TNO Institute for Perception

TNO Defence Research

Kampweg 5
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Fax +31 3463 5 39 77
Telephone +31 3463 5 62 11

TNO-report **IZF 1992 B-7**

J.M. Valeton
A.J.C. de Reus

HIGH-RESOLUTION CONTRAST CONTROL ON A VIDEO DISPLAY: METHOD AND CALIBRATION

Number of pages: 30

Netherlands organization for applied scientific research

TNO Defence Research consists of
the TNO Physics and Electronics Laboratory

CONTENTS

Report No.: IZF 1992 B-7

Title: High-resolution contrast control on a video display: method and calibration

Authors: Dr. J.M. Valeton and Ir. A.J.C. de Reus

Institute: TNO Institute for Perception
Group: Sensory Perception

Date: August

DO Assignment No.: B92-01

No. in Program of Work: 786.1

SUMMARY

In visual psychophysics it is sometimes necessary to be able to display luminances with 12 bit precision. This report describes a method where two 8 bit color outputs of a DeAnza IP8400 image processor are combined into a monochrome signal with an effective resolution of 12 bits. The implementation in hardware and software, and the calibration of the system are described. Measurements show that the system meets the desired specifications.

Rap.nr. IZF 1992 B-7

Instituut voor Zintuigfysiologie TNO
Soesterberg

Hoge-resolutie contrastweergave op een video monitor: methode en ijking

J.M. Valeton en A.J.C. de Reus

SAMENVATTING

Bij visuele psychofysica is soms een luminantie-resolutie van 12 bit noodzakelijk. In dit rapport wordt een methode uitgewerkt, waarbij twee 8 bit kleurenuitgangen van een DeAnza IP8400 image processor gecombineerd worden tot een monochroom signaal met een effectieve resolutie van 12 bit. De implementatie in hardware en software wordt behandeld, alsmede de ijking van het systeem. Uit metingen blijkt dat het systeem aan de verwachte prestaties voldoet.

1 INTRODUCTION

In experiments on contrast detection it is often necessary to present spatially complex spatial stimuli at very low contrast (as low as 0.5%), with a specific temporal profile. Displaying such stimuli accurately on a display system that has basically an 8 bit intensity resolution is not possible. In this report we will first show that an effective resolution of at least 12 bit is required. In the rest of Chapter 2 we describe how a method, proposed by Watson et al. (1986) to solve this problem, was implemented on a DeAnza IP8400 image processor with a Gould Concept 32/67 host computer. Two (8 bit) channels of the RGB color output of the image processor are combined to drive a monochrome display, and hence the method is called *two channel contrast control*. In Chapter 3 we will describe how such a system is calibrated. In Chapter 4 we show the results of test measurements to check the performance of the two channel method. In the appendices the source code of our 12 bit display routine and the technical data of the video monitor used in the test measurements are presented.

In some parts the text of this report relies heavily on the paper by Watson et al. (1986). The report forms the theoretical background of 12 bit stimulus display in our laboratory. Our implementation of Watson's method and the calibration procedures are documented in a separate report as part of the laboratory quality control procedures (De Reus & Valeton, 1992).

In the report, parameters that appear in the computer programs are printed within square brackets, e.g. [red_offset]. Software algorithms are presented in pseudo-code.

2 TWO CHANNEL CONTRAST CONTROL

2.1 The 12-bit resolution requirement

A digital display system renders images in discrete intensity steps and hence is prone to quantization errors. For accurate rendering of a sinewave a minimum of 8 to 10 intensity levels is required. A display system with a b bit digital-to-analog converter (DAC) has a smallest voltage step size[1] of $1/(2^b - 1)$. The corresponding lowest possible (voltage) contrast of a sinewave on a constant background is $2/(2^b - 1)$, which for an 8 bit system amounts to 0.78%. At this contrast, however, there are only 2 intensity levels available, so the signal is a square wave instead of a sinewave. The contrast threshold for spatial sinewave patterns is, under optimal conditions, on the order of 0.5%. In threshold experiments, therefore, sine waves must be reproduced accurately at contrasts well

[1] A system with a b bit output-DAC has 2^b signal levels. Thus an 8 bit system has 256 different levels.

below 0.5%. Since at 0.78% contrast an 8 bit system is already limited to only 2 levels, it is clear that an 8 bit system lacks sufficient intensity resolution. The problem is illustrated in Fig. 1.

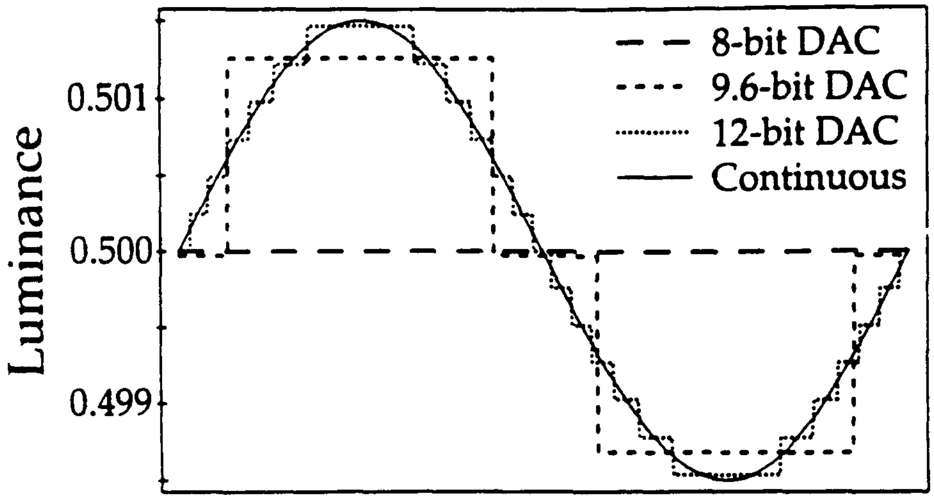

Fig. 1 Sinewave with 0.3% contrast rendered at different uniform quantization levels. The solid line is the original signal, the dashed line is the sinewave quantized to 256 levels (8 bits), the broken line to 776 levels (9.6 bits) and the dotted line to 4096 levels (12 bits). Only at full contrast (100%) all levels are used.

In this figure, taken from Pelli and Zhang (1991), we see what happens when a 0.3% contrast sinewave (solid line) is displayed with an 8 bit, a 9.6 bit and a 12 bit resolution system. An 8 bit system results in zero output, an effective 9.6 bit output generates 3 intensity levels and a 12 bit DAC gives a reasonable electronic rendering of the sinewave. This shows that for sinewave like signals at threshold contrast levels, a 12 bit resolution, or, a luminance step size of about *1/4000* (of full scale) is required.

Such a high intensity resolution output for a display can theoretically be obtained by using 12 bit DACs, but such a system is not on the market and building one would be very costly. An elegant and simple alternative, called *"two channel contrast control"*, was proposed by Watson et al. (1986). Pelli and Zhang (1991) presented an extension of this approach to three channels.

In this method, two channels of the 8 bit RGB color output of a display system are combined to drive a monochrome monitor. One channel is attenuated by a certain factor and added to the other channel. The attenuated channel can display only part of the whole intensity range but it has all 8 bits available. This results in a smaller step size and hence a higher intensity resolution. The other channel is added to put the high resolution section on the required average intensity level. For large contrasts only the unattenuated channel is used and therefore in this case the step size is not smaller than with a normal 8 bit display system.

2.2 Hardware implementation

The output voltage of the red and green channels, V_R and V_G, of the DeAnza image processor are added electronically to yield the following output voltage V:

$$V = (1 - f)\ V_R + f\ V_G$$

where f is an attenuation factor with $0 < f < 1$. We chose $f = 1/16$. The setup is illustrated in Fig. 2.

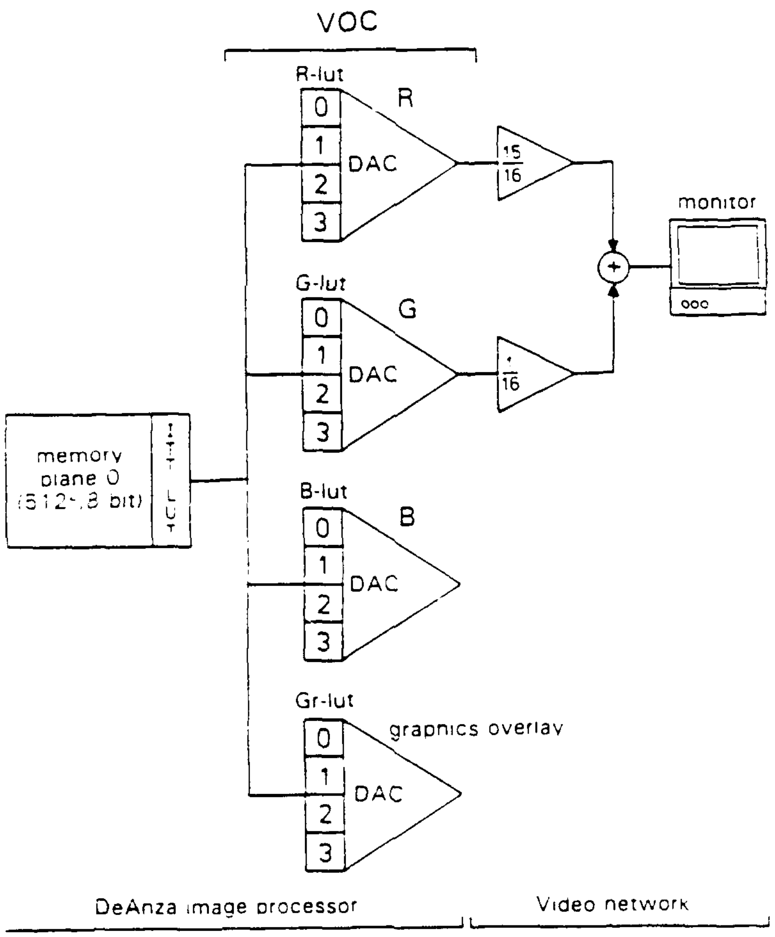

Fig. 2 Hardware diagram of the video output controller (VOC) of the DeAnza image processor and the two channel addition.

In the green channel the step size is decreased by a factor of $1/f$, which means that the intensity resolution is increased by the same factor (16, or: 4 bits). The total resolution of the combined system, for the limited intensity range, now effectively becomes 12 bits.

The Video Output Controller (VOC) is the hardware through which images in memory are sent to the CRT. There are DACs for each color channel R, G, and B and there is also a channel for Graphic Overlay. A Look-Up Table (LUT) precedes each DAC, and each LUT has four sections, numbered 0 - 3. These sections each have 256 entries and are fully equivalent. A LUT section can be assigned by software. Different signal paths in the VOC can be set up under software control. In the present situation the memory plane containing the stimulus image is connected to the R, G, and B DACs, through LUT sections 0; the Graphic DAC is not used. The B-LUT (blue channel) is set to zero, so this channel is effectively not connected. The memory planes in the DeAnza each have an 8 bit LUT of their own (called Intensity Transformation Table, or ITT) but these are bypassed in the present setup.

The DeAnza IP8400 display system has 8 bit resolution output. As Pelli and Zhang (1991) point out, 8 bit DACs have an effective resolution of only 7 bits due to noise in the least significant bit. In the DeAnza this problem has been elegantly solved by building 10 bit DACs into the VOC and then using the 8 most significant bits only.

2.3 Software implementation

The maximum contrast that can be displayed through the attenuated channel is called the *"critical contrast"* C_{crit}. For a linear monitor the critical contrast would be equal to f (1/16 in our implementation), but for practical CRT displays the critical contrast is slightly larger than f (up to a factor of 2, see Chapter 3). The system operates in two modes, for contrasts below and above C_{crit} respectively.

Mode 1 *Contrasts higher than* C_{crit}. Only the R channel is used and the G-LUT is filled with zeros. This mode is in fact a traditional single channel system. Contrast is manipulated by changing the R-LUT (red channel).

Mode 2 *Contrast lower than* C_{crit}. Two channels are used. Signal contrast is manipulated by changing the G-LUT (green channel) while the R-LUT is filled with the constant [red_offset]. This mode generates a limited range of contrasts, but has an effective intensity resolution of 12 bit.

The value [red_offset] is chosen such that when zero contrast must be displayed, and the G-LUT is filled with [bkg_value] (= e.g. 128), the monitor luminance is equal to the luminence in mode 1 when [bkg_value] is loaded into the R-LUT (to produce the stimulus background). The following equation roughly holds:

$$L_2 \{ \text{R-LUT[red\_offset]} + \text{G-LUT[bkg\_value]} \} = L_1 \{ \text{R-LUT[bkg\_value]} \}$$

where: L_1 and L_2 are the screen luminances in mode 1 and 2. The procedure for determining [red_offset] is part of the system calibration and is given in detail in Chapter 3. When [red_offset] is chosen carefully, the mean display and background luminances do not change when the system switches between mode 1 and mode 2.

The source code for the routine which implements the 12 bit display using two modes is given in Appendix 1. Within the subroutine CMVARF2() there are two main streams. When the requested contrast is greater than C_{crit}, a section of code according to mode 1 is executed, and when the contrast is smaller than C_{crit}, the two channel system of mode 2 is used. Note that in the latter case the contrast is divided by C_{crit}. This is where the increase in contrast resolution actually happens: by multiplying a small contrast with $1/C_{crit}$, there are about 1/f times more levels available for rendering the signal. At the output the signal is multiplied by f in analogue hardware. The result thus is more available luminance levels, but only in a small luminance range.

2.4 *Dynamic contrast control*

In this section we explain how the contrast of the stimuli on the display is controlled. Correction for the non-linearity of the CRT display is treated in the next section and in Chapter 3.

The image that must be displayed is stored in an 8 bit 512x512 pixel memory channel at maximum contrast, i.e. all 256 available levels are used. This is done to have the maximum number of levels available in the output signal in order to minimize the quantization error in the image itself. In many cases the signal to be displayed is smaller than 512x512 pixels. In those cases the signal, e.g. a patch of a sinewave grating, is usually placed in the center of the image and the surrounding image area is set to 0. We reserve this pixelvalue to display the background intensity using the LUT. The 8 bit LUTs each have 256 entries. The first position of the look-up table is used to set the background that surrounds the signal, or: LUT[0] = [bkg_index], where [bkg_index] is usually set to 128. An uneven number of 255 LUT positions remain for use in setting the signal contrast. The middle position is 128 and there are 127 positions above and below this level. This enables us to generate both normal and reversed contrasts symmetrically around zero.

The contrast of the signal on the display is manipulated by "rotating" the LUT contents around the center position S (=128), see Fig. 3.

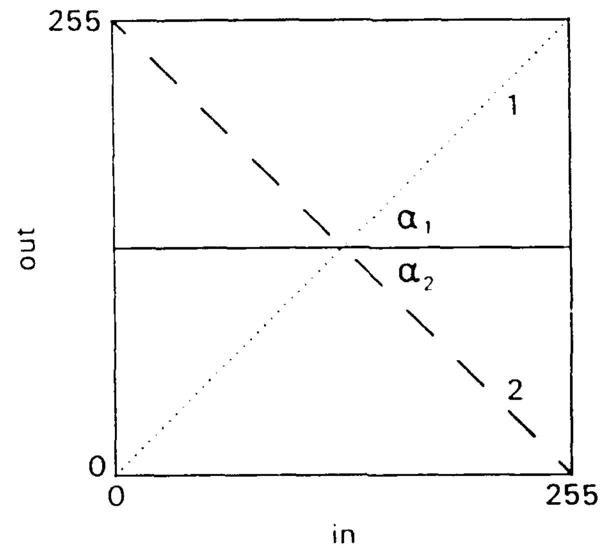

Fig. 3 Illustration of the rotating LUT. Line 1 (dotted) represents the LUT transformation for a full-contrast (100%) stimulus display, line 2 (dashed) the LUT transformation for a negative 100% contrast. The tangent of the angles gives contrasts between 0 and 100%, signed positive for α_1 and negative for α_2.

A LUT loaded with a linear ramp (solid line) produces an image of maximum contrast, a LUT with the value 128 at each location yields a zero contrast "grey" image and a LUT with a slope of -1 (dashed line) shows the image with reversed contrast. Rotation of the LUT around point S effectively changes the contrast to any desired level: the contrast is equal to the slope (or tan(α), where $-\pi/4 \leq \alpha \leq \pi/4$ when S = 128) of the line in Fig. 3.

A stimulus image can be displayed dynamically, with a specified time course, by loading a new LUT for every video frame. In practice this is implemented by using a list of numbers [t_list], e.g. a Gaussian profile as in Fig. 4, representing the contrast for each frame.

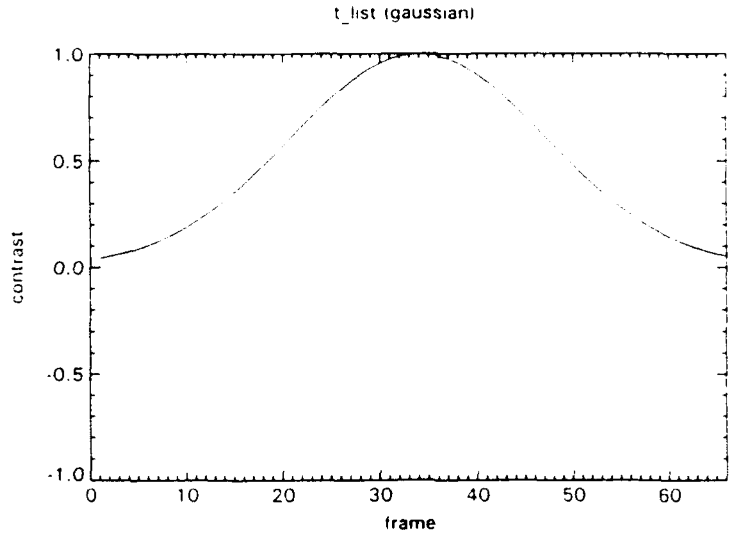

Fig. 4 Gaussian time course for dynamic contrast display. This example extends 1 second at 66 fields/second.

To create the contrasts for a Gaussian profile, the LUT is rotated around point S in Fig. 3 from a horizontal line (slope 0) up to slope 1 and back down again. For maximum resolution the time profile is stored at full contrast, so in order to display the stimulus at a contrast smaller than 1.0 the slope of the LUT for each frame must be multiplied by the desired contrast (see the source code of the display routine in Appendix 1). For this type of dynamic stimulus display the system must be fast enough to recalculate and load several LUTs between two video frames. The Gould/DeAnza is able to calculate and fill two LUTs between two fields at a display rate of 66 fields/second. (In the mode we use, the DeAnza's line-scanning system is interlaced: each frame is composed of two fields.)

2.5 Display linearization

As will be explained fully in Chapter 3, a provision must be made to correct for the nonlinearity of the CRT display. This can be done by using a correction table as look-up table. However, the look-up table is also used for controlling the stimulus contrast. In software both these function are carried out at the same time, using a single look-up table, as follows.

For each image pixelvalue i, given the time course and desired contrast, the value is calculated as if the monitor were linear, using the mechanism of rotating a LUT. In order to correct for the display non-linearity these new values are used as indices for the array correction table CORLUT for filling the actual hardware display LUT:

VOC_LUT[i] = CORLUT[ROTATE[i]]

2.6 Outline of the subroutine CMVARF2

The subroutine CMVAR2F takes care of displaying stimuli of a specified time course using the two channel method. It is written in Fortran because on the Gould computer we use Fortran is proven to be faster than C. Additional advantages are that the low-level DeAnza interface is written in Fortran and that most of the software used on the Gould/DeAnza system is in Fortran. Fortran subroutines and functions can be called from C programs but not vice versa.

Subroutine header:

SUBROUTINE CMVARF2(USER, TLIST, ATTEN, BKGINDEX, CHAN, CO, NFRAMES, MODE, CRIT_CONT, CCM1, CCM2)

where:

Parameter	*Fortran type*	*C type*	*Description*
USER	INTEGER*4	int	DeAnza user number for multi-user environment
TLIST	REAL*4 ARRAY	float *	time course, first element is length of this table
ATTEN	REAL*4	float	stimulus attenuation
BKGINDEX	INTEGER*4	int	background index in CCM1, used for all pixels with value 0
CHAN	INTEGER*4	int	memory plane number of stimulus
CO	INTEGER*4	int	-
NFRAMES	INTEGER*4	int	number of frames in the stimulus
MODE	INTEGER*4	int	display mode: 1 = 8 bit, 2 = 12 bit
CRIT_CONT	REAL*4	float	critical contrast for 12 bit mode
CCM1	INTEGER*4 ARRAY	int *	gamma correction table for red channel
CCM2	INTEGER*4 ARRAY	int *	gamma correction table for green channel

The Fortran and C data types are for the compilers installed on our Gould CONCEPT/32 machine. The parameter CO is not for user-purposes.

The subroutine is split in two major parts, one for the 8 bit mode and one for the two channel 12 bit mode. The 8 bit part has no specifically interesting features. In the 12 bit mode, for each frame the contrast is determined (from the desired maximum contrast and the current value in the time course). When this contrast is below the critical contrast the green LUTs are rotated and the red LUT is set at [red_offset], in the other case the green channel is set to zero and the red LUT is rotated. The subroutine is optimized for speed and two LUTs can be calculated and filled within one field time (1/66 second). The complete source code is presented in Appendix 1.

3 SYSTEM CALIBRATION

3.1 CRT non-linearity

A CRT monitor has a basically non-linear relation between driving signal v and luminance output L that can roughly be described by a power function:

$$L = L_{min} + a\, v^{\gamma} \tag{1}$$

where L_{min} is the luminance at zero input and gamma usually between 2 and 3. This function is often called the *"gamma function"*, after the exponent γ. The effect of this nonlinearity is that an image stored in the display memory is not rendered truthfully on the display. For most psychophysical stimuli a linear relation between pixel value and display luminance is required and this can be realized by displaying the stimuli through a lookup table (LUT) that contains the inverse of L(v). When "two channel contrast control" is used, the situation is slightly more complex because two LUTs have to be calculated and loaded. The calibration program Calibra collects the L(v) curve for two channels, the calculation of the correction LUTs and the determination of [red_offset] and C_{crit}, two parameters that are used in the two channel method. In the following we will present step-by-step procedures to determine the various quantities.

3.2 Measuring the gamma function

The gamma function is measured in an automated fashion by measuring the display luminance with a Pritchard Photometer for all 256 pixel values. The measurement procedure is computer controlled.

3.2.1 *Choice of test pattern*

In most monitors the high tension anode voltage (e.g. ca. 25 kV) is not stabilized and as a consequence this voltage drops with increasing beam current. This means that the luminance generated by a patch of certain (large) pixel value, e.g. 200, is smaller for a large patch than for a small patch. This would make a measurement of the gamma function dependent on stimulus area and this is obviously undesirable. To more or less circumvent this problem we use test images for the calibration that consist of 2 areas, see Fig. 5.

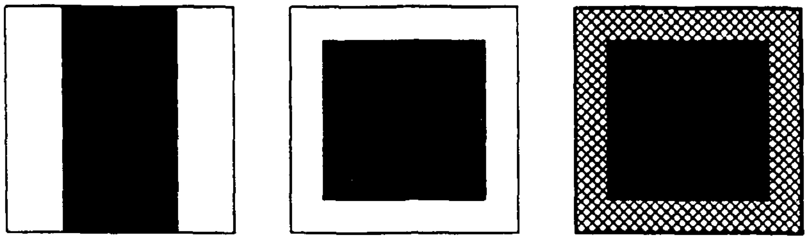

Fig. 5 Three calibration patterns. Each pattern contains 512^2 pixels. The white areas in the patterns contain pixels with value 0, the black areas pixels with value 255. The gray part in the rightmost pattern contains pixels with value 128.

One area of the first two test patterns is light (pixel value 255) and the other area is dark (pixel value 0). Both these areas are varied during the measurements with Calibra. The areas (number of pixels) of the light and dark regions are equal, both for the bar pattern and for the square pattern. If, when the pixel value of the dark area is increased, the pixel value for the light area is decreased at the same rate, the load on the CRT is constant, and the dependence of luminance on pattern size is removed. In a third test pattern we replaced the light area with a border of a constant grey (pixel value 128). This does not satisfy the demand of a constant load and can therefore only be used for CRTs with a sufficiently stabilized anode voltage. The bar pattern has the additional advantage over the square patterns that the average load for each scanline is constant.

A second factor in the choice of test pattern is stray light. Light is scattered within the phosphor and in the glass monitor face. When a dark bar is flanked on both sides by a bright bar, stray light from the bright bars precludes a correct luminance measurement for the dark bar. For this reason the dark area should be as large as possible. The square test pattern has the advantage that the bright surround is removed as far as possible from the center of the dark area. Other problems with stray light can arise when light not coming from the measurement part of the test pattern falls on the measurement spot of the photometer. Care should be taken to avoid problems of this kind.

3.2.2 *Procedure to record the gamma function*

The procedure to record the gamma function is as follows:

1 Load a light-dark test pattern into display memory (dark area has pixel value 0; light area has pixel value 255).
2 Aim the photometer at the center of the dark area.
3 Set the lookup table LUT[0] = 0 and LUT[255] = 255.
4 Repeat
  5 Record the luminance value.

6 Change the lookup table entries as follows:
  - LUT[0] = LUT[0] + 1,
  - LUT[255] = LUT[255] - 1.
  until LUT[0] equals 255.

Note that the choice of the LUT indices 0 and 255 is arbitrary.

3.2.3 *Signal averaging*

Luminance is recorded with a Spectra Physics Pritchard photometer. This instrument is equipped with an TNO-IZF custom made 24 bit digital interface (a so-called Normalized Output Connector, or NOC). This interface is connected to NIC (a Normalized Input Connector) on the Gould host computer. The Pritchard's NOC sends out 3 luminance readings per second to the host computer. In order to get an accurate estimate of the display luminance a number of readings are averaged until an error limit or a maximum number of samples is reached. The following procedure is used:

1 Set pixelvalue to desired value (by setting the LUT).
2 Start reading luminance values and discard first few values (get rid of errors due to range switching and let the photometer adapt to the new luminance).
3 Initialize running average (set to zero) and set COUNT to 0
4 Repeat
  5 Read luminance value from photometer.
  6 Update running average, measurement variance and COUNT.
  until (COUNT ≥ MIN_NUM and variance < ERROR_LIMIT) or (COUNT > MAX_NUM).
7 If (variance > ERROR_LIMIT)
  8 Give a prompt to re-adjust the setup.
  9 Restart this routine again.
10 Return the running average as estimate for the screen luminance.

Usually 10 (= MIN_NUM) luminance values are recorded for one estimate and the error limit is set to 1% of the running average. A complete calibration run, for a single channel, takes about 10 minutes. An example of a gamma curve is presented in Fig. 6 as G(d).

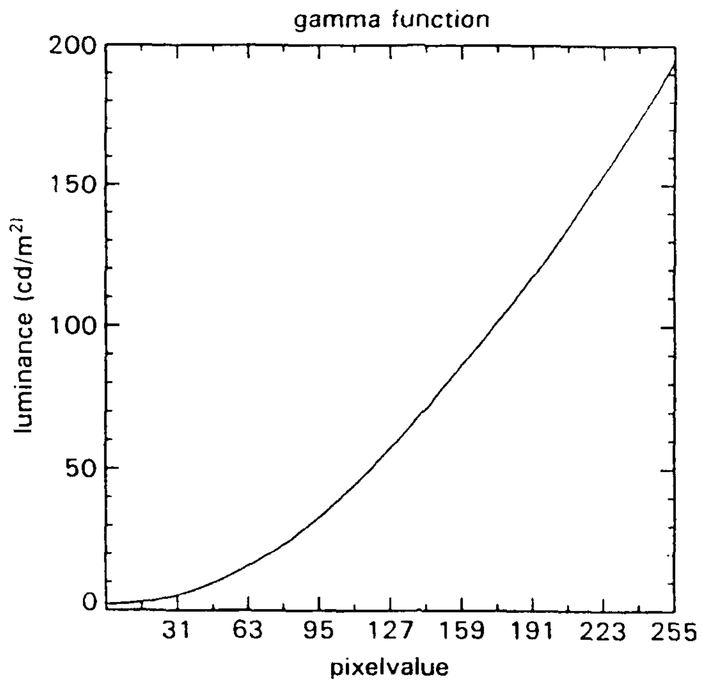

Fig. 6 Example of a measured gamma function.

3.3 Linearization of a single channel display

3.3.1 *Notation*

In the subsequent sections we use the following notation:

p	digital image pixel value (0 =< p =< 255); is also a LUT *address*;
p0	central pixel value (128)
d	digital value of a LUT *entry* (0 =< d =< 255); sent to the CRT
d0	central LUT entry (128)
L_{max}	measured luminance for pixel value 255
L_{min}	measured luminance for pixel value 0 (zero input)
L0	background display luminance (stimuli are superimposed on this value)
G(d)	gamma function (as a function of LUT value d)
L(p)	function representing a linear relation between image pixel value (p) and luminance ($1 \leq p \leq 255$)
C(p)	correction table, inverted gamma function.

In Fig. 7 most of these quantities are shown.

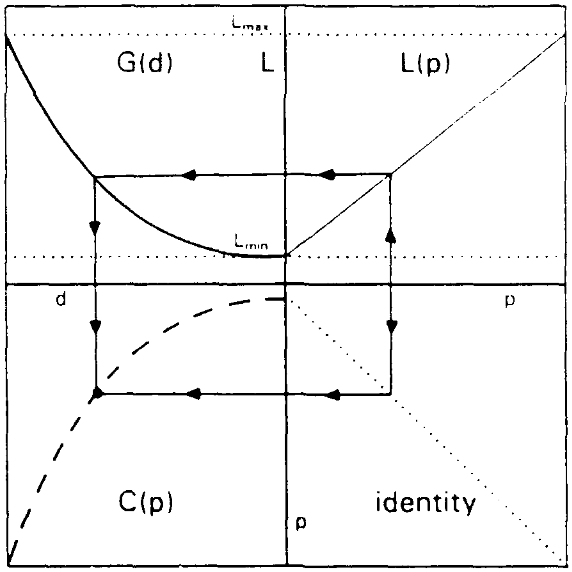

Fig. 7 Graphical demonstration of linearizing a CRT. See the text in sections 3.3.1 and 3.3.4 for details.

Fig. 7 illustrates how the correction table C(p) is constructed. The upper left quadrant shows the gamma function G(d) as it is actually measured: recorded luminance as a function of LUT entry. The minimum luminance L_{min} (≥ 0 cd/m^2) is obtained for LUT entry 0, L_{max} for LUT entry 255. The desired relation L(p) is shown in the upper right quadrant: a linear relation between image pixel values and screen luminance. (note that a different desired relation can also be used.) Since p=0 is used to produce the stimulus background luminance L0, L(1) (and not L(0)!) equals L_{min}; L(255) equals L_{max}. The image pixel values are identical to LUT addresses, which is shown by the mirror operation in the lower right quadrant. Finally, the lower left quadrant shows how the output LUT behaves: it uses image pixel values p as addresses and translates these p's into d's, the LUT entries. These d's are converted to analog values (voltages) by the output DAC and are displayed on the screen.

3.3.2 *Procedure to determine the background luminance L0*

In pseudo-code:
1 Set green LUT to 0.
2 Load the value of 255 into the red LUT.
3 Record the screen luminance as L_{max}.
4 Load the value of 0 into the red LUT.
5 Record the screen luminance as L_{min}.
6 Compute the mean luminance $L0 = (L_{max} + L_{min}) / 2$.

This procedure, however, is not used in the present setup. We calculate L0 from the gamma function of the red channel, according to step 6 in the algorithm, since L_{min} and L_{max} are already available in the measured function.

3.3.3 *Available contrast*

Since there are only 256 possible inputs d, the gamma function G(d) is stored as a table of 256 luminance values corresponding to particular digital inputs. We wish to arrange a linear relation between pixel value p and screen luminance of the form:

$$L(p) = L0\left(1 + C\,\frac{p-p0}{p0}\right) \tag{2}$$

where C is the available contrast, the maximum contrast that can be generated on a background L0. Since $L(0) \geq L_{min}$, we have:

$$C \leq C_{max} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \tag{3}$$

C_{max} is the maximum possible contrast. If $L_{min} = 0$ (i.e. the display can generate a black level of zero luminance) and L0 is set to the mean display luminance ($=(L_{max}+L_{min})/2$), a contrast of 100% can be achieved and C_{max} is equal to 1. In the linear relation of eq. (2) p0 is mapped to L0, regardless of the value of C. It represents a background level on which positive and negative signals can be superimposed.

3.3.4 *Inversion of the gamma function*

The required linear relation between image pixel value p and screen luminance can be described by:

$$L(p) = L0\left(1 + C_{max}\,\frac{p-p0}{p0}\right) \tag{4}$$

and this relation is depicted in the upper right plane of Fig 7. A linear mapping like this is obtained through a procedure illustrated in the same figure. Consider an image pixel value p. By drawing a straight line up from p until the linear relation L(p), and then straight over to the ordinate we find the desired luminance value L(p). In order to find which lookup table input value yields that particular luminance, travel along a horizontal line at ordinate level L(p) to the curve of the gamma function G(d) and drop down to the abscissa. The point where you hit the d-axis is the entry that should be put into the correction (look-up) table C (at address p) to obtain a linear output. This procedure effectively inverts the gamma function G(d) and the inverted table C(p) is also depicted in Fig. 7. The actual software procedure is outlined in the next section.

3.3.5 *Procedure for finding the gamma correction table C(p)*

1 Measure G(d).
2 For each p from 1 to 255
   3 Compute L(p) from Eq. 4.
   4 Find that d (in the range 0..255) for which the value of G(d) is nearest to L(p).
   5 Set C(p) equal the selected d.

Note that p=0 is reserved for the stimulus background. Therefore, when C(0) is filled with [mean_red], the LUT entry for which the screen luminance is nearest to L0, the gamma correction table C(p) can the be used directly as a lookup table to linearize the display.

3.3.6 *Usable levels*

If the gamma function were linear, there would be a 255 distinct luminance levels (one for each LUT entry). But when the relation is non-linear, the table C(p) will have some levels that are used several times, while others are skipped over. This means that there are fewer levels than 255 that are actually used. The number of different levels in C(p) is called the number of *usable levels*. The more nearly linear the display is, the higher the number of usable levels. The linearity of the display depends on the settings of the contrast and brightness controls of the monitor. By carefully adjusting these controls and after repeated calibrations, the number of usable levels in the gamma correction table can be maximized. To facilitate this process, the controls on the monitor each have lockable ten-turn potentiometers with a scale. In practice, we found that a calibration that yields fewer than 170 usable levels (equivalent to about 7.4 bit) should be rejected.

3.4 **Extension to two channels**

When contrasts lower than C_{crit} are displayed, two channels are used. In this case the G_LUT is rotated to produce the required contrast and the R_LUT is filled with a constant value [red_offset] (see section 2.3). The maximum contrast that can be displayed through the attenuated channel is C_{crit}. For a linear monitor this should be equal to the attenuation factor for the green channel (*f*, 1/16 in our setup), but for a non-linear display this value is larger by a factor equal to the slope of the gamma function in the point L0. The exact value is determined experimentally as part of the calibration procedure.

3.4.1 *Procedure to determine [red_offset]*

The exact procedure to determine [red_offset] is as follows:
1 Select a start value for [red_offset] between 0 and 255.
2 Load [red_offset] into R_LUT.
3 Load the value of 255 into G_LUT.
4 Record the screen luminance as [green_max].
5 Load the value of 0 into the G_LUT.
6 Record the screen luminance as [green_min].
7 Set [green_mean] = ([green_max] + [green_min]) / 2.
8 If [green_mean] ≤ L0, increase [red_offset] and go back to 2.
9 If [green_mean] > L0, decrease [red_offset] and go back to 2.

This procedure is repeated until no further adjustments in [red_offset] bring [green_mean] any closer to L0. In practice we may assume that the green channel is approximately linear and therefore we use a different procedure which incorporates this assumption. The alternative is as follows:
1 Select [mean_red] as startvalue for [red_offset].
2 Load 128 into the G_LUT.
3 Repeat
   4 Load [red_offset] into R_LUT.
   5 Measure the luminance L.
   6 If L > L0, decrease [red_offset].
   until |L - L0| is minimal.

3.4.2 *Linearization of the green channel*

The luminance range of the attenuated green channel is limited to a small part of the total luminance range of the display and is situated around L0 (when [red_offset] is loaded into the R_LUT). The monitor is roughly linear in this limited range, and we have the choice to either assume that it is perfectly linear or to calibrate it accurately.

In the first case we use a linear ramp function, with 255 usable levels, as correction table, in the latter case we measure the gamma function of the green channel and use its inversion as correction table. The inversion however, is not trivial since the luminance steps in the attenuated channel are so small that they are smaller than the measurement accuracy of our Pritchard photometer. Therefore, the gamma function of the green channel is rather "noisy" and hard to invert.

In practice we assume the gamma function of the monitor to be linear in the limited range and a 255 level ramp function is used as correction table for the green channel.

3.4.3 *Procedures to measure the critical contrast*

There are two ways to determine C_{crit}. Procedure A is a simple one that assumes that the screen is perfectly linear in the attenuated range; only two luminance measurements are used. Procedure B is more accurate and takes luminance measurements over the whole attenuated range into account.

Procedure A

1 Load test pattern into image memory.
2 Load [red_offset] into R_LUT.
3 Load 255 into the G_LUT and record the screen luminance as [green_max].
4 Load 0 into the G_LUT and record the screen luminance as [green_min].
5 Calculate the critical contrast as

$$C_{crit} = ([green\_max] - [green\_min]) / ([green\_max] + [green\_min])$$

Procedure B

1 Load test pattern into image memory.
2 Load [red_offset] into R_LUT.
3 Record the green channel Gamma function.
4 Fit a linear regression line through to the luminance measurements.
5 Calculate the critical contrast as

[green_min] = calculated luminance for G_LUT = 0
[green_max] = calculated luminance for G_LUT = 255

$$C_{crit} = ([green\_max] - [green\_min]) / ([green\_max] + [green\_min])$$

In practice we use a modified version of procedure A because our present Conrac monitor appears to be almost linear in the attenuated range. We measure the whole gamma function of the attenuated channel, not only the luminances for the G_LUT values 0 and 255, and extract the values for [green_min] and [green_max] from the data.

3.4.4 *The number of usable levels*

The number of levels N, available for a given signal is proportional to its contrast and the total number of usable levels available. For the two modes of operation we find the following:

Mode 1 - one channel, high contrasts

When M1 is the number of usable levels in mode 1, the number of levels available for a signal is

$$N1 = C * M1$$

where

$$C_{crit} < C \leq C_{max}$$

For the lowest contrast that will be displayed in mode 1 this comes down to

$$N1,min = C_{crit} \cdot M1$$

In the present setup this yields, given a critical contrast of about 0.1 and 190 usable levels, 19 distinct levels for the signal. It should be kept in mind that this represents a practical but worst-case situation.

Mode 2 - two channels, small contrasts

When M2 is the number of usable levels in mode 2, the number of of levels available for a signal is

$$N2 = \frac{C}{C_{crit}} * M2$$

where

$$0 \leq C \leq C_{crit}$$

For the maximum contrast in mode 2, which is equal to C_{crit}, we find: N2 = M2, which in the present setup comes down to N2 = 255. Realize that in the attenuated green channel no linearization is performed, i.e. no correction table with an inverted Gamma function is used. For the smallest contrast of practical interest (0.005) and the critical contrast of our current setup, the number of available levels still equals 13.

The present system thus has 19 and 13 levels available for displaying the lowest possible contrasts in the two modes, corresponding resp. to 4.2 and 3.7 bits. These numbers are low but are still considered sufficient for our purposes. A possible problem is that there is a large difference in accuracy between the lower end of mode 1 (19) and the high end of mode 2 (255). A higher number of levels could be obtained by adding a third channel, as was proposed by Pelli and Zhang (1991). Whether these figures are to be considered sufficient or not depends mainly on the contrast region of interest.

4 TEST RESULTS OF MONITOR CALIBRATION

In order to investigate whether the two channel contrast control system performs accurately, we performed a test calibration and with the results of that calibration we checked how wel low contrasts were rendered on our display.

The calibration was done using our 12 bit calibration utility "Calibra" (De Reus and Valeton, 1992), which is based on the two channel contrast control system described in this report. The gamma function of our Conrac monitor was measured with the calibrated Pritchard photometer. Results are presented in Fig. 8. As calibration pattern we used a 512x512 pixels uniform field.

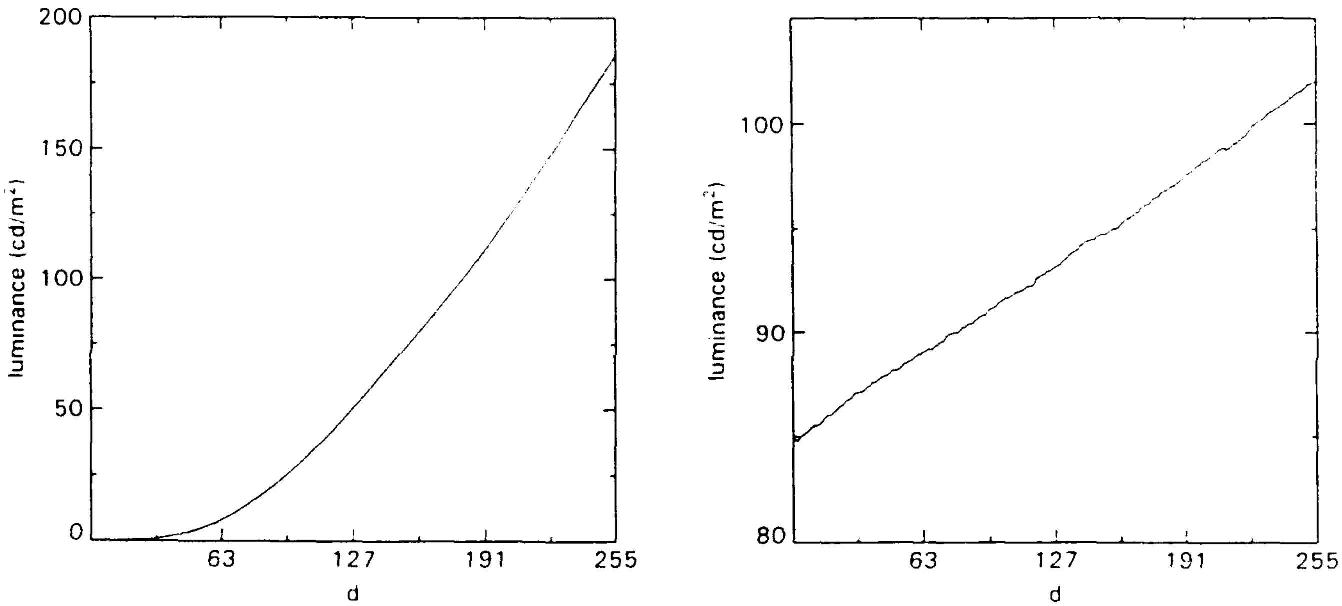

Fig. 8 Measured gamma functions for the (a: left) red and (b: right) green channel in the two channel contrast control system.

The gamma function of the Conrac monitor is shown in Fig. 8a. The attenuated green channel in Fig. 8b shows an almost linear relationship. For this reason the green channel is assumed to be linear. The green gamma function is rather "noisy" because the luminance steps are near the photometer's accuracy. The critical contrast of this calibration was 9.2%, the maximum contrast was 99.8%.

To check the influence of the calibration pattern on the results, we did calibration runs with the test patterns described in section 3.2.1. We found that the calibration pattern had no significant influence on the measured gamma functions, which indicates that our Conrac monitor has a high-voltage power supply of excellent quality. Large loads (high luminance on large areas) are rendered almost as good as smaller loads, there is only a small difference in maximum luminance.

The inverted gamma function of the red channel is shown in Fig. 9.

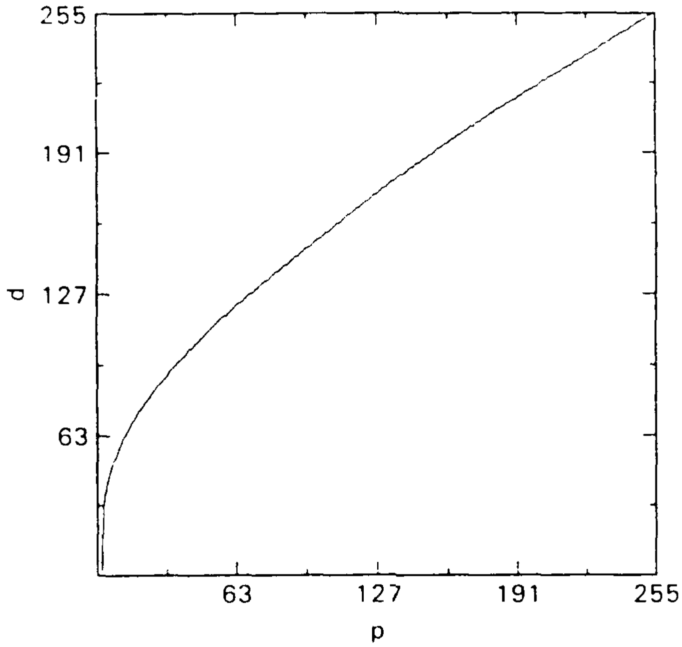

Fig. 9 Inverted gamma function of the red (unattenuated) channel. p is the image pixel value and LUT address, d the corresponding LUT entry.

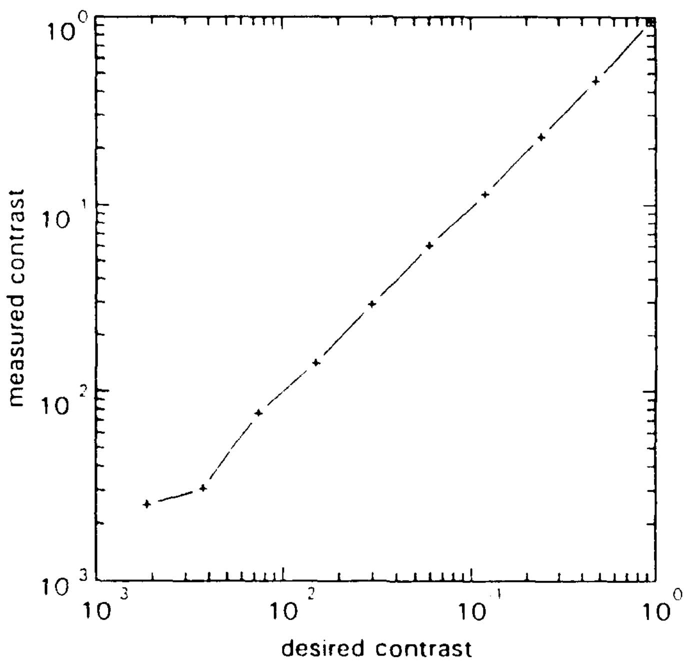

Fig. 10 Desired contrast versus measured contrast for the two channel contrast control system. Around 0.1 the system changes from 1 channel mode to 2 channel mode.

For this setting of the monitor's contrast and brightness knobs, the number of usable levels for the red channel was 190. Since the green channel is assumed to be linear, the number of usable level for that channel equals 255.

As a check on the calibration, the relation between desired and displayed contrast was determined. Contrasts were varied over 3 decades by consecutively adjusting the pixelvalue of a single region on the linearized screen. The luminances of this region were measured and afterwards contrasts were computed from these data. The results are shown in Fig. 10.

From this figure we conclude that the 12 bit system works well since contrasts over a broad range can be rendered on the monitor and no gap between the two operation modes is visible at the critical contrast (about 0.1).

REFERENCES

Pelli, D.G. & Zhang, L. (1991). Accurate control of contrast on microcomputer displays. Vision Research 31, 1337-1350.

Reus, A.J.C. de, & Valeton, J.M. (1992). Calibra user's guide. Report IZF 1992 I-2, TNO Institute for Perception, Soesterberg.

Watson, A.B., Nielsen, K.R.K., Poirson, A., Fitzhugh, A., Bilson, A., Nguyen, K. & Ahumada, A.J. Jr (1986). Use of a framebuffer in vision research. Behavior Research Method, Instrument and Computers 18, 587-594.

Soesterberg, August 25, 1992

Dr. J.M. Valeton

APPENDIX 1

SOURCE CODE FOR REAL-TIME STIMULUS DISPLAY USING TWO CHANNEL CONTRAST CONTROL

```
SUBROUTINE CMVARF2(USER, TLIST, ATTEN, BKGINDEX, CHAN,
     >              CO, NFRAMES, MODE, CRIT_CONT, CCM1, CCM2)
C*****************************************************************
C
C  Purpose:      Display stimulus with time-profile at
C                "12 bit" or "8 bit" accuracy
C
C  Method:       -
C
C  Version:      1.0  (original)
C                2.0  (other calling mechanism: CCM1 and CCM2)
C                2.01 (changed parameter checking)
C
C  Author/Date:  April 10, 1991 - Antoine J.C. de Reus (1.0)
C                April 26, 1991 - Antoine J.C. de Reus (2.0)
C                May 31, 1991   - Antoine J.C. de Reus (2.01)
C
C  Remarks:      1.  Contrary to the C version of this routine,
C                    the TLIST  m u s t  be initialized and
C                    filled with correct values.
C                2.  All contrasts are translated to a linear
C                    luminance scale by the arrays CCMx. Therefore
C                    CCM's are inverted look-up tables of the
C                    RED (CCM1) and GREEN (CCM2) channel.
C                3.  RED OFFSET is stored in CCM2(1)
C                4.  This routine calls the low-level routine
C                    VOCWR(1,...) because it is (much) faster
C                    than LUTRGFIL(). We tested VOCWR() and found
C                    that even 3 luts (RGB) could be loaded
C                    in 1 field time (field-rate 66 Hz =
C                    frame-rate 33 Hz)
C                5.  We found that the LUTs are loaded at the
C                    start of each FIELD. For interlaced modes,
C                    this means that twice as much LUTs can be
C                    loaded, than we expected before (see also 4.)
C                6.  The routine is rather time-critical. This 2.01
C                    version is written for speed, not for clarity.
C                7.  Do NOT use the Fortran function NINT() to round
C                    integer values, it will slow down the display
C                    by a factor of two (every frame instead of
C                    every field)!
C
C  Parameters:
C
C  USER        (I*4)   DeAnza user number (0..3)
C  TLIST(1)    (R*4)   List with time-profile; first
C                      element is the length of the list
C  ATTEN       (R*4)   Attenuation of the stimulus (0.0-1.0)
C  BKGINDEX    (I*4)   Background Index
C  CHAN        (I*4)   Memory plane in DeAnza
C  CO          (I*4)   Don't care
C  NFRAMES     (I*4)   Number of frames to display
C  MODE        (I*4)   Display mode:
C                         1: 1 channel (R)  "8 bit"
C                         2: 2 channel (R + G) "12 bit"
C  CRIT_CONT   (R*4)   Critical contrast; for "12 bit" mode
C  CCM1(256)   (I*4)   Luminance correction table for RED
C  CCM2(256)   (I*4)   Luminance correction table for GREEN
C
C*****************************************************************

      IMPLICIT    NONE

      INTEGER*4   USER         ! DeAnza user number
      REAL*4      TLIST(1)     ! time-list
      REAL*4      ATTEN        ! attenuation
      INTEGER*4   BKGINDEX     ! background index
      INTEGER*4   CHAN         ! DeAnza output channel
      INTEGER*4   CO           ! ?
      INTEGER*4   NFRAMES      ! number of frames
      INTEGER*4   MODE         ! "8 bit" or "12 bit"
      REAL*4      CRIT_CONT    ! critical contrast
      INTEGER*4   CCM1(256)    ! correction table (RED)
      INTEGER*4   CCM2(256)    ! correction table (GREEN)
      INTEGER*4   I, J, VOC, VINP, NT, ITT, TYNW
      INTEGER*4   VOC1, VOC2, ITT1, ITT2, CH1, CH2, VAL
      REAL*4      CONTRAST
      LOGICAL     MIXED_MODE
      LOGICAL     INITED,FIRST /.TRUE./
      REAL*4      TABLE(256), RVAL
      COMMON      INITED,TABLE
      INTEGER*2   LUT(512), VOCBUF(32) /32*0/, OLDLEV, RED_CNT
      INTEGER*2   GRN_CNT, USER2


C********* Check variables ***************************************

      NT = TLIST(1)
      IF (NT .LE. 0) GOTO 111
      IF ((ATTEN .LT. 0.0) .OR. (ATTEN .GT. 1.0)) GOTO 111
      IF (NFRAMES .LE. 0) GOTO 111
      IF ((BKGINDEX .LE. 0) .OR. (BKGINDEX .GE. 256)) GOTO 111
      IF ((MODE .LT. 1) .OR. (MODE .GT. 2)) GOTO 111
      USER2 = USER

C********* Initialize table **************************************

      IF (FIRST) THEN               ! initialize table only the
         INITED = .FALSE.           ! first time this routine
         FIRST = .FALSE.            ! is called
      END IF

      IF (.NOT. INITED) CALL DOINIT2

C*****************************************************************
C********* 8 bit mode ********************************************
C*****************************************************************

      IF (MODE .EQ. 1) THEN

C********* Setup video path **************************************

      VOC  = 0
      ITT  = -1
      CO   = 0
      VINP = 0

      CALL LUTSEL(USER, CHAN, CO, ITT, VOC)

C********* Main temporal loop ************************************

      LUT(1) = CCM1(BKGINDEX)   ! display stimulus
      DO I = 1,NFRAMES
         CONTRAST = ATTEN * TLIST(I + 1)
         DO J = 2,256
            LUT(J) = CCM1(BKGINDEX + NINT(CONTRAST * TABLE(J)))
         END DO
         CALL VOCWR(1, USER2, VOCBUF, 1, 1, 0, 256, LUT)
      END DO

      LUT = CCM1(BKGINDEX)      ! fill entire lut at once
      CALL VOCWR(1, USER2, VOCBUF, 1, 1, 0, 256, LUT)


C*****************************************************************
C********* 12 bit mode *******************************************
C*****************************************************************

      ELSE                      ! "12 bit" mode

C*****************************************************************
C
C Setup video path
C
C The VOC section 0 is used for RED, section 1 for GREEN
C At the "12 bit" connection, BLUE is not connected.
C
```

```
      CH1 = CHAN  ! memory plane for RED and GREEN
      VOC1 = 0    ! start at VOC section 0
      ITT1 = -1   ! bypass ITT
      CH2 = 1     ! memory plane for BLUE
      VOC2 = -1   ! bypass VOC
      ITT2 = -1   ! bypass ITT

      CALL LUTRGBSEL(USER, CH1, ITT1, VOC1, CH2, ITT2, VOC2)

      VOC = 0     ! use VOC sections 0 (RED) and 1 (GREEN)
      ITT = -1    ! bypass ITT

C*****************************************************
C
C Fill luts
C
C According to the actual contrast, which is TLIST(I)*ATTEN,
C use one channel (RED) or two channels (RED and GREEN).
C
C     contrast <= crit_cont --> GREEN, RED at RED_OFFSET
C     contrast >  crit_cont --> RED, GREEN all zero


      DO I = 1,NFRAMES                         ! frame loop

         CONTRAST = ATTEN * TLIST(I + 1)            ! actual contrast

         IF (ABS(CONTRAST) .LE. CRIT_CONT) THEN     ! mixed mode or not
            MIXED_MODE = .TRUE.
         ELSE
            MIXED_MODE = .FALSE.
         END IF

         IF (MIXED_MODE) THEN
            VAL = CCM2(1)     RED at RED_OFFSET
            DO J = 1,256
               LUT(J) = VAL
            END DO

            LUT(257) = CCM2(128)                    ! vary GREEN
            CONTRAST = CONTRAST/CRIT_CONT           ! scale-up to 100%
            DO J = 258,512
               VAL = 128.0 + CONTRAST * TABLE(J - 256) + 0.5
               LUT(J) = CCM2(1 + VAL)
            END DO
         ELSE
            VAL = 0                      ! GREEN zero
            DO J = 257,512
               LUT(J) = VAL
            END DO

            LUT(1) = CCM1(BKGINDEX)  ! vary RED
            DO J = 2,256
               VAL = BKGINDEX + CONTRAST * TABLE(J) + 0.5
               LUT(J) = CCM1(VAL + 1)
            END DO
         END IF

         CALL VOCWR(1, USER2, VOCBUF, 3, 1, 0, 512, LUT)
      END DO

      IF (MIXED_MODE) THEN
         VAL = CCM2(128)                ! reset GREEN to 128
         DO J = 257,512
            LUT(J) = VAL
         END DO
      ELSE
         VAL = CCM1(BKGINDEX)           ! reset RED to RED_OFFSET
         DO J = 1,256
            LUT(J) = VAL
         END DO
      END IF

      CALL VOCWR(1, USER2, VOCBUF, 3, 1, 0, 512, LUT)

      END IF ! mode 8/12 bits

      GOTO 333

C********* Error Messages *********************************

111   WRITE(6, 222) ATTEN, NFRAMES, BKGINDEX, NT, MODE
222   FORMAT(' CMVARF2(): fatal error: parameter(s) out of bounds',/,
     >        '  ( ATTEN =',F6.3,', NFRAMES =',I3,', BKGINDEX =',I3,
     >        ' NT =',I3,', MODE =',I1,' )')
      STOP

C********* Return ****************************************

333   RETURN

      END

      SUBROUTINE DOINIT2()

      IMPLICIT    NONE

      INTEGER*4   I

      LOGICAL     INITED
      REAL*4      TABLE(256)
      COMMON      INITED,TABLE

      DO I = 0, 255
         TABLE(I + 1) = I - 128.0
      END DO

      INITED = .TRUE.

      RETURN

      END
```

APPENDIX 2

CONRAC MONITOR SPECIFICATIONS

This appendix contains the main monitor specification of our CONRAC Model 2400 High-Resolution Monitor. All figures are taken from the *"Installation, Operation, and Maintenance Manual, Change 1"*, supplied by the manufacturer.

Resolution	1280 horizontal x 960 vertical pixels
Geometric distortion	No point on raster deviates from its proper position by more than 1% of raster height
Raster size stability	< 1% change from zero to 100% APL[1] at
170 cd/m^2	
Actual display size	Height: 29.46 cm, width: 39.37 cm
Aspect ratio	4:3 or 1:1
Video bandwidth	100 Hz to 40 MHz, +0/-3 dB
Sync	Internal or external
Scan rate (line frequency)	Any single scan rate from 15 to 37 kHz
Scan system	Interlaced or noninterlaced

[1] APL = average picture level

REPORT DOCUMENTATION PAGE

1. DEFENCE REPORT NUMBER (MOD-NL)	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER
TD 92-2282		IZF 1992 B-7
4. PROJECT/TASK/WORK UNIT NO.	**5. CONTRACT NUMBER**	**6. REPORT DATE**
786.1	B92-01	August 25, 1992
7. NUMBER OF PAGES	**8. NUMBER OF REFERENCES**	**9. TYPE OF REPORT AND DATES COVERED**
30	3	Final

10. TITLE AND SUBTITLE

High-resolution contrast control on a video display: Method and calibration

11. AUTHOR(S)

J.M. Valeton and A.J.C. de Reus

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Institute for Perception
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

TNO Defence Research
Schoemakerstraat 97
2628 VK Delft

14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

In visual psychophysics it is sometimes necessary to be able to display luminances with 12 bit precision. This report describes a method where two 8 bit color outputs of a DeAnza IP8400 image processor are combin d into a monochrome signal with an effective resolution of 12 bits. The implementation in hardware and software, and the calibration of the system are described. Measurements show that the system meets the desired specifications.

16. DESCRIPTORS	IDENTIFIERS
Contrast Resolution	Monitor Calibration

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)

18. DISTRIBUTION/AVAILABILITY STATEMENT	17d. SECURITY CLASSIFICATION (OF TITLES)
Unlimited availability	

VERZENDLIJST

1. Hoofddirecteur van TNO-Defensieonderzoek

2. Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie

3. { Hoofd Wetenschappelijk Onderzoek KL
Plv. Hoofd Wetenschappelijk Onderzoek KL

4, 5. Hoofd Wetenschappelijk Onderzoek KLu

6. { Hoofd Wetenschappelijk Onderzoek KM
Plv. Hoofd Wetenschappelijk Onderzoek KM

7, 8, 9. Hoofd van het Wetensch. en Techn. Doc.- en Inform. Centrum voor de Krijgsmacht

10. Ir. J.W. Klumper, TPD-TNO/TU Delft

11. Dhr. A.J.A. Bruinsma, TPD-TNO/TU Delft

12. Ir. A.N. de Jong, FEL-TNO, Den Haag

13. Ir. J.A. Boden, FEL-TNO, Den Haag

Extra exemplaren van dit rapport kunnen worden aangevraagd door tussenkomst van de HWOs of de DWOO.