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Digital System for Convergence of Three-Beam High-Resolution Color Data Displays

This paper describes a new method of generating and adjusting convergence waveforms required by a delta-gun cathode-ray tube for digital color data display applications to ensure that the primary color images produced by three guns are correctly registered with respect to each other. The display is divided into 480 zones, and a number of correction values are associated with each zone. Digital values are converted into convergence currents using special smoothing techniques to ensure that quantizing effects do not cause unacceptable image distortion. A microprogram is described which enables the total of 2016 digital correction values to be adjusted rapidly from the keyboard by a simple procedure using a crosshair adjustment pattern which is displayed sequentially at 13 positions on the screen. Special attention is paid to rounding errors which can occur during adjustment. Also accounted for in the waveform generation is the effect of phase delay between convergence coil current and its effect on the electron beams. Improvements necessary to the design of the radial and lateral convergence coil assemblies, normally found in the television industry, to reduce spot distortion and to improve sensitivity and temperature stability, are also presented. The design is realized in the IBM 3279 Color Display Station.

Introduction

The advent of the high-resolution delta-gun shadow-mask CRT with a phosphor triad pitch of approximately 0.3 mm [1, 2] has provided the basis for a high-quality color data display with a normal viewing distance of about 50 cm. At this distance the requirements for granularity of the image caused by the finite phosphor dot size, spot quality, and convergence are much more severe than for television, where viewing distances are much greater. Although the high-resolution shadow-mask CRT represents a substantial improvement in granularity and spot quality, little advancement has been made in convergence techniques compared to those available from the television industry.

The cause of misconvergence and its relation to the design of the deflection coil are well understood and have been described in the literature [3–5].

The three beams from the delta gun are required to converge statically, *i.e.*, when no deflection is applied, and also dynamically, *i.e.*, under all conditions of deflection. In a television display, waveforms generated in synchronism with the horizontal and vertical deflection currents are applied to convergence coils external to the CRT. The currents in these coils, in conjunction with internal pole-pieces, move each beam radially to achieve dynamic convergence [6].

A fourth waveform, which produces horizontal movement of the blue beam relative to the red and green beams, can be applied to a dynamic blue lateral coil assembly. Whether this waveform is needed or not depends on the required convergence accuracy, the behavior of the deflection coil, and gun placement accuracy. Use of dynamic lateral correction is uncommon in television, although it is referred to in the literature [7].

There exists relatively little published information concerning visual error rates when reading secondary color characters composed of misconverged images of primary colors. Some published work [8] indicates that misconvergence up to 67% of the spot size does not significantly increase reading error rate, but for ease of use as well as for aesthetic reasons it is desirable to keep misconvergence to not more than 25% of the spot size. Figures 1 and 2 show characters with 0% and 67% misconvergence, respectively (scale factor ×5 approx.), photographed from the screen of an IBM 3279 Color Display Station.

The IBM 3279 display for which the digital technique was developed has a maximum capacity of 2560 seven-color dual-case alphanumeric and special characters. In this display the nominal spot size is 1.0 mm, and therefore the target for maximum misconvergence is 0.25 mm in any direction at all parts of the screen, which is three to six times the accuracy normally expected from a properly adjusted good quality television monitor.

The ability to adjust the display so that all character positions are converged to a given accuracy depends on the number of adjustments that are provided. Table 1 presents an estimate of the accuracy that can be obtained on a production display as a function of the number of adjustments. Three or four controls are normally associated with a particular adjustment area on the screen. These areas are the screen center, each side of the major and minor axes, the corners, and the mid-axis areas (*i.e.*, areas centered between the screen center and the ends of the major and minor axes). Ideally there should be no interaction between the adjustments associated with each area and between areas, but this is not always the case even in high-quality displays. Although the requirements for dynamic lateral and corner convergence can be largely eliminated by selection or adjustment of the deflection yoke, this technique is very time-consuming and is impractical if very small convergence errors are required.

Furthermore, drift in convergence can occur during shipment to the customer, during relocation, or as a result of long-term mechanical changes, and must be adjusted on the customer's premises. With digital convergence, in contrast to an analog system, the problem is no longer how to achieve the accuracy potential but how to provide an operator interface so that adjustment can be carried out quickly by the user. This problem has been solved in the system which is described in this paper. This digital convergence system [9, 10] differs from conventional analog convergence in the following ways:

1. Use of a keyboard to accept user input to make the adjustment.
2. Use of a crosshair pattern which is placed sequentially at each of 13 positions on the screen and which changes as the adjustment takes place, directing the user to the next step.
3. Use of a microprogram to accept user adjustment commands associated with each of the 13 adjustment positions and to spread the information over a number of words in a digital store, according to predetermined algorithms.

Figure 1 0% misconvergence.

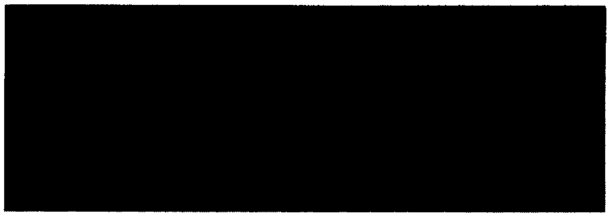

Figure 2 67% misconvergence.

Table 1 Comparison of analog convergence systems for delta-gun CRTs.

Type	*Adjustment areas*	*Controls*	*Max. misconvergence (optimum adjustment)*
Television receiver (no dynamic lateral)	5	16	1.5 mm
Television monitor (dynamic lateral on horizontal axis only)	9	30	0.75 mm
Data displays with mid-axis correction and yoke adjusted for corner and dynamic lateral correction	9	28	0.5 mm
Hypothetical display, with corner, mid-axis, and dynamic lateral correction (no yoke adjustment)	13	52	0.25 mm

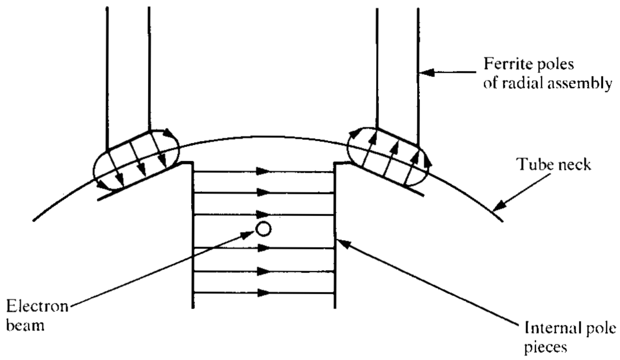

Figure 3 Magnetic field between pole pieces of external assembly and internal pole pieces of cathode-ray tube.

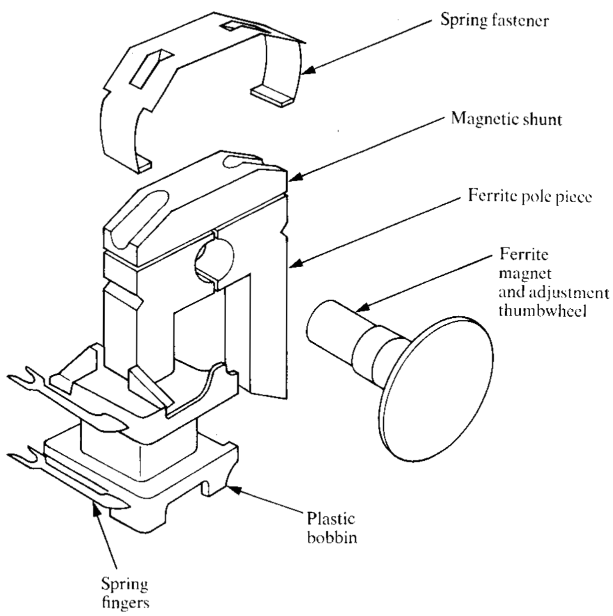

Figure 4 Radial convergence assembly (three required for each cathode-ray tube). (Note: winding not shown on plastic bobbin. Second bobbin on other leg omitted for clarity.)

4. Use of a nonvolatile store to retain the adjustment information.

In the following sections of this paper the significant aspects of the developments made in the magnetic convergence assemblies are presented, and the methods whereby the problems of digital-to-analog conversion were overcome by the chosen system organization are discussed. In addition, the major functions of the microprogram are described, concentrating on the spreading algorithms, operator interaction, and rounding problems.

Convergence coil design

• *Radial unit*

There are six major factors to be considered in the design of the radial convergence assemblies (three of which are required for a delta-gun tube). These are the following:

1. The assembly must have good magnetic coupling with internal pole pieces inside the tube neck (Fig. 3).
2. Electrically energized coils must allow for dynamic convergence correction at line and field frequency rates.
3. Means must be provided for the correction of static convergence errors (*i.e.*, due to gun misalignments).
4. Long-term stability must be ensured.
5. Spot distortion must be minimized.
6. Sensitivity should be such as to avoid high power dissipations.

A simplified and partly exploded view of the assembly used in the 3279 display is shown in Fig. 4. The magnetic fields produced by the assembly, when fitted to the tube, are illustrated in Fig. 3. The basic structure is similar to conventional TV assemblies, but certain features have been optimized for data display application.

1. Pole piece legs were shaped to fit the tube neck, with the spring fingers on the bobbins acting to provide electrical connections and also to hold the pole pieces in contact with the glass to maximize sensitivity by eliminating airgaps.
2. External and internal magnets were tested for static convergence adjustment. Magnetic field plots indicated large stray fields from external magnets, giving rise to excessive spot distortion. The cylindrical magnet structure shown in Fig. 4 (contained within the ferrite pole pieces) was thus chosen; magnetic field plots for this structure indicated virtually no stray fields.
3. Power dissipation in the circuits used to drive the dynamic coils is a function of deflection sensitivity and coil inductance; sensitivity is a function of the number of turns, while inductance increases as the square of the number of turns. Splitting the winding into two sections, one per pole piece, reduces the inductance, and the addition of the magnetic shunt has two benefits: First, sensitivity increases at a faster rate than the inductance; second, through the choice of suitable magnetic material the effect of any temperature coefficient of the magnet can be minimized.

These temperature effects are illustrated in Fig. 5, which shows the results of an experiment performed with different shunt thicknesses. The material used for the shunt was a nickel-iron alloy formulated to give a large negative temperature coefficient of permeability. The material used was Telcon Metals type 2800R alloy, but many other similar alloys exist.

• *Lateral unit*

The elimination of static and dynamic lateral convergence errors, introduced by gun misalignments and coma distortion [5] in the deflection yoke, is an important requirement in total convergence correction for a data display. A useful discussion of deflection-yoke-induced convergence errors may be found in [5]. However, because there are no internal tube pole pieces for lateral correction, and because the magnetic field structure is more complex than for the radial case, consideration of sensitivity (and, hence, circuit power dissipation) and spot distortion are critical. Basic requirements are that the blue beam should move horizontally in one direction, with the red and green beams moving in the opposite direction, that the red and green beams should not separate, and that the blue beam must not move vertically with respect to the red and green beams.

A structure with five external poles was finally implemented, as shown in Fig. 6.

The closed magnetic core reduces stray field emission, and careful placement of pole pieces gives good field uniformity to minimize spot distortion. Sensitivity was found to be largely influenced by the length of the poles on which the windings are placed. Therefore, these were sized and shaped to fit as closely as possible to the glass neck of the tube.

It is difficult to use permanent magnets in such a structure for static convergence adjustment, and extra windings for electromagnetic control are clumsy and expensive. Therefore, static control was implemented by combining dc currents and ac currents in a single winding.

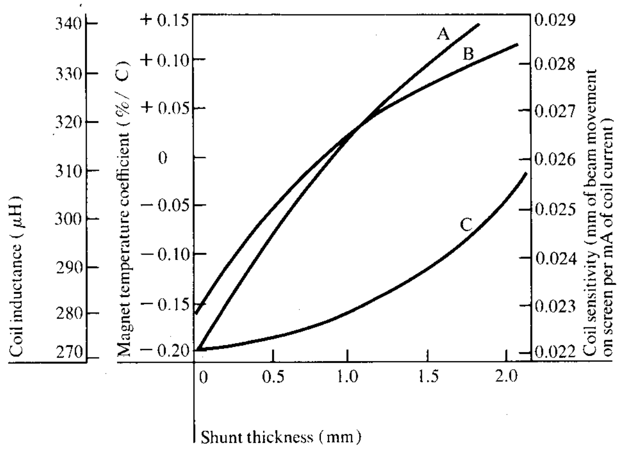

Figure 5 Effect of shunt thickness on radial convergence performance: curve A, magnet temperature coefficient; curve B, coil sensitivity; curve C, coil inductance.

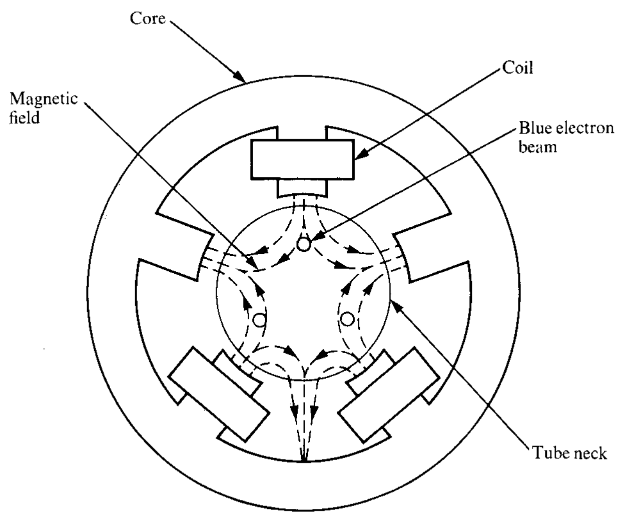

Figure 6 Lateral convergence assembly.

Digital-to-analog conversion

• *General principles*

To achieve convergence, dynamic currents are applied in synchronism with field and line rates to the coils of the one lateral and three radial assemblies. The basic shapes of the currents are modified parabolas, and of course must be smooth curves. However, since the convergence waveforms are digitally generated, a conversion process is necessary to give the required smooth analog waveforms.

• *Zone structure*

In the quantization of the waveform amplitudes introduced by digital generation, these amplitudes are changed at finite intervals during the scan period. The screen is thus effectively divided into zones, both horizontally and vertically, with a zone boundary corresponding to a change of convergence waveform amplitude. The 3279 display uses a structure of 15 horizontal and 32 vertical zones as shown in Fig. 7. The extreme left-hand zone is wider than the rest because it corresponds to the horizontal fly-back period. All zones associated with the visible parts of the screen are evenly spaced.

It is necessary to distinguish between the meaning of zones and waveforms. In Fig. 7 there is a different horizontal waveform for each of the 32 vertical zones, with

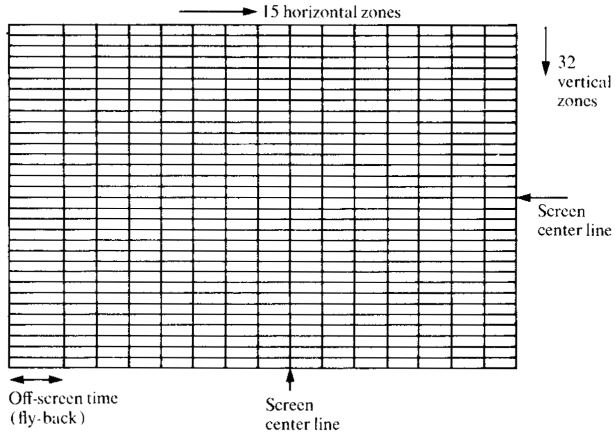

Figure 7 Illustration of zone structure.

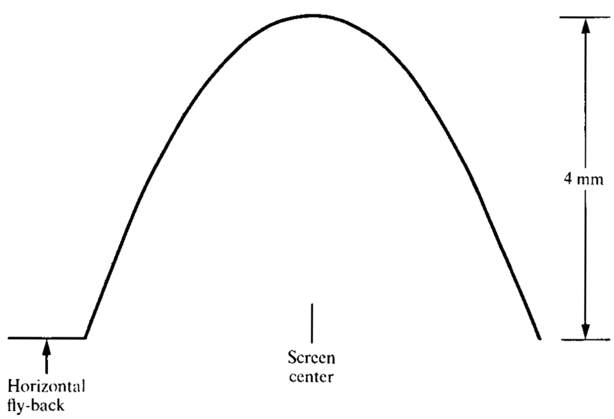

Figure 8 Typical required horizontal waveform.

the waveforms changing at the vertical zone boundary. The reason for the large number of horizontal waveforms is discussed in a subsequent section ("corners"). The amplitude of each horizontal waveform is quantized into 15 steps, corresponding to the 15 horizontal zones.

The discussion has so far been limited to horizontal waveforms (*i.e.*, waveforms in synchronism with the high-frequency horizontal scan). A vertical waveform is also generated (*i.e.*, a waveform in synchronism with the low-frequency vertical scan). This is extracted from digital storage during the horizontal fly-back period and is naturally quantized into 32 steps corresponding to the 32 vertical zones. Only one vertical waveform is produced, however, in contrast to the 32 separate horizontal waveforms.

The total convergence correction is generated by adding horizontal and vertical waveforms together.

There is no theoretical requirement to have evenly spaced zones. Indeed, since the correction waveforms are of square law form, it might appear an improvement to make the zones smaller towards the screen edges. In practice, however, the requirements to smooth the digital outputs (from D/A converters) means that even-zone (*i.e.*, constant time interval) spacing is necessary unless complex and expensive filter circuits are used.

- *Discontinuities*

If only horizontal waveforms are used, filtering could only be applied to the horizontal direction and there would be an unsmoothable step change in convergence vertically at each vertical zone boundary. It is to avoid these discontinuities that separate vertical waveforms (which can be smoothed) are generated and are added to the horizontal waveforms.

- *Corners*

If no corner correction were needed, then only two waveforms per color would be generated and added together to give the total correction. However, corner correction is essential in order to meet the convergence performance target, and for this reason a separate horizontal waveform is generated at each vertical zone boundary. The differences between these waveforms are determined by the amount of corner correction needed and by the shape of the correction waveform generated by the microprogram. Since corner corrections are implemented only by horizontal waveforms, these will introduce discontinuities. However, such discontinuities are small by comparison with the primary on-axis correction, and the number of zones in the vertical direction are selected to keep this effect to a negligible level.

- *Lateral waveform*

The lateral correction waveform is similar to the radial, except that no vertical waveforms are generated. Lateral corrections, though important, are much smaller than radial, and discontinuities introduced by the lack of vertical smoothing are too small to be visible. One major difference between lateral and radial corrections is that the radial is always positive, while the lateral may be positive or negative. Parabolic waveshapes, with mid-point and corner modifications, are still used.

- *Smoothing*

Since we have horizontal waveforms with step changes in amplitude occurring 15 times over the screen width and vertical waveforms with step changes occurring 32 times over the screen height, the step changes must be smoothed in order to eliminate discontinuities.

A typical required horizontal waveform is shown in Fig. 8. A current following this shape would be applied to one of the radial convergence assemblies described in the previous section, thereby producing a radial movement of one of the electron beams. The amplitude of the waveform is shown in millimeters, corresponding to a typical observed movement on the screen.

The waveform, however, is produced by a D-to-A converter and is thus quantized (into 15 steps). Figure 9 shows the quantized waveform. A "real-time" waveform would follow the dotted line; however, we extract the data from digital storage with a one-step advance, as shown by the solid line. This makes the waveform much more amenable to simple smoothing techniques.

Consider now just one step of this quantized waveform. A very good method of smoothing is linear interpolation between points; however, the implementation of this type of smoothing is expensive. The simplest form of smoothing is exponential, but this gives a relatively poor result with a large ripple content. An acceptable compromise was found in a second-order Bessel filter function, which has a time response to a step input [11] of the form

$$y = 1 + \left(2e^{-\frac{0.866\,t}{T_c}}\right) \sin\left(\frac{0.5\,t}{T_c} - 2.618\right),$$

where t = time, $T_c = 1/2\pi f_c$, and f_c = 3-dB frequency point.

Selection of the most suitable simple filter form was made by graphical comparison of different responses using information from [12] and [13].

Figure 10 illustrates the step responses for linear interpolation, exponential smoothing, and second-order Bessel smoothing. The Bessel smoothing clearly shows a useful improvement over exponential. The improvement is easily quantified; comparative ripple magnitudes in response to steps with different smoothing approaches are given in Table 2.

By utilizing the convergence coil as part of the filter transfer function implementation, only one extra capacitor is needed for second-order Bessel compared to exponential smoothing.

There is an additional advantage with second-order Bessel compared to exponential smoothing, which is apparent between successive steps of the digital waveform. As shown in Fig. 11, a smooth transition is obtained with second-order Bessel smoothing. On the other hand, exponential smoothing results in a rather sharp transition. The smooth transition is a further help in reducing visual effects of discontinuities.

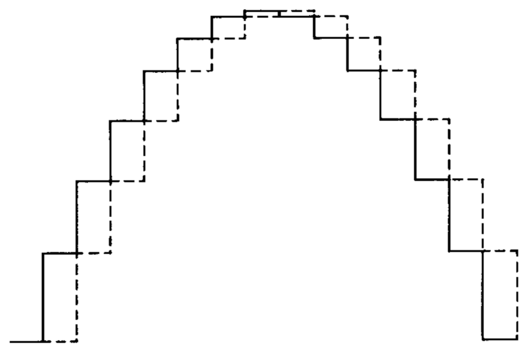

Figure 9 Quantized waveform.

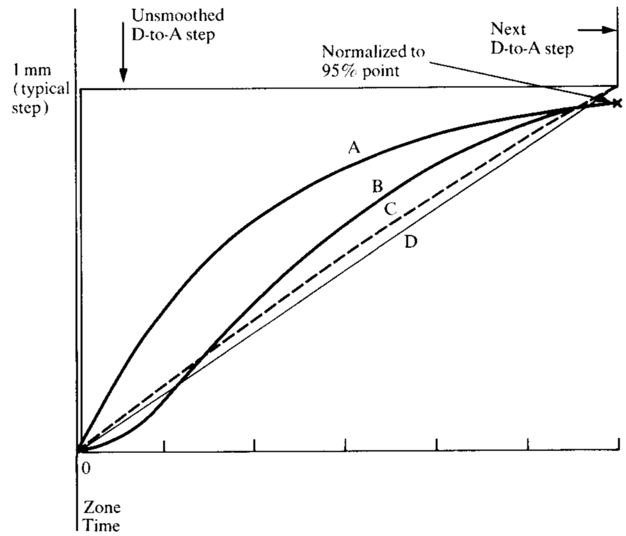

Figure 10 Step responses for different types of smoothing: curve A, exponential; curve B, second-order Bessel; curve C, desired waveform (parabolic); curve D, linear interpolation.

Table 2 Ripple (*i.e.*, departure from ideal waveform) produced by various smoothing circuits on a D-to-A step.

	Unsmoothed D-to-A step (mm)	*Ripple* (mm)		
		Exponential	*Bessel*	*Linear*
Horizontal	1.00	0.26	0.13	0.03
Vertical	0.30	0.14	0.06	0.02

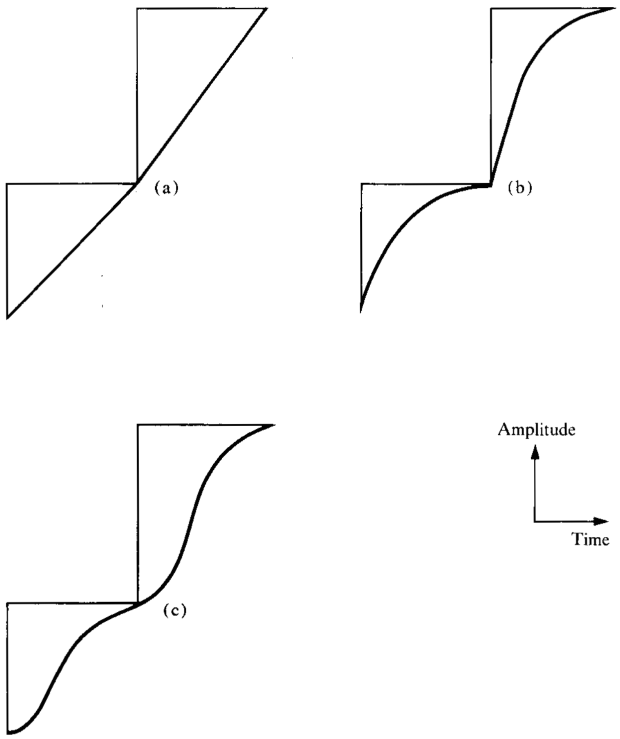

Figure 11 Effect of different types of smoothing on successive steps of a digital waveform: (a) linear interpolation; (b) exponential smoothing; (c) second-order Bessel smoothing.

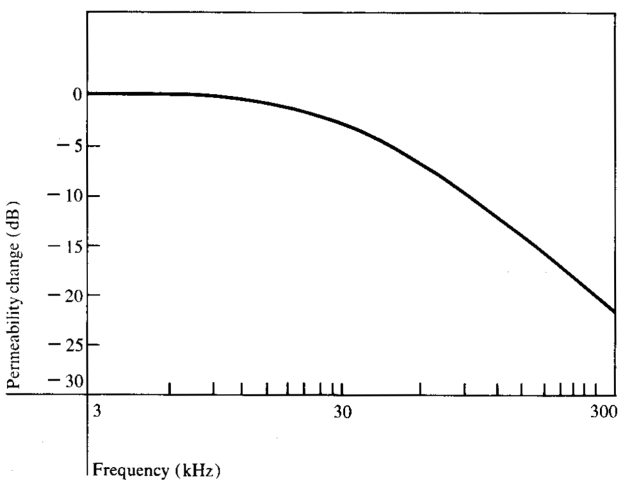

Figure 12 Permeability change, with frequency, of internal radial convergence pole pieces.

• *Frequency response, phase delay*
Field rates are relatively slow, so that circuit frequency responses are no problem. However, line rates are of the order of 15 kHz so that magnetic circuits must be carefully designed to avoid dynamic response problems.

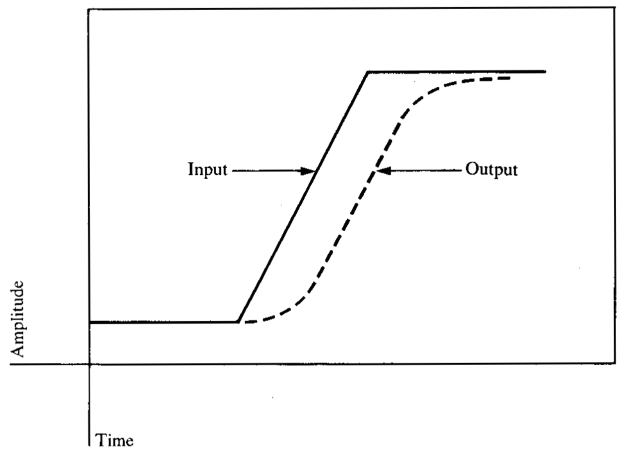

Figure 13 Response of a low-pass filter to a ramp input.

A delta-gun CRT contains internal pole pieces to direct the radial convergence magnetic fields. These pole pieces are made from high-permeability magnetic strip which has a permeability-frequency response illustrated in Fig. 12.

The 3-dB point of this curve is less than the significant frequencies in the magnetic fields produced by the convergence coils, so that the field in the pole pieces has typical low-pass filter characteristics. Consider a low-pass filter driven by a ramp source input similar to one step of the smoothed digital waveform previously discussed. The response of such a filter is illustrated in Fig. 13.

The output response closely approximates a time- or phase-delayed replica of the input. The time delay in the tubes used in the 3279 display is about 2.5 μs. Since one zone of the quantized horizontal waveform is about 3.7 μs (equivalent to about 20 mm across the screen), the time delay has a pronounced visible effect which is particularly noticeable in a bowing of blue horizontal lines at the left of the screen. This problem was overcome by a combination of phase advance on the start of the convergence waveform generation and the use of optimally shaped mid-point correction waveforms.

Logical structure

• *Principal objective*
Using the analysis, to be given subsequently in this paper, that convergence current waveforms are basic parabolas

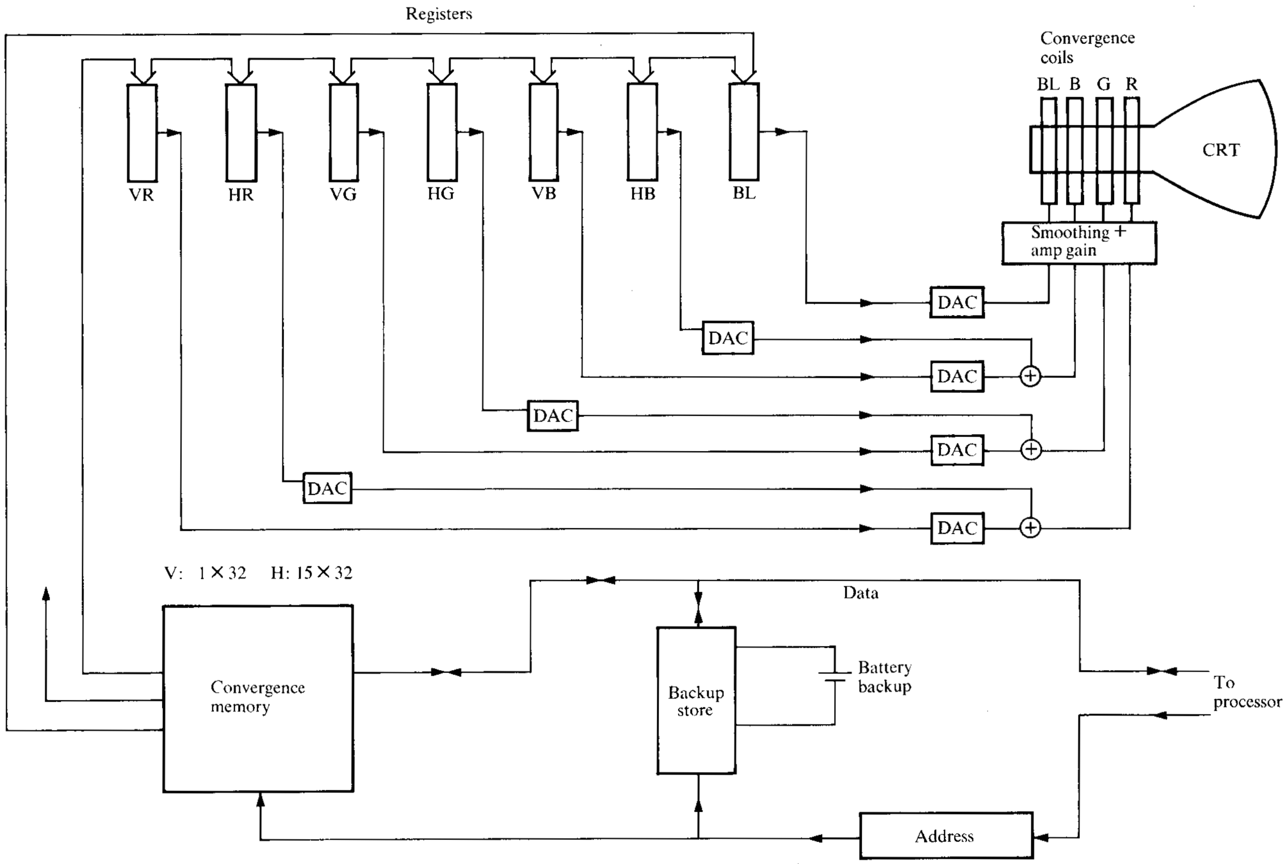

Figure 14 Logical flow of data to convergence coils. Key: V—vertical channel; H—horizontal channel; R—red; G—green; B—blue; BL—blue lateral; DAC—digital-to-analog converter.

with predictable higher-order terms, we derived a simple procedure to reduce the number of steps required to converge the display. It was clear that with a zone structuring system it is necessary to have a random access memory (RAM) device that maps over the structure. By altering the value in one of the RAM words, only one zone area on the screen would visually change.

Advantage was taken of the alphanumeric keyboard attached to the display for selecting function keys to perform logical steps through a procedure under microprogram control.

- *Convergence memory format*

With four convergence coils and a matrix of 32 vertical and 15 horizontal zones for the horizontal channel, the requirement was a RAM with 32 × 15 × 4 = 1920 addressable words. In addition, the vertical channel requirement resulted in 2016 words; therefore a 2048-word RAM was chosen. Figure 14 illustrates the logical flow of data to the convergence coils. The backup store is required if the device is to be powered off because all the data in the RAM will then be lost. As will be explained later, the backup store does not need to hold all of the 2048 RAM words.

Operator procedure

- *Screen pattern*

In order to reduce the number of operator adjustments, the screen was divided into thirteen adjustment areas. In each area a pattern was displayed and the operator was asked to adjust this pattern so that the primary colors visually merge together. We experimented with patterns containing various combinations of secondary colors and white, and concluded that minimum operator confusion resulted from the use of the secondary colors, namely magenta, a combination of red and blue, and yellow, a combination of red and green. We chose the vertical stroke symbol and minus sign, in a symmetrical pattern. Figure 15 illustrates the pattern and the thirteen adjustment areas as the operator steps through the procedure.

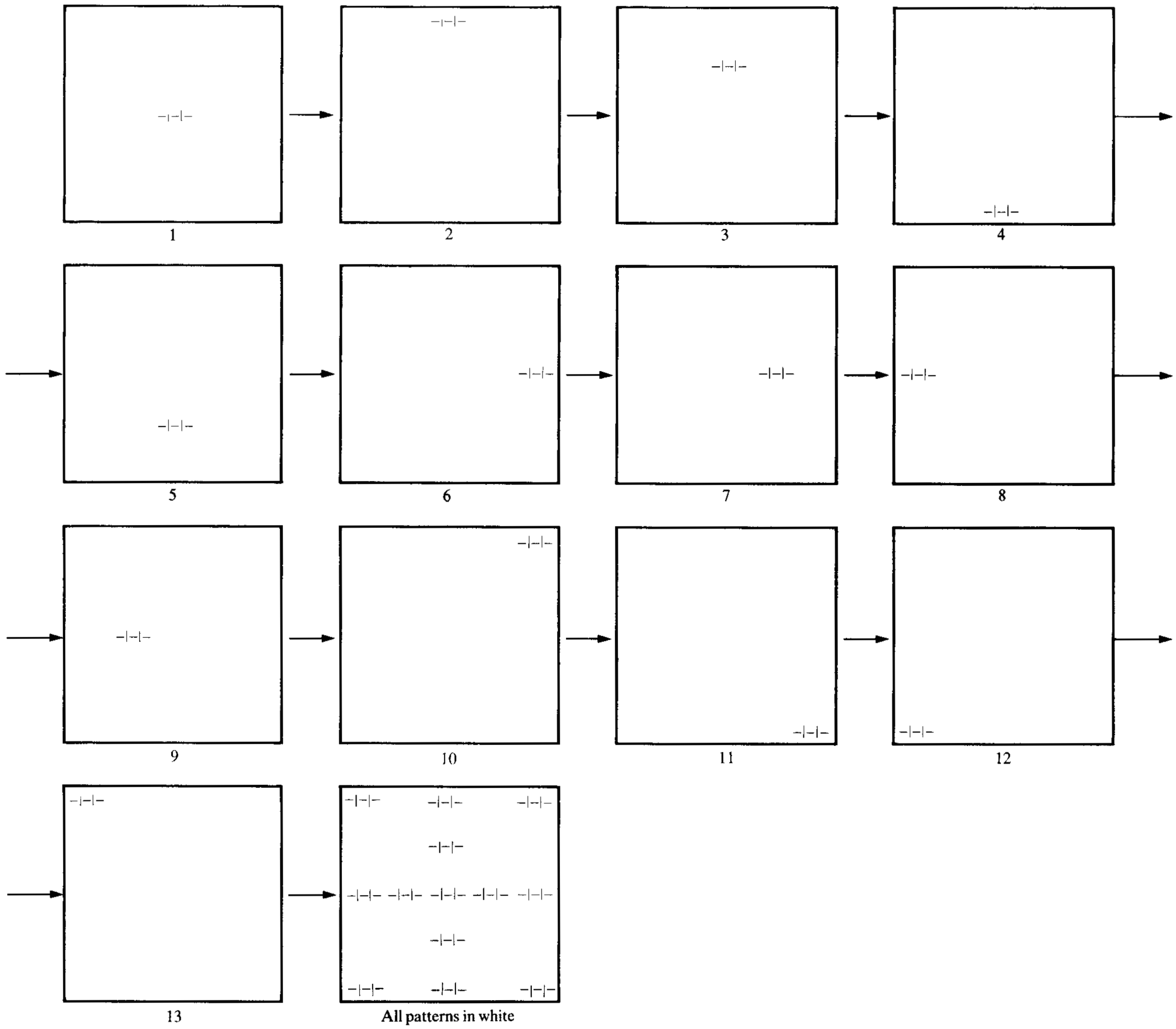

Figure 15 Operator procedure convergence pattern, illustrating the 13 adjustment areas. Arrows represent depression of space bar.

- *Choice of keys*

The most logical key to use for selecting the next adjustment area, as shown in Fig. 15, was the space bar.

The obvious qualities of the cursor move keys, repeat rate, and key inscriptions presented us with no human factor problems except the choice of which color should move in the direction of the arrow on the key inscription. Table 3 describes each of those function keys with the result that the operator views the convergence pattern in each adjustment area in two color modes, namely yellow and magenta.

In accordance with usual practice, matrixing of red and green radial movements was provided, in this case by the microcode, translating these to horizontal and vertical movements only. In other words, when the yellow pattern is viewed, the green color moves with respect to the red in response to the operator's key controls, and the blue color moves with respect to the red when the magenta patterns are viewed, thus aligning the three guns with respect to one another. As a final check of the overall convergence, all thirteen area patterns are displayed in white.

Microprogram functions

- *Shape tables*

Associated with each adjustment area on the screen is a waveform which is represented in the convergence memory by a group of zones whose values range from small in

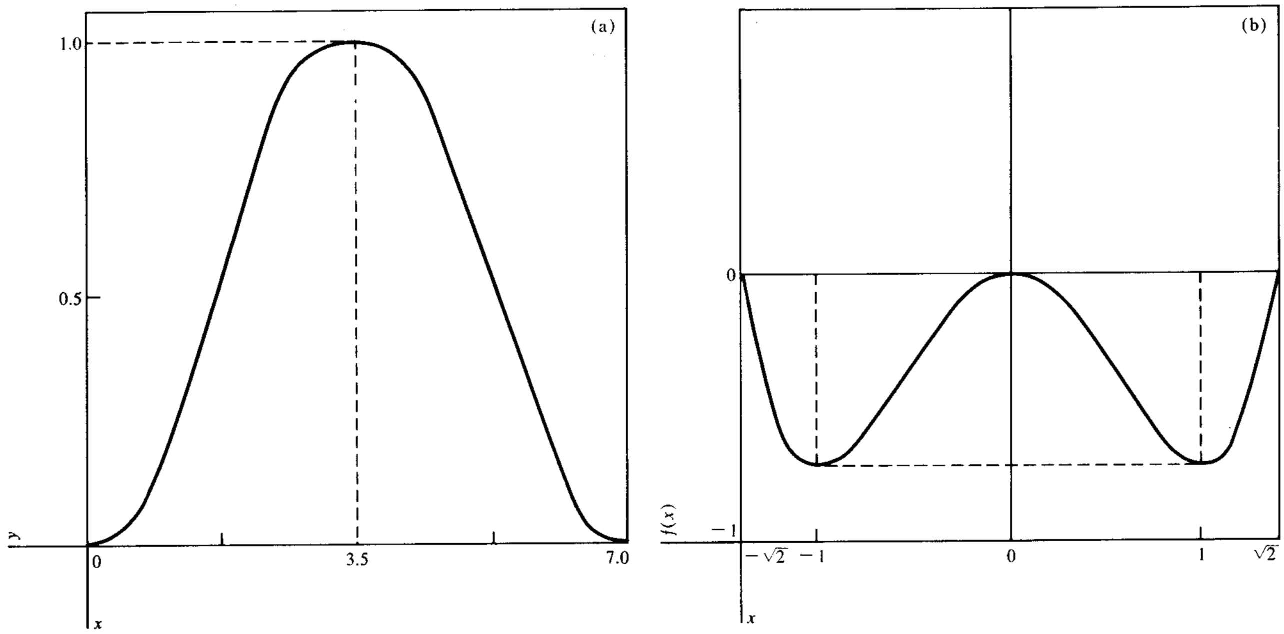

Figure 16 Mid-point correction waveshape: (a) the required quartic waveshape; (b) mathematical model of the required waveshape.

the screen center to large on the screen edge. Since the screen zone representation is symmetrical about the X and Y axes, we derived the basic parabolas X^2 and Y^2. However, further adjustments were required in the mid-point areas of the axes and corner areas. This resulted, together with the center static condition (dc values), in a total of six different shapes for all thirteen adjustment areas. All six shapes were kept under microprogram control in tabular form where values varied between 1.0 and 0.

- *Shape derivation*

The on-axis waveforms are known to approximate parabolas along the vertical and horizontal axes [6]. As a generalized expression for the correction current I at a distance r from the screen center, experiments and observation lead to the following equation:

$$I = A + Br^2 + Cr^4 + Dr^6 + \cdots.$$

The constant term A is the static value, and as the screen center is converged this term is assumed zero. If powers greater than r^2 are assumed small, then r^4, r^6, $\cdots$ may also be regarded as zero, and the equation reduces to

$$I = Br^2, \qquad (1)$$

a parabolic shape.

If the quartic terms are considered (see Fig. 16), then

Table 3 Operator procedure keys and their functions.

Key	*Color mode*	
	Yellow	*Magenta*
Cursor up	Moves green relative to red up.	Moves blue relative to red up.
Cursor down	Moves green relative to red down.	Moves blue relative to red down.
Cursor left	Moves green relative to red left.	Moves blue relative to red left
Cursor right	Moves green relative to red right.	Moves blue relative to red right.
Space bar	Changes color of pattern to magenta.	Changes to next screen position.
"R"	Changes color of pattern to magenta.	Changes color of pattern to yellow.

$$I(r) = A + Br^2 + Cr^4.$$

From Fig. 16, transforming the required waveshape for a seven-zone system (center to screen edge) to a mathematical model in Fig. 16(b), as a generalized expression:

$$f(x) = a(x^4 + bx^2 + c), \qquad f'(x) = a(4x^3 + 2bx). \qquad (2)$$

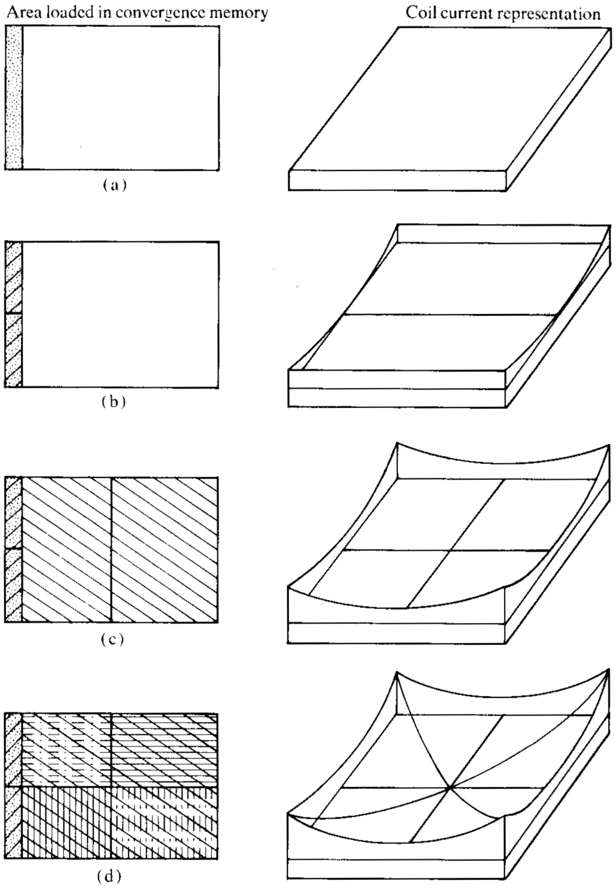

Figure 17 Relationship between convergence memory and current waveforms for red, green, and blue. Left side shows sections of memory affected during adjustments (a) to position 1; (b) to positions 2-5; (c) to positions 6-9; (d) to positions 10-13.

It is true to say, for maxima and minima, that

$$f'(-1) = f'(0) = f'(1) = 0.$$

Then, since $f(0) = 0$, from Eq. (2), $c = 0$. Also, since $f'(\pm 1) = 0$, then $a(4 + 2b) = 0$, and therefore $b = -2$ and $f(x) = a(x^4 - 2x^2)$.

Substituting $f(\pm 1) = -1$, $a(1 - 2) = -1$, and therefore $a = 1$. Substituting in Eq. (2),

$$f(x) = x^2(x^2 - 2). \quad (3)$$

Now, transforming the general waveshape equation to the required correction for a seven-zone system, we have

$$y - 1 = f\left(\frac{x - 3.5}{3.5}\right) = \left(\frac{x}{3.5} - 1\right)^4 - 2\left(\frac{x}{3.5} - 1\right)^2.$$

Therefore, for an n-zone system, the expression may be written as

$$f\left(\frac{2x}{n} - 1\right) = \left(\frac{2x}{n} - 1\right)^4 - 2\left(\frac{2x}{n} - 1\right)^2,$$

where $I(r) \equiv f(x)$.

By using the ability to apply different waveforms to the convergence system simply by changing the shape tables, we experimented with several types of waveforms for corner correction. We concluded that a quartic term gave the best results over many CRT and deflection yoke combinations. Parabolic terms along the screen edge and the product of these terms, x^2y^2, tending to zero at the screen center, give a matrix shape table of 8 × 16 words.

- *Screen positions*

Each adjustment area was assigned a screen position from 1 to 13. By pressing the cursor move keys, the pattern would either converge or diverge. The relationship between convergence memory and current waveforms is shown in Fig. 17. For screen positions 1 to 5 [Figs. 17(a) and (b)] in the red, green, and blue colors, values were written to the vertical channel; for screen positions 6 to 9 [Fig. 17(c)], the horizontal channel from center to the screen edge which was contained by that screen position was written; for the corners [Fig. 17(d)], each quadrant was written. Blue lateral, a special case with no vertical channel, was treated in a different manner.

- *Special case of blue lateral*

With no vertical channel, the entire horizontal matrix for blue lateral was updated during the adjustment procedure. Figure 18 illustrates an example of this special case as the waveforms build up when the convergence memory is loaded. When adjusting screen positions 6 to 9 [Fig. 18(c)], the center component remains intact in the convergence memory. The operator, naturally, does not see the effect of these values, but they remain there as a record of the adjustments required in positions 2 to 5. Only when corner areas are selected does the center component become relevant and it is therefore introduced to the convergence memory by using matrix manipulation from screen center to screen corner.

- *Zone strips and spreading*

Strips of zones are read from or written to the convergence memory. The zone strip is a vertical or horizontal line of zones. For adjusting positions 1-5, the vertical channel zone strip is written, *i.e.*, a sixteen-word buffer is required to transmit to the memory. In screen positions 6-9, a zone strip of eight words are held as a buffer and arithmetic matrix manipulations are used to spread the values in memory. Each word of the buffer is copied down the memory from screen center to screen edge. This gives a waveform either side of screen center (Fig. 17).

In the blue lateral case for screen positions 1-5, the entire horizontal channel is affected by spreading a sixteen-byte buffer. Each word is copied across the memory from screen edge to screen center (Fig. 18).

Corner areas are taken as zone strips which are read from memory as eight data words into a buffer. Two zone strips are read and adjustments are made on those values. Only when the next area is selected is the remaining quadrant of memory for the current area, eight horizontal and fourteen vertical zones, spread. The multiplier for the number of times that the shape table is added to the zone strip is equal to the count of keystroke adjustments required in the current corner area. Each zone strip, up to fourteen, is read, updated, and then written to the convergence memory.

- *Backup store*

Figure 14 illustrates the use of a backup store. Since the keystroke adjustment counts are used as multipliers, values for the entire convergence memory can easily be recomputed by storing these counts for the thirteen areas and four colors, in the backup store. At the time the device powers on and the display is in its "warm-up" period, the microprogram reads these multipliers and recomputes values for the convergence memory using the same method as for the operator procedure. Thus, the display is converged typically two or three seconds later.

Waveforms and rounding

- *Waveform buildup*

Each waveform is built up by a process of addition of the shape table to a buffer and transmission of the buffer value to convergence memory. For screen positions 2 to 5, each zone strip is sixteen words, the shape table is sixteen words, and this table is either added to or subtracted from the sixteen-word buffer depending on which cursor move key was pressed. The waveform buildup can be expressed as

$$I(x, y) = \lfloor f(x, y) + 0.5 \rfloor. \quad (4)$$

The buffer values consist of integer and fraction parts, where the fraction builds up and overflows to the integer. The integer I is the section of the buffer which is transmitted. The 0.5 in Eq. (4) is the initialized fraction part to give automatic rounding.

- *Compensation for magnetic lag*

As described earlier, phase advance is introduced into the convergence waveform timing to compensate for the low-pass filter effect of the radial convergence pole pieces. Phase advance is, of course, only a partial solution, so the microprogram was used to enhance the compensation.

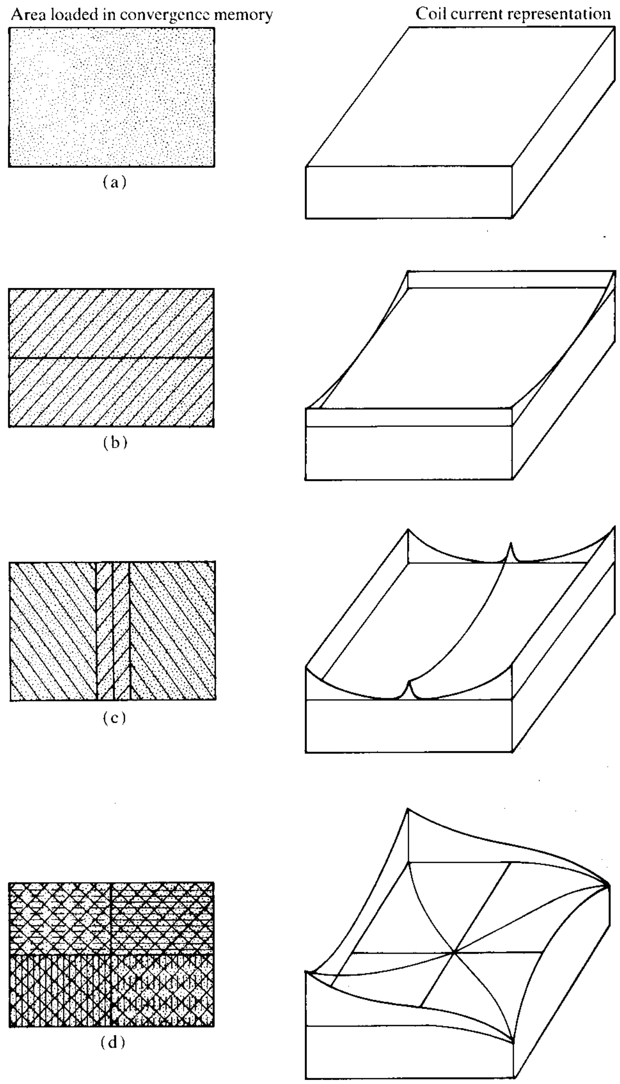

Figure 18 Relationship between convergence memory and current waveforms for blue lateral only. Shading illustrates section of convergence memory buildup of values. Left side shows sections of memory affected during adjustments (a) to position 1; (b) to positions 2-5; (c) to positions 6-9 (note: center column left intact from adjustments made in positions 2-5); (d) to positions 10-13.

An alternative shape table was derived, by experiment, for horizontal mid-axis correction and Eq. (3) was only implemented in the Y plane. This shape was a ramp that rose sharply and decayed linearly, as illustrated in Fig. 19.

- *Accumulation of errors*

For reasons of economy the D/A converters were limited to six bits, and the main disadvantage of this limitation

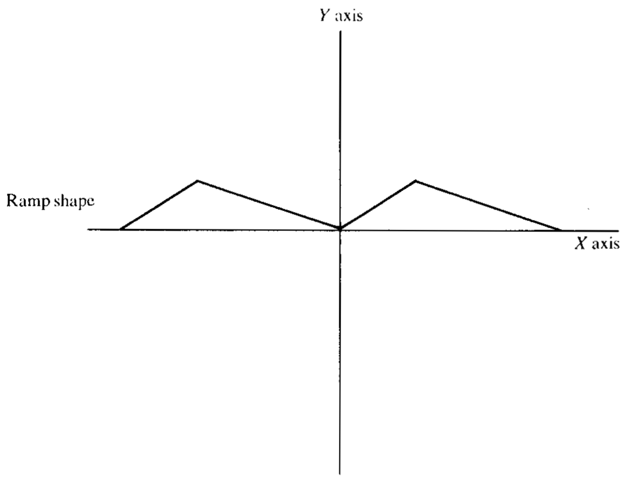

Figure 19 Ramp shape used to compensate for magnetic lag.

was that least-significant-bit errors would accumulate to become significant. The initially developed algorithm read zone strips from the area converged, updated these values, and spread them in the convergence memory. The fraction part was initialized to 0.5 prior to updating. This did not reflect the buildup of the fraction part, which meant that single changes and continuous re-reading of the same strip accumulated errors. The improved procedure was to recalculate each integer part by using the backup-store count as a multiplier, following the method used when powering on the device. This initialized the fraction part to the correct rounding condition and eliminated single-bit error accumulation.

Nominal set of values

Some interaction occurs between beams, when adjustments are made, due to stray magnetic fields. The interactions are small but noticeable when large adjustments are made. We considered the idea of using the microprogram to eliminate the effect of interaction, but we found that use of a nominal set of values and the "R" key for regression to the previous color pattern was quite satisfactory. The nominal set of backup-store values was derived by analysis of a representative population of displays which, on power up, would put the display in a nominally converged state. To complete the screen convergence, the operator procedure is entered and each area is taken sequentially. The provision of nominal values has the following benefits.

1. The number of keystrokes to be entered in the operator procedure is reduced.
2. In most cases the need for repeating the procedure due to interaction of the adjustments is eliminated.
3. A known state of convergence is provided at the manufacturing stage.
4. An immediate indication of major malfunction, *e.g.*, battery failure, is provided.

Summary and conclusion

We have described a digital convergence system for a delta-gun CRT which is equivalent, in terms of convergence accuracy, to a conventional analog system with 52 separate controls. A microprogram-driven procedure enables the user of the display to carry out the adjustment within a few minutes without special training. The system which has been developed achieves the design performance targets without imposing costly design or manufacturing constraints on either the CRT or the deflection yoke. Optimal solutions have been found and were described for the many problems of magnetic, electrical, programming, and human factors design.

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