{ain} \quad (34)$$
$$\text{for } G = 1, \quad \mathrm{K} = 0.587(Y\mathrm{ain} - 1)/(0.299V\mathrm{ain} + 0.114U\mathrm{ain}) \quad (35)$$
$$\text{for } G = 0, \quad \mathrm{K} = 0.587Y\mathrm{ain}/(0.299V\mathrm{ain} + 0.114U\mathrm{ain}) \quad (36)$$

Using similar arguments to those given in Section 3.2, the required value of the K factor is the minimum positive value given by Eqns. 31 to 36 except that if this minimum is greater than unity then the required K factor is equal to unity. The latter condition sets K = 1 for all valid combinations of $Y\mathrm{ain}$, $U\mathrm{ain}$ and $V\mathrm{ain}$.

A procedure for determining the required K factor is given by the following psuedo computer program:

Psuedo computer program 3.

```
                                                   comments

input Yain,Uain,Vain                               enter input YUV values

if Yain > 1 OR Yain < 0                            if Y above white or
    K = 0                                          below black, set U = V = 0
else proceed as follows

    if Uain > (1-Yain)                             test for B > 1
        Kblue = (1-Yain)/Uain                          find K for B = 1
    else if Uain < - Yain                          test for B < 0
        Kblue = -Yain/Uain                             find K for B = 0
    else                                           else
        Kblue = 1                                      B is valid

    if Vain > (1-Yain)                             test for R > 1
        Kred = (1-Yain)/Vain                           find K for R = 1
    else if Vain < -Yain                           test for R < 0
        Kred = -Yain/Vain                              find K for R = 0
    else                                           else
        Kred = 1                                       R is valid

    let C = (0.299Vain+0.114Uain)/0.587
    if C > Yain-1                                  test for G > 1
        Kgreen = (Yain-1) / C                          find K for G = 1
    else if C < Yain                               test for G < 0
        Kgreen = Yain / C                              find K for G = 0
    else                                           else
        Kgreen = 1                                     G is valid

    K = lowest(Kblue, Kred, Kgreen)                select minimum K

Uaout = K × Uain                                   calculate output U
Vaout = K × Vaout                                  calculate output V
```

It can be seen that the above program is very similar to the psuedo computer program given in Section 3.2.

The procedure given above can be converted to handle digital components Yd, Ud and Vd using the following relationships derived from Eqns. 7, 8 and 9:

$$Y\text{d} = 219Y\text{a} + 16 \quad (37)$$

$$U\text{d} = 112U\text{a}/0.886 \quad (38)$$

$$V\text{d} = 112V\text{a}/0.701 \quad (39)$$

Note that an expression for the parameter $V\text{o}(Y)$ used in Section 3.2 can now be obtained by writing Eqn. 22 in terms of Yd, Ud and Vd to give:

$$V\text{d} = -0.4819U\text{d} + 1.432(Y\text{d} - 16 - 219G) \quad (40)$$

Comparing Eqn. 40 with Eqn. 13, i.e. $V = -0.482U + V\text{o}(Y)$, shows that:

$$V\text{o}(Y) = 1.432(Y-16) \text{ for } G = 0 \quad (41)$$

$$V\text{o}(Y) = 1.432(Y-235) \text{ for } G = 1 \quad (42)$$

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