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MAN-COMPUTER GRAPHICS: CURRENT AND NEW HARDWARE IMPLEMENTATIONS

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"VIDIOGRAPHIC": FEASABILITY AND IMPLEMENTATION

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AUTHOR'S NOTE

The length of this Thesis necessitated the work to be bound in two volumes. Volume I contains the Introductory chapters and the Appendices while Volume II discusses the proposed Interactive Graphics Console, "VIDIO-GRAPHIC", and examines its feasability, and implementation.

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PART 11

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CHAPTER 3

THE PROPOSED INTERACTIVE GRAPHICS CONSOLE "VIDIOGRAPHIC"

3.1 INTRODUCTION

The previous chapter described the requirements of an IGC and indicated the current techniques and methods in implementing them. The emphasis was mainly on the hardware requirements.

Briefly these were:

(i) a graphics display subsystem.

(ii) an information input subsystem (including an alphanumeric keyboard) capable of accepting user-specified graphic information and having user "pointability".

(iii) vector and alphanumeric generating subsystems.

(iv) a display refresh store to maintain the display information in a flicker-free mode.

(v) control and software support.

Of interest in this project are the requirements (i), (ii) and (iv). The requirements of software support is excluded because this is a hardware-orientated study, while vector and character generating subsystems are excluded also, because these are readily available, are relatively inexpensive (several hundreds of dollars), and so diversely implemented, that for any given application several options exist.

This chapter contains an introduction to the proposed IGC based on the above requirements, along with some of the problems to be encountered in realizing this IGC.

Later chapters contain a more detailed account of the derivations of some of the expressions and concepts introduced.

The proposed IGC is called "VIDIOGRAPHIC" (Video Integrated Display and Input Optical GRAPHics Interactive Console) since it is a self contained system based on TV equipment and TV-mode operation ("video") and is fully interactive between the user and the CPU; also, optical systems play a major part in its implementation.

3.2. GENESIS OF "VIDIOGRAPHIC"

3.2.1 The Display Subsystem

In choosing a starting point for the design of a workable, yet economic, IGC satisfying the above requirements, the Display Subsystem is the most logical choice. After all, presenting information graphically was, and still is, the "raison d'etre" of Computer Graphics.

It was seen in the previous chapter that a display subsystem based on a CRT was not only the most economic solution, but also perhaps the only realistic solution for some time to come, considering such factors as speed of response, size factors etc.

The most economic of CRTs are those operating in a TV-raster-scan mode; a commercial TV receiver stripped of inessentials like the audio and the RF-IF and detection stages costs in the vicinity of about $100(A).

CRTs operating in a TV-raster-scan mode are the starting point around which the proposed system is designed.

3.2.2. The Graphic Input Subsystem.

Of the Input graphics devices the only one inherently compatable with the TV-raster-scan mode is a TV camera, focussed on some area on which the required graphic input is being drawn. There are several types of TV cameras based on different photoelectric effects, but the simplest and most economical, are those cameras using "Vidicon" tubes, based on a photoconductive effect.

Vidicons also have certain desirable properties from our viewpoint. On the other hand they have disadvantages, particularly their slow speed of response to changes in illumination, which need be overcome. Vidicon cameras start in cost from about $300(A); the average cost is of the order of $800 - $1000.

A user could feasibly "write", or rather "draw", with a very narrow light-beam projecting device or pen, projected onto an area which is in turn imaged onto the Vidicon tube image target. With the scanning beams of both the CRT and the Vidicon camera synchronized to the same timing source, the CRT would display whatever was being drawn on the input area in the same relative position on the CRT screen as on the input area, by feeding the output of the TV camera into the CRT input.

The next logical step is to have projected onto the input area scanned by the Vidicon camera, an image of the CRT screen, to enable positioning of input graphics relative to displayed graphic data. This projected image, however, cannot interfere with the image displayed on the CRT; that is, it must not be detected by the Vidicon camera, otherwise a double image on the CRT display would appear (unless exact 1:1 geometrical positioning is present). After each scanning cycle, this "double" image would itself "double" again, to finally result in an apparently meaningless display.

The Vidicon must thus selectively accept data as seen on the input area, either through optical filtering or through simple light intensity level detecting, by making the user-input data of a much higher light intensity than the projected CRT background reference information.

3.2.3 The Display Refresh Storage Sybsystem.

The problem of providing a display refresh memory capable of refreshing at some 25-30Hz rate still remains. Typically the number of locations on a TV-type display approaches $4 \cdot 5.10^5$ locations. To refresh this at 25Hz requires refresh rates at just over 10Mhz; only cyclic stores can achieve these rates. Some form of fast-access random storage is still necessary to store the updating information during the interval when this information is specified, to the instant when it is injected into the cyclic memory.

The idea arose of having the TV camera look back at its own output, being displayed on the CRT screen. The input to the TV camera would, at each cycle (a TV frame time of 40ms duration), be its own output at the previous cycle. The display would thus be self-perpetuating at TV refresh rates (i.e. 25Hz) satisfying the requirement of a flicker-free display.

3.2.4 The Optics Subsystem.

An optics system is necessary to extract from this direct "line-of-sight" arrangement of the CRT scanned by the TV camera, an image of the CRT display screen,to enable direct user-specified graphics to be input and for direct user viewing. Such an optics system is the Schmidt Optical System used some years ago in domestic TV-projection receivers (243,244,245).

Similarly the electric link between the output from the TV camera and the input to the CRT need be accessed to enable input and output of graphics information between the IGC and the CPU.

3.2.5 The Storage Process.

The actual storage process, although apparently similar to a cyclic memory such as a delay line, differs from the latter in that storage, within the refresh cycle interval, is due to physical charge storage on the Vidicon photoconductive surface; the delays present due to propagation time between the CRT and the Vidicon and in the electronic link, are negligible with the refresh interval. However, the address of a particular location is, as in cyclic memories, directly related to its time location from the start or the end of the refresh cycle interval. Its numerical coordinates may be given by the horizontal scan line count and its time count within each horizontal scan line.

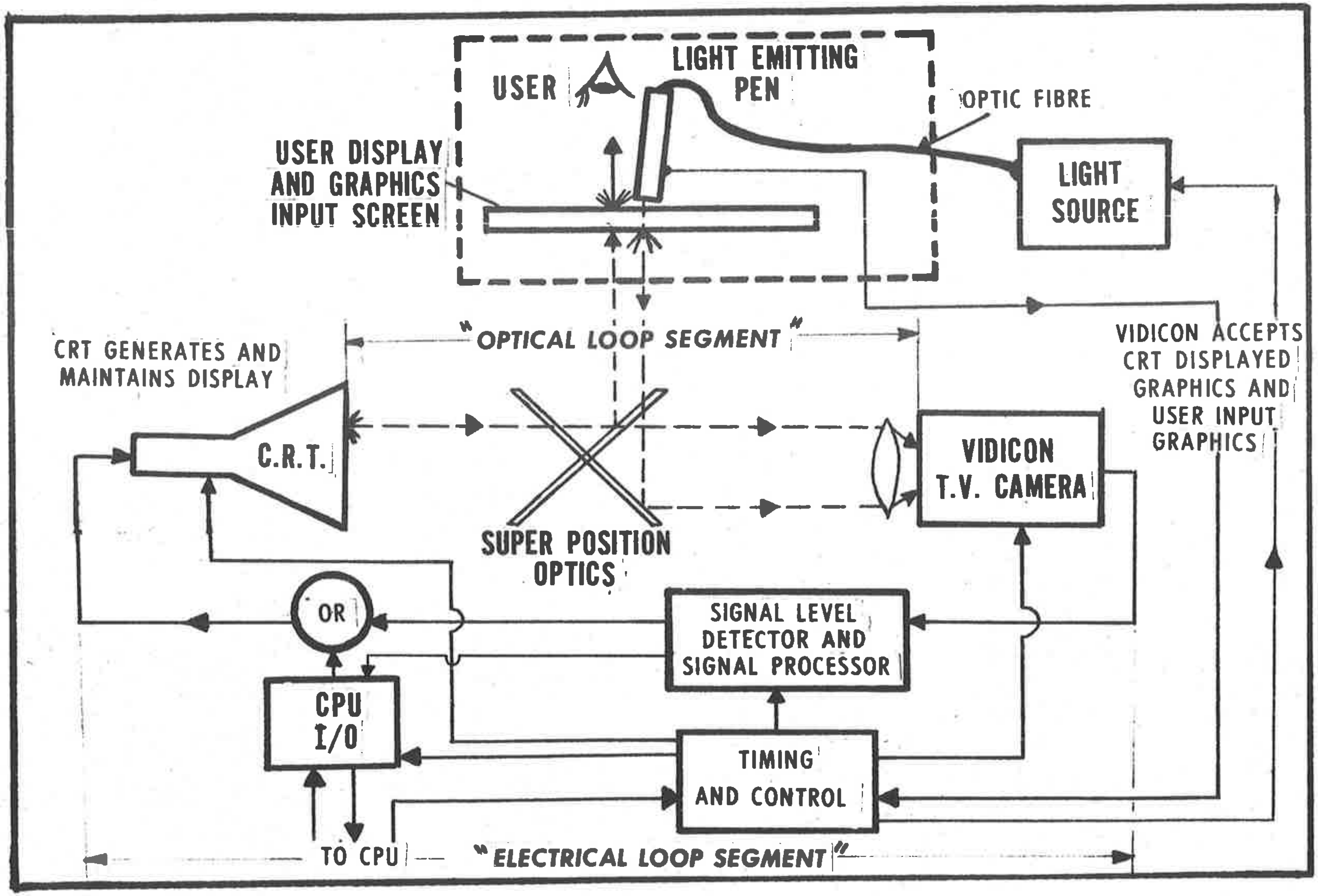


Figure 60, Functional Block Diagram of the Proposed IGC "VIDIOGRAPHIC"

A functional schematic of "VIDIOGRAPHIC" is shown in Fig.60, with the major features labelled.

3.2.6 Brief Description of System Operation.

The actual signals circulating within the CRT-Vidican closed loop are of two forms:

(i) optical signals within the "optical" loop segment.

(ii) electrical signals within the "electrical" loop segment.

3.2.6.1 Optical Signals.

In the optical section of the system, that is CRT to Vidicon, CRT to User and User to Vidicon, graphics display data and associated information originates as luminous flux on the CRT screen and is transmitted therefrom; part of this flux is available to the user for his observance on a viewing screen and another part is imaged onto the Vidicon photoconductor target for recirculation in the closed Vidicon-CRT loop to maintain the display.

The actual optical signal, corresponding to some particular display element forming a part of some graphic figure, curve, alphanumeric etc, manifests itself as emitted brightness "B(t)" of some peak value, located at some given CRT screen coordinates, and decreasing with time depending on the CRT phosphor persistance characteristic.

The luminous flux associated with this brightness "B(t)", when incident on the user display screen at a screen position corresponding to the CRT-screen coordinates, is viewed by the user. Similarly, another portion of this emitted luminous flux is imaged and incident on the Vidicon photoconductor target and generates a stored charge at a location corresponding to the CRT screen coordinates.

Other optical signals originate from the user's light-emitting pen which, by the "Superposition Optics System", are guided and imaged as luminous flux onto the Vidicon target, again with resultant stored charge.

The result is that during each system "frame time" or "scan time interval time" (i.e. the time required for an image to be displayed, and equal to 40ms), a charge pattern is built up on the Vidicon target, the magnitude and location of which correspond to the CRT-screen-or user-initiated signals (and also from noise or stray signals etc).

3.2.6.2. Electrical Signals

The scanning mechanism of the Vidicon converts this two-dimensional charge storage pattern into a one-dimensional time sequence, the duration of which is one frame time interval. The output signal from the Vidicon is thus a sequence of current (or voltage) pulses, whose amplitude is proportional to the stored charge on the photo-conductor (and hence proportional to the incident luminous flux), and whose position in time, relative to the beginning of the scan interval, is dependent on the location of the originating stored charge on the Vidicon photoconducting target (and hence on the location on the CRT screen).

The Vidicon thus converts optical signals into electric signals and inserts them into the "electrical" loop segment.

Electrical signals propagate from the Vidicon to the CRT, from the Vidicon to the CPU I-O interface, and from the CPU via the I/O interface to the CRT. Upon arriving at the CRT, these electric pulse signals are again converted by the CRT scanning mechanism and by cathodoluminescence,into the CRT screen luminance, the magnitude of which is proportional to the CRT input pulse amplitude; the resultant CRT screen display position depends on its time arrival relative to the beginning of the CRT scan time.
The display refresh cycle is thus reinitiated again.

3.2.63 Signal Requirements.

For such a system to have any practical significance or use, the following must be satisfied:

(i) The positioning and conversion of the optical signals to the time-pulse sequence (the "video" signal) by the Vidicon,and conversely, the conversion from video signal to CRT screen position, must be in an exact 1:1 spatial and time relationship, between the two devices and must be identical at every successive scan interval. Otherwise during successive scan intervals the display elements are progressively displaced; and because 25 such scan intervals (in a 625-line system) occur per second, a system without the above requirement would result in a very transient display, that is, after several cycles, the display would be shifted from the display screen and disappear from view.

The most obvious requirement is thus a steady display!

(ii) Display information, once inserted optically by the user Light-emitting Pen, or electrically by the CPU via the I/O Interface, must be self-maintaining i.e. self-refreshing. It is useless to have a system where inserted new display information disappears after several frame time intervals.

Thus the resultant Vidicon video signals, when fed into the CRT, must result in adequate screen luminance at corresponding locations so as to :

(i) provide adequate user-screen display brightness for user viewing comfort.

(ii) when incident on the Vidicon target, they must regenerate adequate Vidicon output signals to restart the cycle again.

Variations in CRT luminance or Vidicon output signal mean variations in successive frame time intervals with resultant increase or decrease in signal amplitude, until either the signal vanishes (luminance variation decreasing), or until perhaps the equipment breakdown point is reached (luminance, and hence signal variation, increasing).

Since Vidicons and CRTs are, when normally operated, analog (i.e. linear signal) devices, such signal variations are to be expected (noise, for example, changes the absolute signal amplitude).

Constant signal levels for the optical and electrical signals are required; this is ensured if an electric signal Level Detector is used to detect and control signal amplitude.

3.2.7 Signal Level Requirements.

3.2.7.1 Introduction

Variations in signal output level (whether within the CRT luminance or Vidicon output pulse amplitude) are most apparent at the injection of new dispaly information, as both devices show, to some degree, build-up and decay effects in phosphor luminance and photo-conductivity with input signal variations. Of critical importance is whether the resultant output signals,after new display information injection, are adequate to be "signal level" detected.

This requirement, and the requirement ensuring that dispaly locations,after each recycling in the CRT-Vidicon loop,are always displayed in identical positions, is best performed on the electrical signal. This electrical videosignal between Vidicon and CRT, it was seen, consists of a time sequence of pulses, the position of which,within this time sequence, is indicative of its display position coordinates, and the amplitude of each pulse indicative of the CRT screen luminance.

Constant display position at successive cycles means constant time-sequence position. Deviations from 1:1 Vidicon and CRT spatial relationship are manifested by pulse position deviations from some nominal values. Appropriate pulse repositioning (say by variable delays) is thus equivalent to display spatial repositioning, leading to a resultant 1:1 spatial relationship; a stable, static display thus results. The method of doing this is described in chapter 8.

Constant display luminance, and ensuring that new injected display information remains displayed, implies the maintenance of a constant electric signal level.

3.2.7.2 Classes of Electrical Signals.

Two types of electric signals are recognized, "i_{s1}" and "i_{s2}", thus requiring two Signal Level Detectors, having detecting levels "i_{L1}" and "i_{L2}" respectively, with

$$i_{L2} > i_{L1} \quad \ldots\ldots\ldots\ldots\ldots 3.1$$

The first class of signals, "i_{s1}", has the requirement of

$$i_{L1} < i_{s1} < i_{L2} \quad \ldots\ldots\ldots\ldots 3.2$$

The Vidicon output signals are fed directly to both Level Detectors in parallel. "i_{s1}" enables the "i_{L1}" detector "ON"; its output is the input to the CRT. So long as expression 3.1 is satisfied, the system does not differentiate between the origin of this signal; it may originate from the CRT screen or from the user light-pen. These signals thus specify user input graphics data or existing display data.

The second class of signals is defined by

$$i_{s2} > i_{L2} \quad \ldots\ldots\ldots\ldots\ldots 3.3.$$

and originate from the user and specify user interaction with existing display information.

Basically when interacting or pointing to existing display information, the user does one of two things. He may :

(i) wish to erase an existing display element.

(ii) indicate an existing display element on which some operation need be performed. This requires a transfer to the CPU or else (for graphics operations such as "SCALE", "ROTATE", etc) to the Display Processor.

Thus "i_{s2}" signals indicate display location erasure or transfer of display location coordinates to the CPU I/O Interface or the Display Processor I/O Interface.

For erasure, the "i_{L2}" detector may inhibit the "i_{L1}" detector and thus cause a "no-signal" condition to appear (and hence erasure).

For I/O Interface detection, the "i_{L2}" Detector opens a gate which make the "i_{L1}" output signals available to the I/O Interface at the appropriate time intervals.

These signal requirements are discussed in greater detail in sections 4.3.5., 4.3.6.

3.2.8 System Features.

The above system offers additional interesting possibilities. In addition to display, graphic input and storage capabilities, the system requires minimal CPU intervention. Display refresh is certainly self-maintaining without CPU intervention. More significantly no CPU interrupts occur when user-specified graphics are input. Display refresh storage capacity inherently matches the capability (both in speed of updating and in capacity) to the graphics Input and Display subsystems.

The speed of updating or erasing is such that a whole display can be read-in or erased within a frame time (40ms); however the average access time to each display location, whether to write-in or erase, is half the frame time.

3.2.9 Basic Requirements for Feasability

As elaborated in more detail below the successful implementation of the system depends on three main factors:

(i) the generation of adequate light energy by the CRT and adequate light energy incident on the Vidicon target surface.

(ii) adequate speed of response by the Vidicon to the incident light energy, within the relatively short frame time interval of 40ms.

(iii) geometrical linearity of each sub-system during display area scanning to be such that each display location is located at each successive frame in exactly the same position as in the previous frame.

The remainder of this chapter is a brief summary of the proposed system, the problem areas, and an outline of the major requirements indicating the feasability of the proposed IGC. The expressions used within this feasability study are derived in later chapters or Appendices, and only a "capsuled" feasability study is given to provide an overview and feeling for the major requirements of the system developed in the later chapters.

3.3. BRIEF DESCRIPTION OF SUB-SYSTEMS

3.3.1 Cathode Ray Tube

The main function of the CRT is to convert pulse-time information at its input to position information on its display screen. Each location on the screen is sequentially accessed in a predetermined order (the "raster" scan) by deflecting the scanning electron beam with a time-varying magnetic (or electrostatic) field. This beam is blanked out where no information is required to be displayed; otherwise at locations where information is to be displayed, the beam is unblanked. At these locations the electron beam strikes the phosphor screen whereupon its kinetic energy is converted to radiant energy ("cathodoluminescence" (section 2.3.7.2.)). Depending on the beam energy (beam current and accelerating screen potential), and on the phosphor type, radiant energy of a given intensity, spectral distribution, and time distribution is emitted and that location becomes visible from the outside of the CRT screen. Fig.61 illustrates a schematic of a CRT.

In the proposed IGC, part of this visible radiant energy is projected onto a screen to be visible by the user, while the remainder is available for projection onto the Vidicon camera target surface.

Of interest here are the following :

(i) <u>the amount of visible radiant energy generated by the CRT</u>.
This is to be adequate for both the user's viewing comfort and to ensure fast Vidicon response. For commercially available CRTs, the emitted luminance may vary by several orders of magnitude.

(ii) <u>The time variation of this radiant energy</u>.
The output of the radiant energy within each

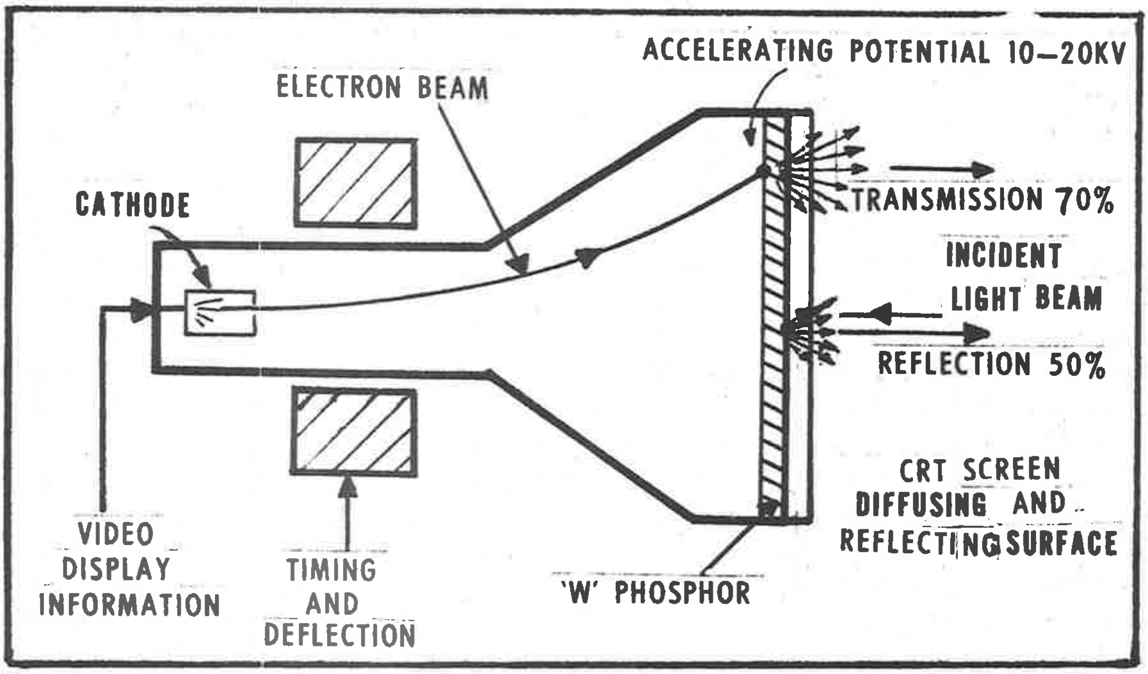


Figure 61. Functional Diagram of C.R.T.

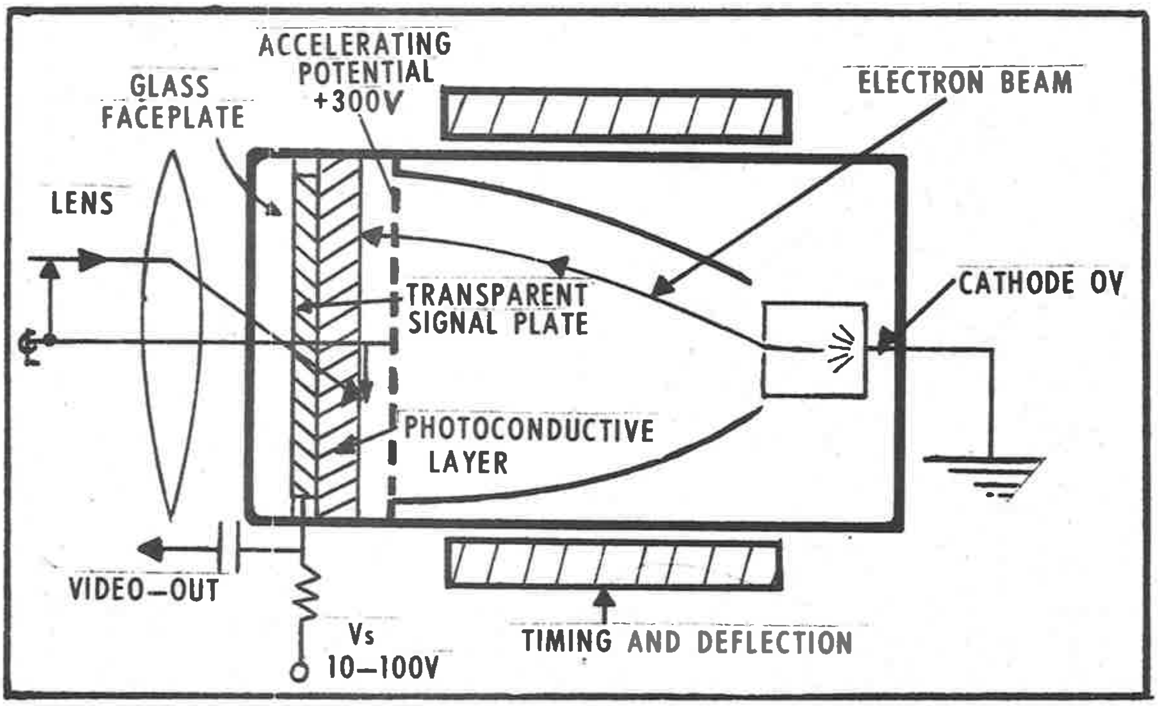


Figure 62. Functional Diagram of VIDICON Tube

frame time interval of 40ms is not constant; in TV-CRTs it usually falls to approximately 0.1 - 0.2% of its peak value after 40ms. The actual time variation depends on the phosphor used.

(iii) <u>The geometrical linearities of the CRT and capabilities of this for correction</u>.
In commercial CRTs, linearity varies from 0.5-10% (for definition of linearity see section 2.2.2.7).

In this study, figures are quoted for several CRTs. The CRT which was available was a 14" (8" x 10•5" screen size) PYE TV-monitor, of about 1955 vintage, on loan from WRE, Salisbury (Department of Supply).

3.3.2 Vidicon TV Camera

The main function of the Vidicon TV-camera is to intercept adequate radiant energy emitted by the CRT to generate an output signal of sufficient strength to restart the display cycle again by feeding this signal back to the CRT.

As shown in Fig.62, the image of the display on the CRT screen is focussed onto a photoconductive layer of size 0•375" x 0•5", whose conductivity increases as the intensity of the illumination increases. A voltage, provided by "Vs," of some tens of volts exists across the photoconductor; the signal plate providing this "Vs," is transparent at the high voltage side, while the photoconductor surface facing the inside of the tube is nominally at cathode voltage (OV), kept thus by the scanning electron beam. Variation of "Vs," alters the "sensitivity" of the Vidicon to the incident illumination - the greater "Vs" is, the larger is the output signal for any given illumination.

The photoconductor is almost an insulator with no incident illumination; any current flow due to "Vs" (the "dark current") is negligible (about 0.01uA say). When the photoconductor is illuminated, the conductivity increases greatly, and under the electric field due to "Vs", charge leakage occurs due to these resultant photo-currents. A potential "ΔV_T" results on the cathode side of the photoconductor due to the charge leakage "Q", given by $\Delta V_T = Q/c_m$ where "c_m" is the capacitance of the photo-conductor element at that location. Typically "ΔV_T" is several volts at the end of a frame time interval. Thus a charge "Q" or "ΔV_T" distribution occurs on the photoconductor target which is representative of the incident illumination.

A scanning electron beam, analogous in many respects to the electron beam in a CRT, accesses each location on the photoconductor in a sequential predetermined order - again by deflecting this beam by a time varying magnetic field. The beam restores or neutralizes this accumulated charge "Q"; the resultant charging current appears at the signal plate and across the signal resistor generating the resultant video output signal. Its amplitude is proportional to the charge "Q" and hence proportional to the incident illumination.

The requirment here is to have as large a charge image as possible for a given illumination, and to have the electron beam completely discharge the charge in the short instant the beam is present at that location, i.e. during the "beam dwell time". This reduces "image lag".

Of interest here are the following:

(i) The geometrical linearity of the Vidicon, when converting the position coordinates of the stored charge locations on the photoconductive surface to the pulse time coordinates. Nominally in Vidicons linearities are of the order of 1-5%.

(ii) The "lag" or frame-to-frame storage characteristics (not to be confused with the necessary requirement of charge storage during a frame time interval). This has the result that a charge image representative of the incident image, is not erased completely by the electron beam at the one scan, but persists (with reduced amplitude) for several scan periods until completely erased. This poses problems with the desired requirement of complete erasure of information within a single scan; unless complete (or near complete) erasure occurs, difficulty will be experienced in erasing display information.

(iii) The buildup process of photoconduction due to changes in illumination.
Vidicons are "notoriously" slow in response to changes in illumination. In our case the requirement is that within one frame time interval, adequate charge be built up due to the CRT phosphor-type illumination. Similarly, when display information is to be erased, the photo-conductive lag must not be such as to generate a spurious signal at the next scan.

Little data exists as far as transient properties of Vidicons go. The expressions derived for Vidicon transient behaviour in Appendix 10 and used within this feasibility study were checked against whatever data was available. Thus results are given for several different available Vidicons.

The available Vidicon is a SONY M-3016 within a purchased SONY CV-100 Vidicon camera; very little information is available about this tube even after direct inquiry from the manufacturers.

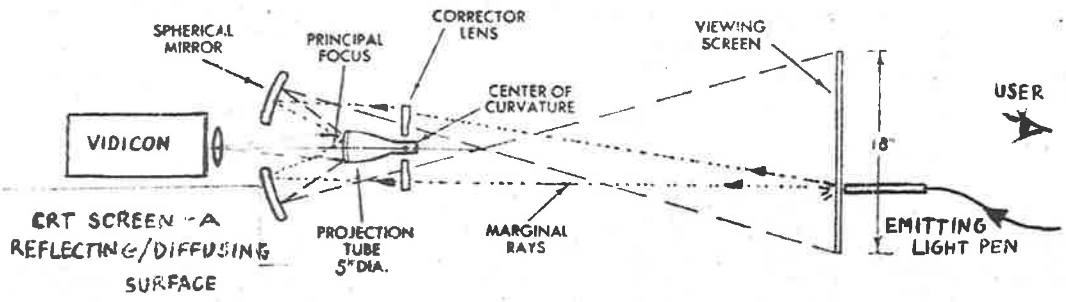
3.3.3. Schmidt Optical System.

The main function of the Schmidt Optical System is to project the CRT display information onto a viewing screen to be observed by the user and simultaneously to enable the user to input new information. This latter capability is effected by the phosphor coating on the CRT screen being a natural diffusing-reflecting surface (a "Lambert" reflecting surface) of similar properties as a "front-projection" white screen. The phosphor screen thus performs the function of an optical adder, adding emitted CRT-luminance and any reflected luminance originating from, say, a light emitting pen held by the user and projected onto the CRT screen.

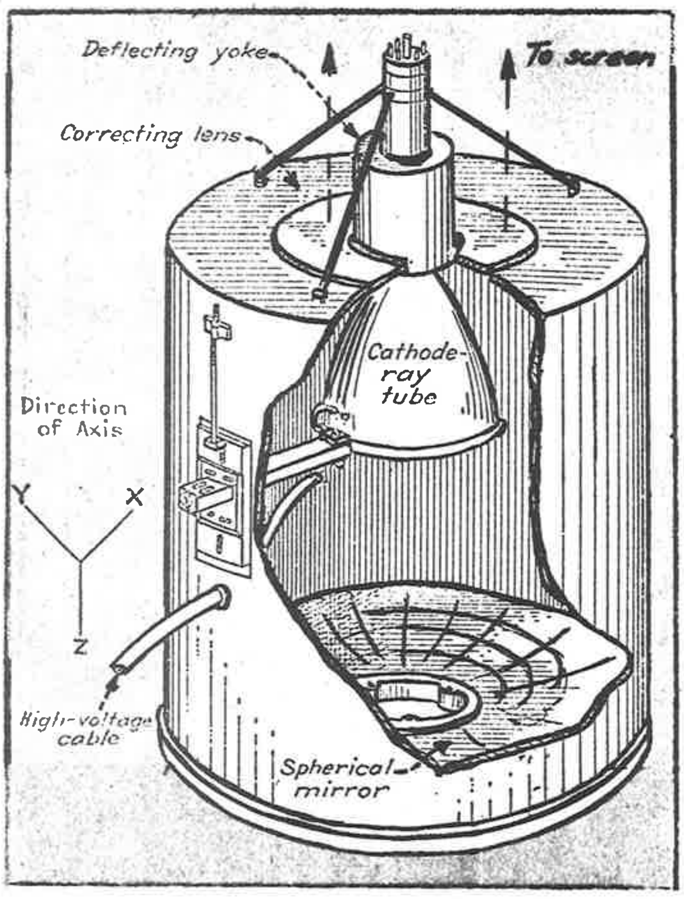
The Schmidt Optics has been chosen for several reasons:

(i) Of the various alternatives of other optics configurations, this system is the most efficient so far as light utilization goes.

(ii) The cost of such a system is very favourable compared with its alternatives, due to its availability (at least from surplus stock) as a sub-component of domestic TV projection receivers of some twenty years ago.



(a) Functional layout of Display and Input Superposition Optics based on Projection TV Schmidt Optics.



(b) Physical appearance of Projection TV optics unit (from [243]).

Figure 3. Display and Graphics Input Superposition Optics

The actual optics system required is that from an RCA Projection TV system (243,244,245). Fig.63 shows the principal light rays of the Optics system.

3.3.4 The Light Pen and Projection Screen

The main function of the Light Pen is to enable the user to input new display information and to be able to point to graphics features on the dispaly.

Since the user sees the CRT display projected on a screen, he points the Light-emitting Pen at locations on the screen whenever new information is to be input. The screen material is light diffusing and has "directive" properties, that is, when light is projected onto it, it tends to concentrate the transmitted light in a preferred direction, usually in a cone of about 20° - 30° about the normal to the screen. Since the screen is at the real image plane of the Schmidt Optics System, the conjugate focal plane being the CRT screen, a high intensity spot projected by the user appears on the other side of the screen as a high intensity spot (as it is a diffusing screen) and is reverse imaged onto the CRT screen. The reflecting-diffusing phosphor screen of the CRT, reflects this spot onto the Vidicon photoconductive target.

Similarly as for the CRT, the light pen must emit adequate visible radiant energy, which, when imaged onto the Vidicon, generates within a frame time interval adequate output signal. This "light pen" must not be confused with the usual "light detecting" pen used currently with CRTs and described in Appendix 5.

3.4. OUTLINE OF FEASABILITY STUDY

The salient points on which the feasability of the system is based on, are in turn:

3.4.1 Adequate light energy transfer between the CRT and the Vidicon during each frame time interval to enable the Vidicon to generate a suitable output signal. This depends in turn on:

(i) The brightness, and rise and fall time characteristic of the CRT phosphor under excitation, and the spectrum of its radiant energy output.

(ii) The lens and imaging system of the Vidicon camera, governing the quantity of radiant energy reaching the photo-conductive Vidicon target.

(iii) The rise and fall time of photocurrents in the photoconductor under changes of illumination.

3.4.2 Complete or near-complete erasure of stored charges on the photoconductor after a single scan of the Vidicon electron beam, to ensure that no spurious signals are present at subsequent scans. This requires a study of the scanning mechanism of the Vidicon.

3.4.3 The measurement, causes and correction of display distortion of the CRT and Vidicon to ensure that display information is generated at the identical locations at each successive frame. Otherwise display drift occurs from frame to frame until the display drifts out the display screen area.

3.4.4. An efficient (from the viewpoint of light utilization efficiency) optics system, such as the Schmidt Optical System, which enables the superposition of images, particularly user specified graphics information.

3.4.5 In conclusion, layout, size, special features etc of the proposed IGC are mentioned.

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CHAPTER 4

LIGHT ENERGY REQUIREMENTS IN "VIDIOGRAPHIC"

4.1. LUMINANCE of the CRT PHOSPHOR

4.1.1. Introduction

The primary function of the CRT is to generate radiant energy at predetermined locations on the CRT screen, a fraction of which is incident on the Vidicon photo-conductive target; this fraction may be quite small even with a relatively efficient optical system.

Of this light generated on the CRT screen, the following are the main sources of losses as far as light reaching the Vidicon is concerned :

(i) reflection and absorption from the glass face-plate in front of the CRT phosphor screen.

(ii) light emission in the direction of the user viewing screen.

(iii) light emission in directions other than viewing screen and Vidicon optical system directions.

(iv) losses in the Vidicon camera optical system such as

  (a) reflections at lenses

  (b) reflection at Vidicon faceplate.

Typically about 5% of the light flux emitted from the CRT is incident on the photoconductor. Of this light flux actually incident on the photoconductive target only a very small fraction is converted into carriers resulting in the photocurrent; this fraction may be typically 1-2%. Thus less than 0·1% of the light flux emitted from the CRT directly contributes to the Vidicon output signal.

A crude way to see this poor utilization of CRT luminance is to compare the beam current power in the CRT with the output beam current power of the Vidicon. For the CRT beam, currents of 1-2mA, accelerated by a voltage of some 15KV, are required, with about 2-5% efficiency in generating light flux. In the Vidicon, a beam of some 1µA, accelerated by a voltage of some 300V, to fully discharge the stored charge, is typical.

The beam power ratio R_p in the two devices is thus

$$R_p = \frac{300 \times 10^{-6}}{2.10^{-3} \times 15.10^{3} \times 0.05}$$

$$= 0{\cdot}02\%$$

which compares favourably with the previous value of "less than 0·1%".

4.1.2 Phosphor Luminance In CRTs

Analytic expressions relating the brightness of the CRT screen light output or luminance with such factors as beam current, type of phosphor, accelerating potential etc, are well known (see Appendix A.9.2). For particular CRTs, however, manufacturers supply curves which directly give the above necessary relationships or from which the required information can quite easily be deduced. These are of the form shown in Fig.64.

Typically brightness ranges from about 30ft-L (foot-lamberts) to more than 10^4ft-L in projection CRTs.

In Table 1 are listed, amongst other parameters, the brightness for several CRTs. The CRTs listed are not representative but were selected for their high luminance, as this is one of the major requirements in this study.

The CRT luminance is in fact the average luminance perceived by an observer over a whole frame time interval. The light flux emitted, and hence the brightness, are not constant but vary greatly, from the maximum occuring just after the instant of excitation , to a fraction of a percent of its peak brightness after one frame time interval. This luminance decay varies from phosphor to phosphor, and to a smaller degree depends on the incident beam current (see for example decay curves in (248)).

The decay characteristic (sometimes called the "persistance" characteristic) of "W" phosphor, the phosphor with the required characteristic from our viewpoint, is shown in Fig.64(a). It is assumed that there is no great change in the form of the persistance at various beam currents; this is a valid assumption when the curves shown in (248) are analysed.

If "B(t)" is the luminance variation with time, then "B_{AV}", the average luminance variation is simply,

$$B_{AV} = \frac{1}{T_F} \int_0^{T_F} B(t)\, dt \quad \ldots\ldots\ldots 4.1$$

where T_F is the frame time interval (40ms).

B(t) is of the form (see Appendix A.9.3),

$$B(t) = B_{peak} \int_0^{T_F} \frac{dt}{(1+Kt)^{\alpha}} \quad \ldots\ldots\ldots 4.2$$

TABLE 1 TYPICAL CRT CHARACTERISTICS

TYPE	PHOS-PHOR	Max Av. BEAM CURRENT	Final ACCELE-RATING VOLTAGE	Max. AVERAGE BRIGHTNESS B_{AV}, ft–L	Max. PEAK BRIGHTNESS B_p, ft–L	SCANNED AREA SIZE $(H \times 4H/3)$	MAGNIFI-CATION $M = 9.6/H$ (inches)	E(t), ILLUMATION on VIDICON $E(t) = K.B(t)$	R_S, RADIUS OF SCREEN CURVATURE	ΔS, Max. DEPARTURE FROM SCREEN FLATNESS
AW 36–48 MULLARD MONITOR	W	1·2mA	14KV	160	10^4	210x280 mm^2	·045	·048B(t)	680mm	24mm. (0·95")
MW 13–38 MULLARD PROJECTION	W	2·5mA	50KV	$>2{\cdot}4.10^3$	$>1{\cdot}6.10^5$	69x92 mm^2	·14	·040B(t)	207mm	7·2mm. (0·28")
5NP4 RCA PROJECTION	P4	1mA	25KV	$2{\cdot}5.10^3$	$1.57.10^5$	76x102 mm^2	·126	·041B(t)	180mm	10mm. (0·4")
7NP4 RCA PROJECTION	P4	2mA	80KV	$1{\cdot}2–1{\cdot}4.10^4$	$8{\cdot}2.10^5$	96x128 mm^2	·1	·043B(t)	390mm	7·8mm. (0·31")
M17–140W MULLARD FLAT SCREEN	W	50uA	16KV	170	$1{\cdot}1.10^4$	93x124 mm^2	·1	·043B(t)	∞	0
17 CF P4 RCA DOMESTIC TV	P4	2 mA	16KV	680	$4{\cdot}3.10^4$	280x374 mm^2	·035	·048B(t)	530mm	51mm. (2·0")
21 DEP4–A RCA DOMESTIC TV	P4	2 mA	16KV	680	$4{\cdot}3.10^4$	370x494 mm^2	·026	·050B(t)	730mm	66mm. (2·6")

Facing p.156

where "K" and "α" are constants. Thus

$$\frac{B_{AV}}{B_{peak}} = \frac{1}{T_F}\int_0^{T_F}\frac{dt}{(1+Kt)^{\alpha}} \quad \ldots\ldots\ldots 4.3$$

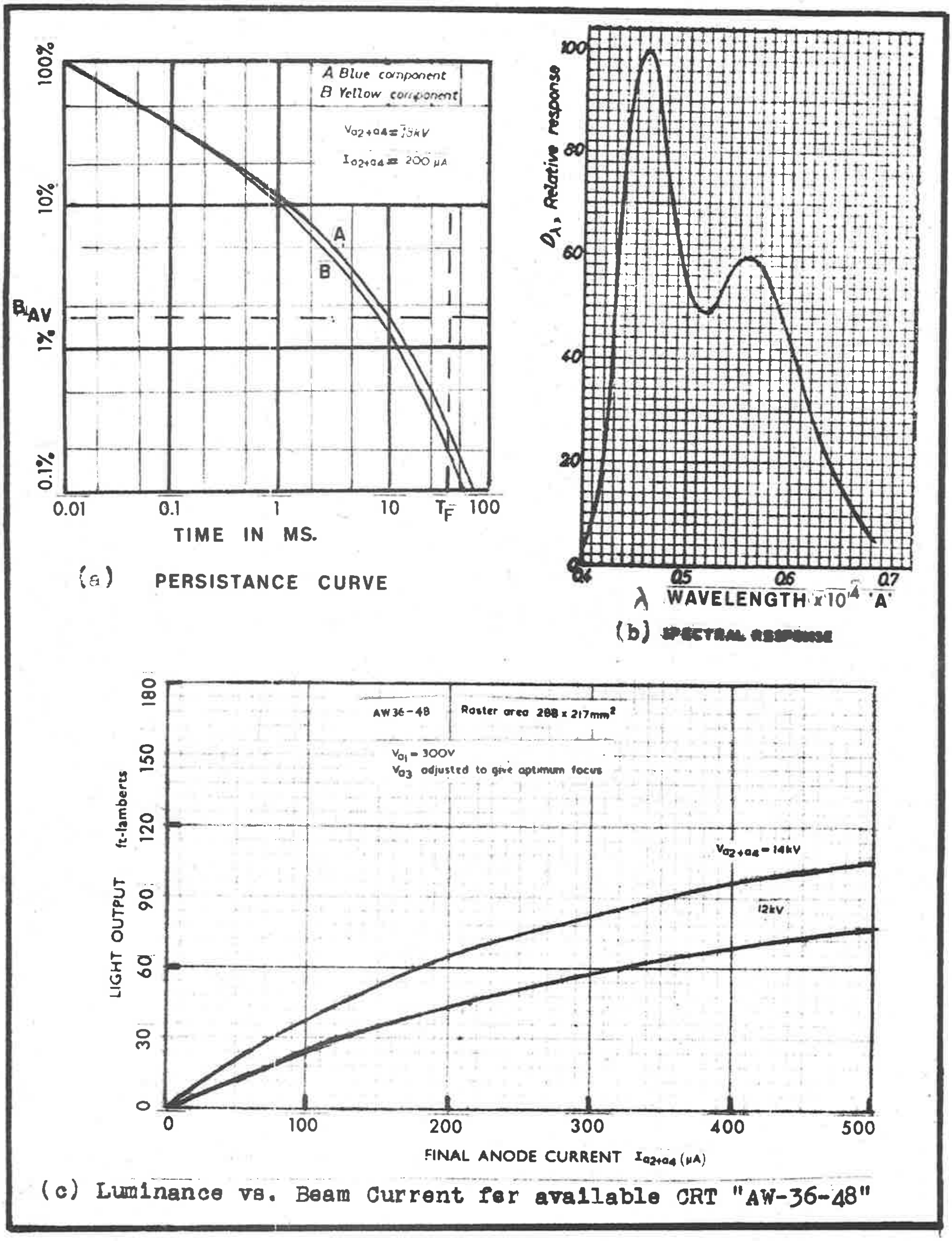
This integral on the RHS evaluates to 0·016 for "W" phosphor (see Appendix A.9.3), giving

$$B_{peak} \approx 63\, B_{AV} \quad \ldots\ldots\ldots\ldots 4.4$$

Hence the luminance-time variation curve can be calibrated in ft-L for various levels of average luminance, B_{AV}. Leverenz in (246) states that "B_{peak}" for projection CRTs can sometimes reach 10^7ft-L!

The maximum peak brightness or luminance is also given in Table 1. It has been assumed for these calculations that the decay characteristic of "P-4" phosphor (US usage) is identical to "W" phosphor (UK usage). In fact the decay of "P4" is specified to be such that "brightness does not exceed 7% of peak brightness 33ms after excitation is removed" (249), the major criterion being its spectral content making it suitable for monochrome TV. "P-4" decay curves are thus rarely given. This should be compared with 0·16% of peak brightness, 40ms after excitation has been removed, for "W" phsophor.

It must be noted that although the figures given in Table 1 give the maximum available brightness output from the CRT considered, the actual output depends on the beam current used (the other parameters being usually fixed), which depends on the available video signal at the input of the tube and the biasing point of this



(a) PERSISTANCE CURVE

(b) SPECTRAL RESPONSE

(c) Luminance vs. Beam Current for available CRT "AW-36-48"

Figure 64. Performance of "Y" Phosphor and of available CRT

control grid relative to the cathode emitting the beam (see Appendix A.9.2). The maximum brightness, however, indicates the potentially available light output from a given CRT.

4.1.3 Buildup Characteristics of "W" Phosphor

The fact that some remanent light output remains for longer than the frame time interval, makes it clear that the light output, and hence brightness at any instant, is not only due to the energy delivered by the beam current at the beginning of that particular frame time interval but also due to the remanent light output from previous excitation.

Thus at, say, the n-th excitation after new data has been displayed at some point, the average brightness is

$$B_{AVn} = B_{AV} + \sum_{i=1}^{n-1} B_{Ri} \quad \ldots\ldots\ldots\ldots 4.5$$

where "B_{AVn}" is the average brightness after the n-th excitation,
"B_{AV}" is the average brightness due to the incident beam energy,
"B_{Ri}" is the contribution due to the remanent brightness of the i-th-prior excitation.

For new information displayed on the CRT screen during the first frame interval, there is no remanent brightness; thus

$$\sum_{i=0} B_{Ri} = 0$$

Thus the difference in output brightness between the steady case brightness after n-frame time intervals and the initial frame time interval brightness, ΔB, is

$$\Delta B = \sum_{i=1}^{n-1} B_{Ri} \quad \ldots\ldots\ldots\ldots \quad 4.6$$

This should be as small as possible compared with "B_{AVn}".

It can be shown (Appendix A.9.4) that

$$\sum_{i=1}^{n\to\infty} B_{Ri} = \frac{1}{T_F} \int_{T_F}^{t\to\infty} B(t)\, dt. \quad \ldots\ldots \quad 4.7$$

which when evaluated for "W" phsophor is much less than 10% of B_{AVn}. Hence a variation in output brightness during the display of information occurs, this being the relatively small "buildup effect", with

$$B_{AV(worst\ case)} \geqslant 0.9\ B_{AV(steady\ state)} \quad ..4.8$$

This luminance variation is relatively negligible.

The above discussion assumes that efficiency in converting the incident beam energy into light flux does not vary appreciably between the previously unexcited phosphor and the steady-state previously excited phosphor. The major factor causing any such variation in efficiency would be changes in temperature of the phosphor, as part of the incident beam energy is converted to thermal energy. As the excitation progresses, the steady state temperature slowly rises. Any variation in luminance due to this is negligible (246).

4.1.4 Spectrum of "W" PHOSPHOR

For calculations of expected output signals from the Vidicon tube illuminated by radiant energy emitted from a CRT phosphor to be valid, allowance must be made for the fact that the spectral distribution of this illumination differs greatly from the spectral distribution of the illumination from which performance curves of the Vidicon supplied by the manufacturers are derived.

The sensitivity of the Vidicon, governing its output signal magnitude, varies greatly with the wavelength of the incident illuminant, to a greater or lesser degree approximating the spectral sensitivity of the human eye; a typical sensitivity curve is shown in Fig.66(d).

In Appendix A.8.2.2 it is shown that the total output signal current for a Vidicon is given by

$$\int_{\lambda 1}^{\lambda 2} S_{\lambda}.D_{\lambda}.d\lambda \text{ amps}$$

where "S_{λ}" is the photoconductor sensitivity response (see Fig.66(d)).

"D_{λ}" is the illuminant's spectral energy distribution (see Fig.64(b)).
and "λ_1" and "λ_2", the limits of the integration usually corresponding to 3800A and 7600A respectively, the wave length limits of visible radiation.

In Appendix A.8.2 are calculated the relative output currents, when Vidicons having the two major classes of Photoconductors (see A.10.3.3) are illuminated by 1ft-L of "W" phosphor brightness and 1ft-L of the standard illuminant used in deriving the Vidicon characteristics as supplied by the manufacturers.

It is shown that for a "Photoconductor class I" Vidicon, 1ft-C (foot-candle - see Appendix 8.1.5) of "W" phosphor produces about 50% more output signal than 1ft-C of Standard Illuminant for which the curves are given; while for a "Photoconductor class II" Vidicon, 1 ft-C of "W" phosphor produces about 15% less current than 1ft-C of the Standard Illuminant.

As a first approximation then, the manufacturers' curves can be used to estimate current outputs when the illuminant is due to "W" phosphor.

4.1.5 Summary

(1) Table 1 lists the peak and average maximum brightness or luminance available for several representative high-brightness output CRTs with "W" type phosphor.

(2) The variation of this output brightness at any time within the frame time interval is given by the decay curve in Fig. 64(a) appropriately scaled by the maximum output brightness.

(3) Relatively insignificant buildup of brightness occurs, the variation between the lowest peak brightness and the steady-state peak brightness being much less than 10%. For calculating the worst case CRT output brightness, a scaling factor of 0·9 is used.

(4) The spectral characteristics of "W" phosphor illumination are such that for photoconductors

of "class I", the expected signal output is given by that read off the output current-incident illumination (Fig.66(a)(b)) multiplied by 1.5. For photoconductors of "class II", this multiplying factor is 0·86 (see Fig.66(b)(a)).

4.2. ILLUMINATION INCIDENT ON VIDICON PHOTOCONDUCTIVE TARGET.

The scanned area on the photoconductive target of 1" Vidicons (the usual size) is 9·6 x 12·8mm (4:3 aspect ratio) or 0·375" x 0·5". The display area on the CRT screen is $(H \times \frac{4}{3}H)$mms, say. A 1:1 positioning relationship between the CRT and Vidicon display and imaging areas is required (see section 7.1.2).

The most common lenses available with Vidicon cameras have focal length, "f", of 25mm.

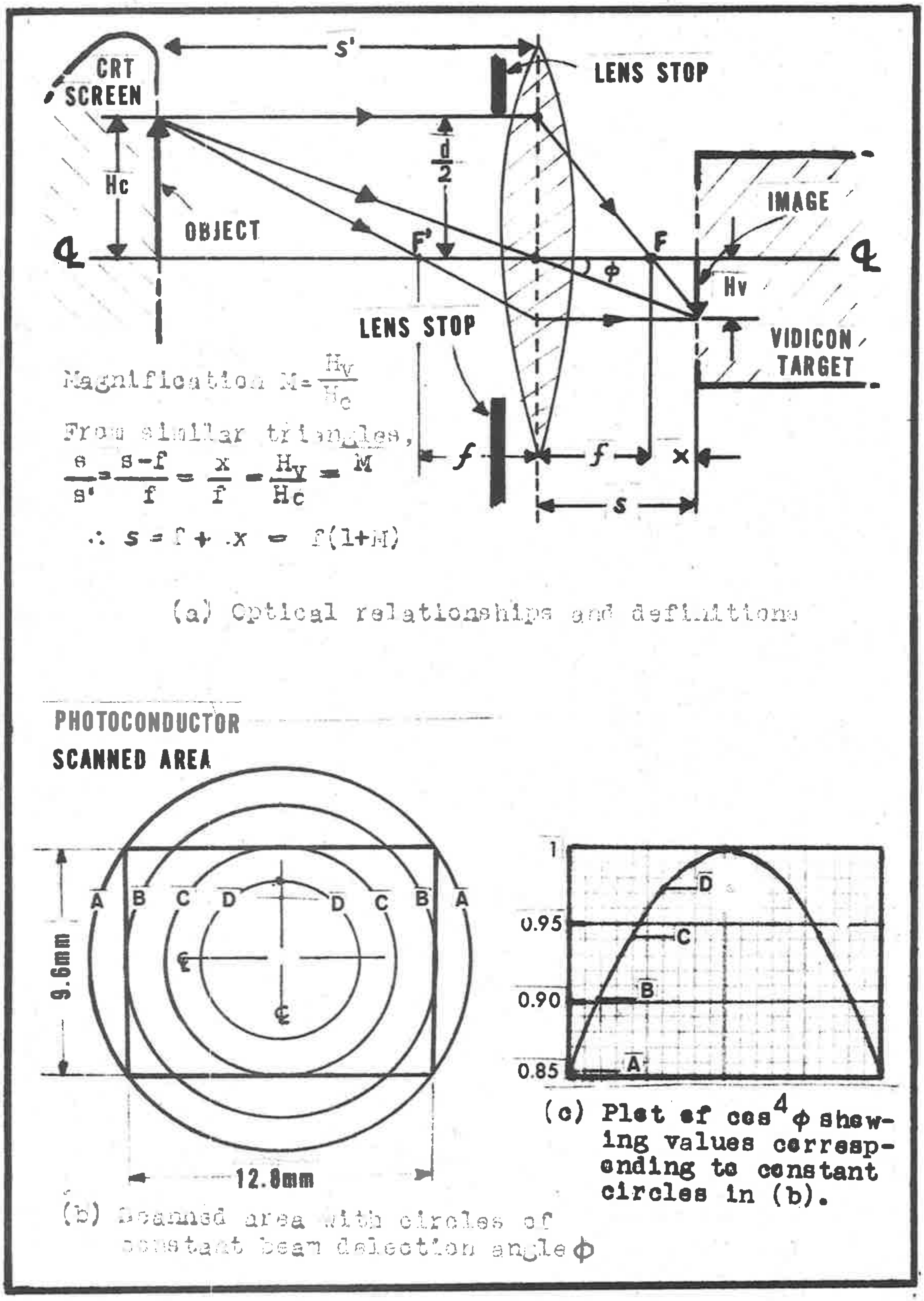
If Magnification, "M", is defined as the ratio of the linear dimensions of the Vidicon image "H" to that of the CRT screen object i.e.

$$M = \frac{9 \cdot 6}{H} \quad \text{(H in mms)}$$

and "F", the "F-number" is defined as the inverse ratio of aperture, or useful diameter of the lens, "d", to the focal length, "f" i.e.

$$F = \frac{f}{d}$$

then it can be shown (Appendix A.8.3.3) that the illuminance "E" incident on the image plane, (coplanar with the photoconductor when the Vidicon lens is focussed) is given by :



(a) Optical relationships and definitions

(b) Scanned area with circles of constant beam delection angle φ

(c) Plot of $\cos^4\phi$ showing values corresponding to constant circles in (b).

Figure 65. Optical Relationships of Vidicon Camera Lens.

$$E(t) = T.\ B(t).\frac{\cos^4 \varphi}{4F^2.(1+M)^2} \ldots\text{(ft-candles)} \ldots 4.9$$

where

"B(t)" is the brightness illuminating the Vidicon target in ft-L.

"T" is the transmission of the lens system (which allows for internal reflection, losses etc), and typically is equal to 0·75.

"M" and "F" are as above.

"φ" is the angle between the centre of the optics system and the point on the photoconductor where "E(t)" is being measured.

i.e. $\varphi = \arctan \sqrt{\frac{x^2+y^2}{f(1+M)}}$

and x and y are the coordinates of the point in question.

The illumination decreases as "H" increases (this can be shown by differentiation (i.e. for the smaller CRTs) and at points nearer the corners of the Vidicon image areas.

"M" for the CRTs listed in Table 1, varies from 0·14 to 0·03. Using an average value of M = 0·1 and f=25mm, "$\cos^4\varphi$" is plotted in Fig.65(c). Within the area indicated by "circle B", $\cos^4\varphi$ is greater than 0·9.

Now the smallest "F-number" in a typical lens is usually f=1·9 (F varies in approximate step ratios of $\sqrt{2}$, up to F=22, by varying a diaphragm). This value of "F" is also acceptable from its ability to focus curved object planes (such as a CRT screen on a flat image field (see Appendix A.8.3.4).

Thus the maximum illuminance on the Vidicon target available from the typical CRTs in Table 1, is given by

$$E(t) = \frac{0{\cdot}75 . \mathrm{Cos}^4\varphi . B(t)}{4.(1{\cdot}9)^2.(1{\cdot}1)^2} \text{..(ft-candles)..} \quad 4.10$$

$$= 0{\cdot}043.\mathrm{Cos}^4\varphi.B(t) \quad \ldots\ldots\ldots\ldots \quad 4.10a$$

and within the circle "B" indicated in Fig.65(b),

$$0{\cdot}039\ B(t) < E(t) < 0{\cdot}043\ B(t)\ \text{(ft-candles)}$$

(when B(t) is in ft-Ls). 4.11

4.3. SIGNAL BUILDUP IN VIDICON AND RESPONSE TO "W" PHOSPHOR ILLUMINATION.

4.3.1 Introduction

The mechanism of charge storage on the Vidicon photoconductive target due to incident illumination was briefly mentioned in section 3.2.2. The higher the incident illumination, the greater is the charge built up which, when neutralized by the electron scanning beam at each frame time interval, produces at the signal plate of the Vidicon (and hence at the camera output) a correspondingly higher output video signal.

This charge, and hence the signal, is that due to the illumination within the frame time interval of 40ms; since the illumination is constantly changing within this interval, having the form of the "W" phosphor persistance curve in Fig.64(a), the photocurrent which produces the charge buildup also continually changes. The response of the photoconductor to these changes in illumination must thus be known to ensure that it is adequately fast to enable sufficient charge to buildup within the frame time interval.

As hinted at briefly before, the rise and fall time constants of signals in a Vidicon are comparable with the frame time interval; this is for illuminations in the range of 0·1 - 10ft-candles, that is, those encountered in usual everyday surroundings. However the time-constants strongly depend on the illumination ,decreasing with increasing illumination. It is seen thus that at the beginning of each frame time, where the illumination is highest, charge buildup is expected to be fastest, while towards the end of the frame time interval, the photocurrent will be greatly reduced, and the time constant, though high, ensures that little photocurrent flows in the next frame time interval due to the slow decay in the previous frame time interval. The CRT-generated illuminance is thus ideally suited to the Vidicon requirements.

Work done on the transient response of photoconductors, particularly in Vidicon applications, and available data, is scarce. This is due to several reasons:

(i) There are still some gaps to be filled before the theory of photoconductivity explains adequately some of experimental results obtained.

(ii) Vidicons are mainly used for closed-circuit TV or live-TV applications where illumination is constant; therefore no need is seen to research the behaviour of Vidicons under conditions which are unlikely to occur.

(iii) Present day techniques of manufacturing the Vidicon, particularly its photoconductive surface, are such that valid models of the photoconductor structure, thickness, etc, are difficult to make.

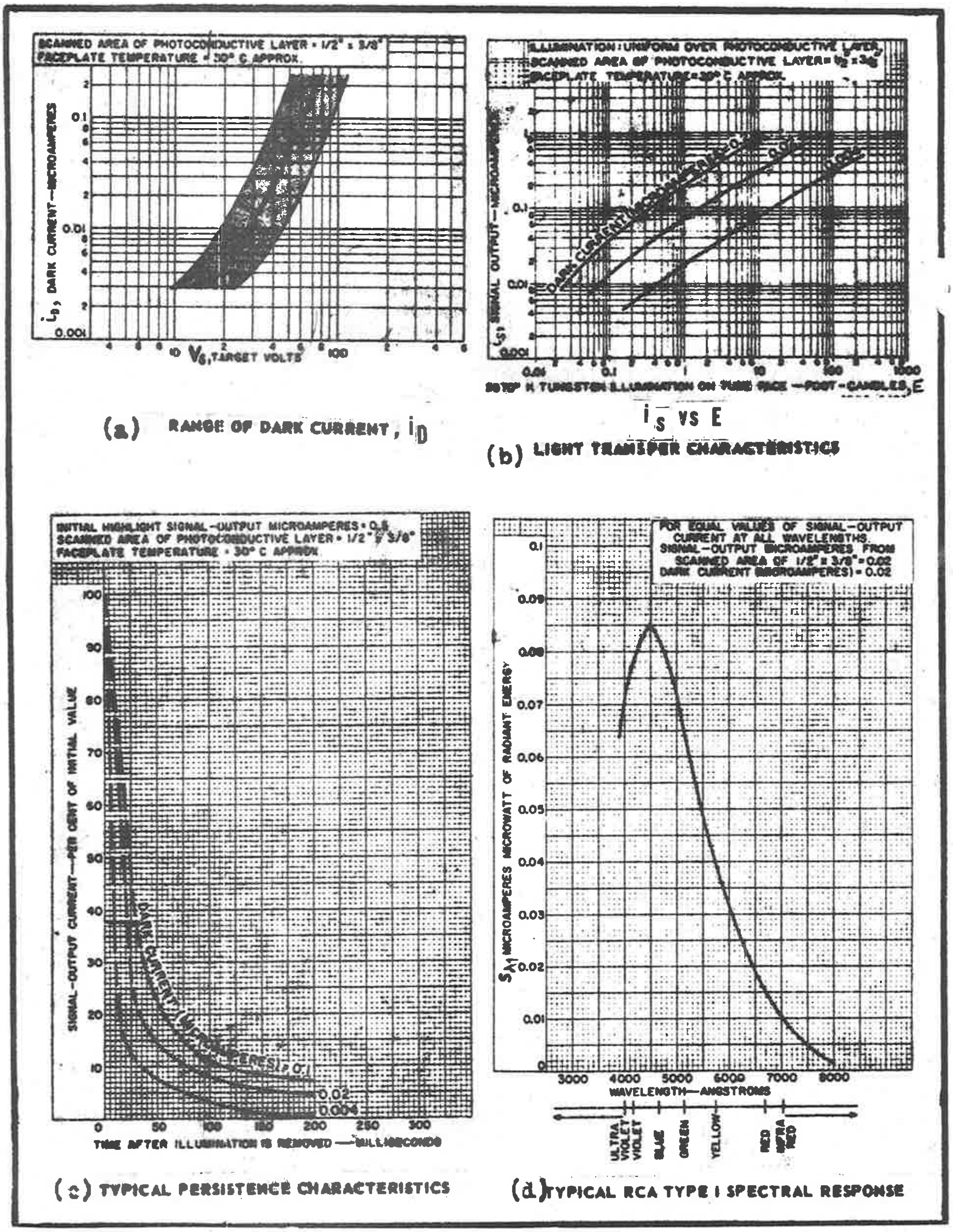


Figure 66(a) Typical Performance Curves Available for a Vidicon Tube (example shown is RCA 8572A - Photocond. type I)

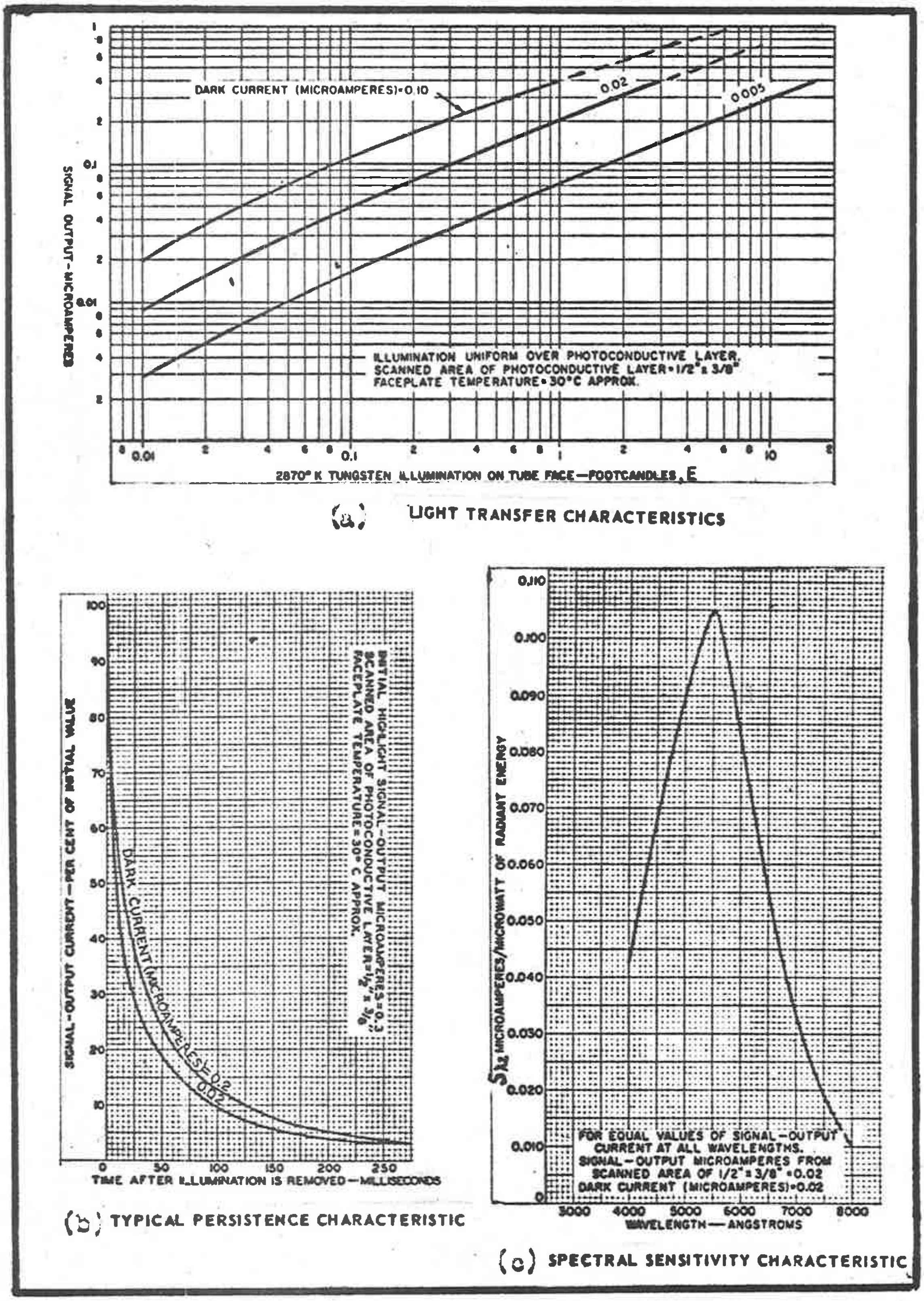


Figure 65(b). Performance Curves of a Class II Photoconductor (RCA 7262A)

Quality control is such that parameter variations of 50% or more from nominal values are quite common.

Some manufacturers provide "transient response curves" of the Vidicon to changes in illumination, particularly graphs of the output signal remaining when illumination has been blocked (see for example Fig.66(c)). These curves must be treated with some reservations, as a secondary delay is also present therein, not due to photo-conductive effect. The presence of a remanent signal is detected when the electron scanning beam deposits charge to neutralize any remaining signal charge. However, as mentioned previously, the scanning beam is a far from perfect means of supplying charge to the photoconductor, this being particularly so at low signal outputs, or to point to the reason, when the remanent voltage $\Delta V_T = Q/C_m$, (where "Q" is the remanent charge, "C_m" is the capacitance of the element associated with the charge), approaches the potential of the cathode from which the beam was emitted. This either happens when the initial charge "Q" is low (i.e. low illumination) or when the beam has erased most of the charge due to high illumination. In either case, the inability to supply charge results in the charge requiring a longer time to be erased, resulting in an increased delay. What the manufacturers' response curves thus give is the delay of the signal due to :

(i) Photocurrent time delay.

(ii) "Capacitive" on "Beam Discharge" delay, which becomes significant at low values of the remaining signal.

To extract a meaningful decay time constant of the photocurrent, only the initial decay, near the high signal output, should be used.

The "beam discharge" delay is not present at photocurrent and signal charge buildup, and for this reason, observed rise-times of photocurrents have always been stated to be faster than photocondive decays (252).

4.3.2 Exponential Rise and Decay of Photocurrents

It has been usual to assume (and tentative theoretical reasons have been put forward to back this up) that photocurrent buildup and decay is governed by an exponential law, although, similarly as for phosphors, combinations of exponentials and power law relationships can be used to best fit the observed rise times and fall times. In this study it is assumed a single time constant governs both photocurrent buildup and decay.

It is easy to show that the general relationship for any buildup or decay governed by an exponential rise or decay law, is given by;*

$$I(t) = I_o + (I_{SS} - I_o)\left(1 - \exp\left(\frac{-t}{\tau}\right)\right) \quad . \; . \; 4.12$$

where 'I(t)' is the resultant quantity (such as the photo-

---

* For example with initial value $I_o = o$, the above reduces to the usual buildup expression

$$I(t) = I_{SS}\left(1 - \exp\left(\frac{-t}{\tau}\right)\right)$$

For an exponential decay, with the initial value I_o, and final value $I_{SS} = o$, the above reduces to

$$I(t) = I_o \cdot \exp\left(\frac{-t}{\tau}\right)$$

current) at time "t",

"I_o" is the initial current at time $t = 0$,

"I_{SS}" is the final current at time $t = \infty$

"τ" is the time constant governing the buildup or decay.

In section 4.3.4, it is shown that the average photocurrent "i_p", for any given illumination "E", is equal to the signal output current "i_s", for that illumination "E" (obtained from the "I_s vs E" curves supplied by the manufacturers (see Fig.66(b)), divided by "m", the number of point elements on the Vidicon target, which ideally is of the order of $4{\cdot}5 \times 10^5$ (but in practice of the order of $3{\cdot}5 \times 10^5$).

Thus $i_p(t) = \dfrac{i_s(t)}{m}$ 4.13

However, it is simpler for our purpose to use $i_s(t) = m\, i_p(t)$ in the expressions for current buildup; this will become evident below.

In evaluating the photocurrent buildup and decay using expression 4.12, an iterative method must be used as "i_o", "i_{ss}" and "τ" are functions of illumination "E", which for "W" phosphor illumination, constantly varies with time within a frame time interval; thus "$i_s(t)$", "$i_{ss}(t)$" and "$\tau(t)$" are themselves functions of time. Analytically, the expression is extremely hard, if not impossible, to solve.

For small intervals of time, "Δt_i", not necessarily of equal length, the illumination "E(t)" can be considered constant, thus making "$i_{ss}(t)$" and "$\tau(t)$" constant over that interval.

Furthermore, for $\Delta t_i \leqslant \tau(t)$

$$\left(1 - \exp\left(\frac{-\Delta t_i}{\tau(t)}\right)\right) \text{ reduces to } \frac{\Delta t_i}{\tau(t)}$$

Hence expression 4.12 reduces to the iterative form

$$i_s(\Delta t) = i_o + (i_{ss}(\tfrac{\Delta t}{2}) - i_o)\cdot\frac{\Delta t}{\tau(\frac{\Delta t}{2})} \quad \ldots\ 4.14$$

At any arbitrary time, within the frame time interval

$$i_s(t+\Delta t) = i(t) + \left(i_{ss}(t+\tfrac{\Delta t}{2}) - i(t)\right)\cdot\frac{t}{\tau(t+\frac{\Delta t}{2})} \quad \ldots\ 4.14(a)$$

where "$i_s(t+\Delta t)$" is the signal current $(=m.i_p(t))$ at time "$t+\Delta t$",
"$i(t)$" is the signal current at the beginning of the time interval "Δt", (and evaluated at the previous iteration),
"$i_{ss}(t+\frac{\Delta t}{2})$ is the signal current read off the "I vs E" curves for an illumination corresponding to time "$(t+\frac{\Delta t}{2})$" from the curve in Fig.66(b).
and "$\tau(t+\frac{\Delta t}{2})$" is the time constant evaluated at the same illumination as "i_{ss}" is; the expression for this is given below.

4.3.3. Photocurrent Time Constants

An expression for $\tau(t)$ has been found in section A.10.4 The form of the expression was suggested initially by graphical curve fitting to the few available time constants of Vidicons, at various levels of illumination, in the literature; however its present form is based on theoretical grounds, and when used to evaluate time constants for which data was available, the calculated and given values of the time constants check to within ±15%.

There are two types of photoconductors of interest, called Class I and Class II Photoconductors respectively. It is shown in Appendix A.10.4 that

(a) for Class I photoconductors

$$\tau = \frac{R_d \cdot C \cdot I_o \cdot (E)^{\gamma - 1}}{4 \cdot 2 \times 10^{-6}} \quad \text{(Seconds)} \quad \ldots \ldots 4.15$$

where "R_d" is the "dark current" resistance, obtained from the "Dark Current vs V_s" curves supplied by the manufactureres and evaluated at a particular "V_s" (see Fig. 66(a)); it is of the order of $10^9\Omega$.

"C" is the capacitance of the Vidicon photoconductor target, and is of the order of 1500 pF,

"I_o" is the signal current at an illumination "E" of 1 ft-candle at the given current, and found from the "Is vs E" curves or "light transfer characteristics" (see Fig.66(b).

"E" is the illumination in ft-candles,

"γ" is the "gamma" or slope of the "Is vs E" curves and is the order of 0·6 - 0·7, but may decrease to about 0·3 - 0·4 at very high levels of illumination.

The factor $4 \cdot 2 \times 10^{-6}$ arises from the number of photons in a ft-candle of illumination incident of the Vidicon target.

Typically for a dark current of 0·02ua,

$$\tau = 45(E)^{-0 \cdot 35} \text{ ms} \quad \text{("E" in ft-candles)} \quad \ldots \ldots 4.15\text{(a)}$$

(b) For a photoconductor of class II

$$T = \frac{R_d . \ C. \ I_o.(E)^{\gamma-1}}{4 \cdot 2 \times 10^6 .(a + Mb)} \quad . . . . 4.16$$

where the quantities R_d, C, I_o, E, γ are as above

and a + b = 1

$1 < M \leqslant 10$ and depends on the "dark current", increasing with it.

Typically for a dark current of 0·02ua

$$\tau = 25(E)^{-0.35} ms, \quad \text{("E" in ft-candles)} . . . 4.16(a)$$

The accuracy of this expression 4.16, when evaluated is rather poor. The exact numerical values of "a", "b","M" cannot be stated with any certainty as they depend on the knowledge of the solid state structure of the photoconductor, one of the quantities which is difficult to determine, as stated previously. Moreover this information is rarely released (even if it were known!) by the manufacturers to safeguard 'proprietary rights'.
The numerical values given in expression 4.16(a) are based more on experimental values given in manufacturers' data sheets rather than on expression 4.16 and in our case have been weighed in a conservative direction.

4.3.4 Photocurrent Buildup

The current buildup curves can now be evaluated using expressions 4.14(a), 4.15(a) 4.16(a), as all the values therein can now be evaluated for a given illumination "E" and thus can be evaluated at any given time "t". A sample evaluation is given in Appendix **A.10.4.**

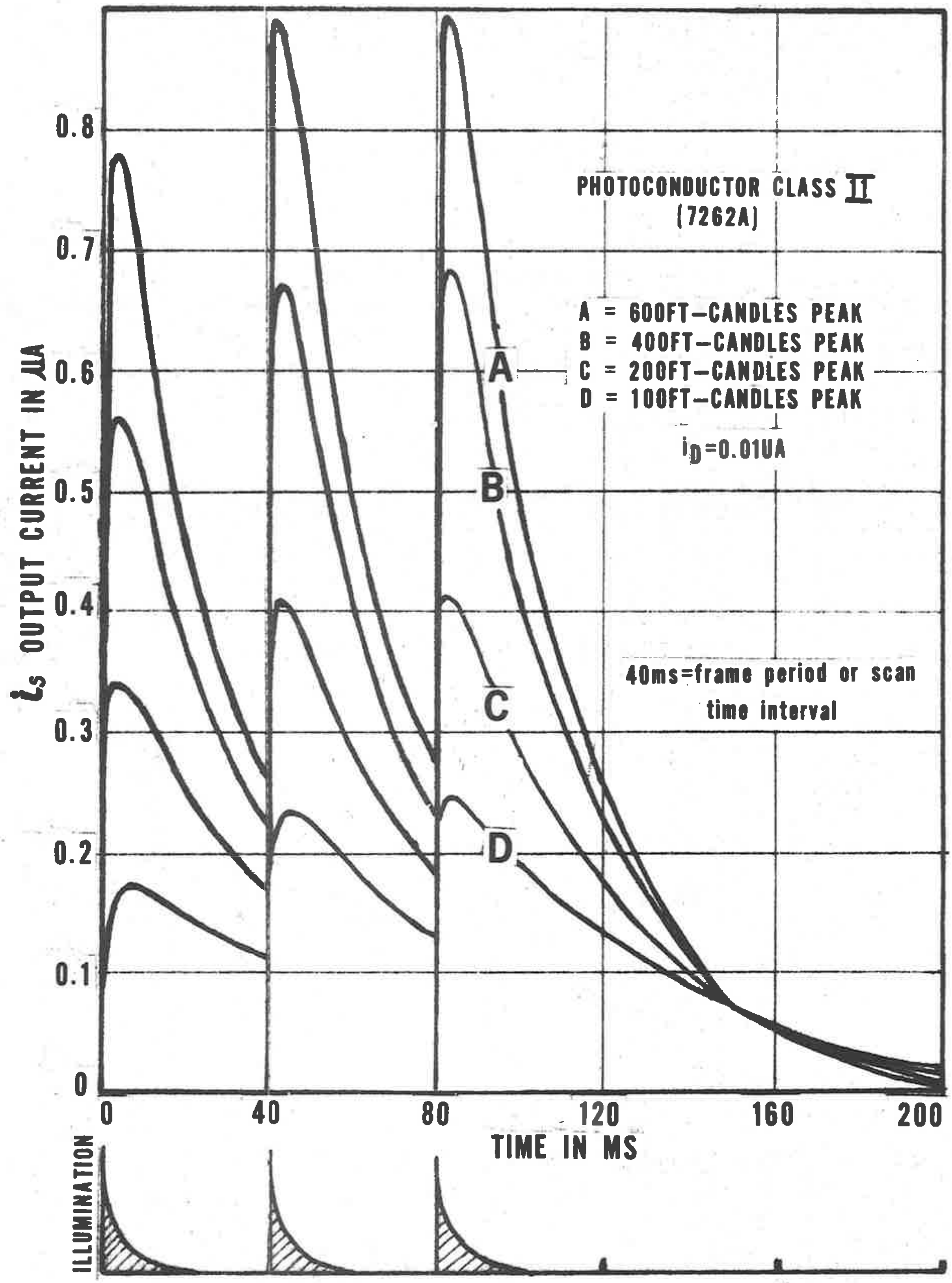


Figure 57(a) Resultant Photocurrent Due to "W" Phosphor TV-mode Excitation.

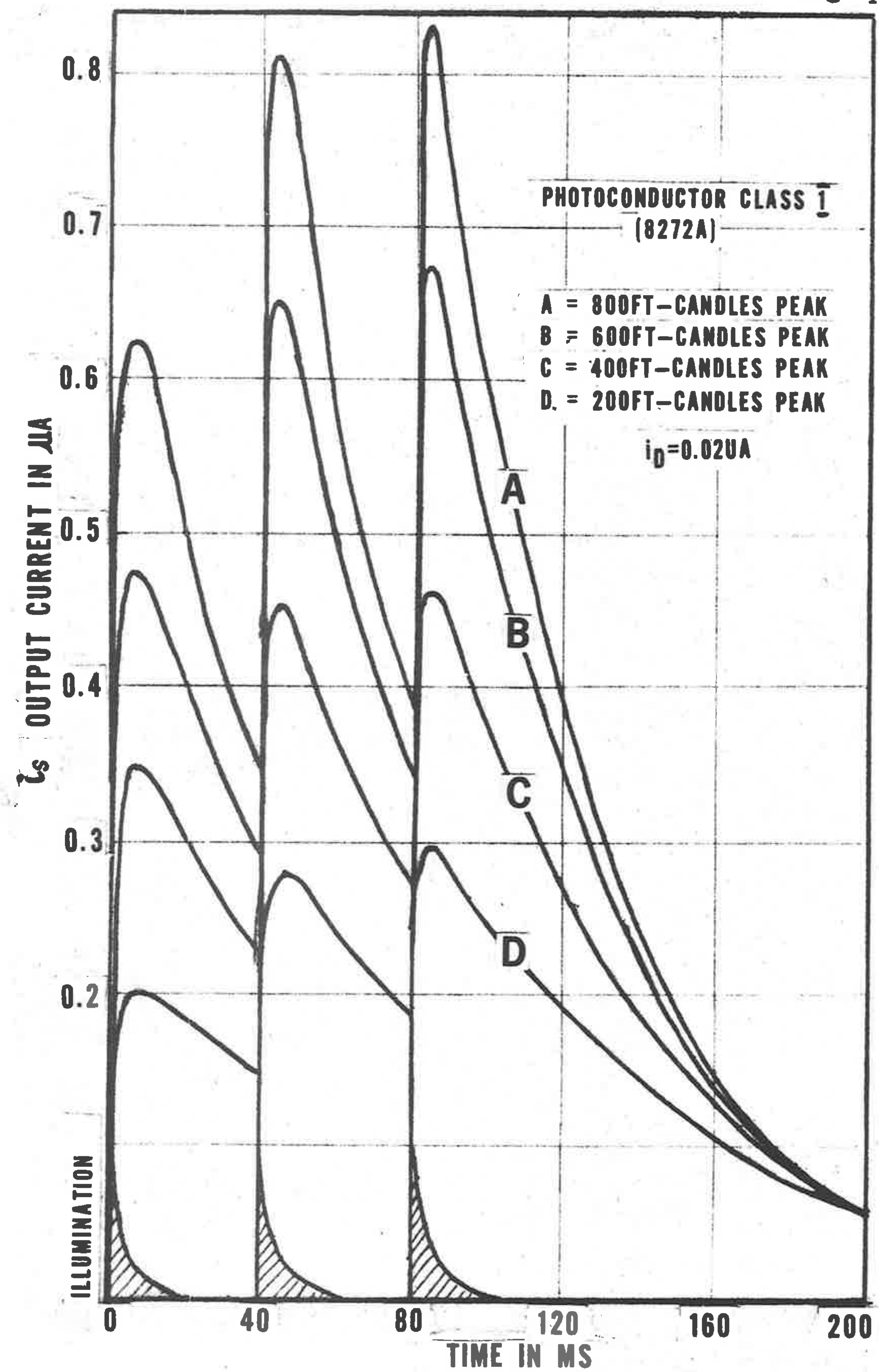


Figure 67(b). Resultant Photocurrent.

Curves are plotted for :

(i) several values of peak illuminance "$E(t)_{peak}$", knowing the capabilities of CRT luminance and Vidicon lens light-catching ability (see section 4.2).

(ii) for several frame time intervals to indicate any current buildup over several cycles and to determine photocurrent flow remaining when illumination has been cut-off (i.e. at display locations requiring to be"erased").

(iii) for several values of "i_d", the "dark current", at the same level of illuminance (only plotted for a photoconductor of class II).

The data for the buildup curves calculated and graphed have been taken from existing Vidicons representative of class I & II photoconductors for which data is available (namely "dark current" and "current sensitivity"). The current amplitudes are modified by the factors indicated in section 4.1.4 to allow for the different spectrum of "W" phosphor from the Tungsten Filament Illuminating source used by the manufacturers.

The resultant plotted "photocurrent buildup" curves are shown in Figs.67(a), 67(b).
At the first frame-time interval "i_o", the initial current value, is taken as the dark current "i_d". At subsequent frame time intervals, the initial current is the photocurrent flowing at the end of the previous frame time interval.

From these curves the expected signal current output due to the scanning electron beam at the end of each frame time interval can be easily deduced (see however section 5.2.).

During a frame time interval, the charge "Q", built up at any point on which an illumination of peak brightness "E_p" falls is clearly given by

$$Q = \int_0^{T_F} ip(t)\ dt \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ 4.17$$

where "0 to T_F" is the frame time interval.

This charge "Q" gives rise to a potential ΔV_T at that point in conjunction with the capacitance "c_m" at that point through the usual relationship $Q = c_m \Delta V_T$. Now the scanning electron beam acts as current source and neutralizes this charge "Q" via a discharge current transmitted to the signal plate and hence detected at the Vidicon tube output as the required signal output. Assuming complete charge erasure (see however section 5.2), the beam neutralizes this charge "Q" in the beam dwell-time "T_d", at that location; this "dwell time" is of the order of 0.1us.

$$\text{Thus} \quad i_s = c_m \frac{\Delta V_T}{T_d} \quad (\text{from } i = \frac{cdv}{dt}) \ . \ . \ 4.18$$

As a constant-velocity scanning beam is used, the whole Vidicon image area of "m" locations is scanned in approximately "T_F", the frame time interval (neglecting that fraction of "T_F", spent in flyback time etc - which is typically of the order of 10%).

$$\text{Thus} \quad m.T_d = T_F$$

$$\text{and thus} \quad i_s = m.\ c_m.\frac{\Delta V}{T_F} \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ 4.19$$

and substituting for Q from 4.17 and $Q = c_m \Delta V_T$, then

$$i_s = \frac{1}{T_F}\int_0^{T_F} m.i_p(t).dt \ . \ . \ . \ . \ . \ . \ . \ . \ . \ 4.20$$

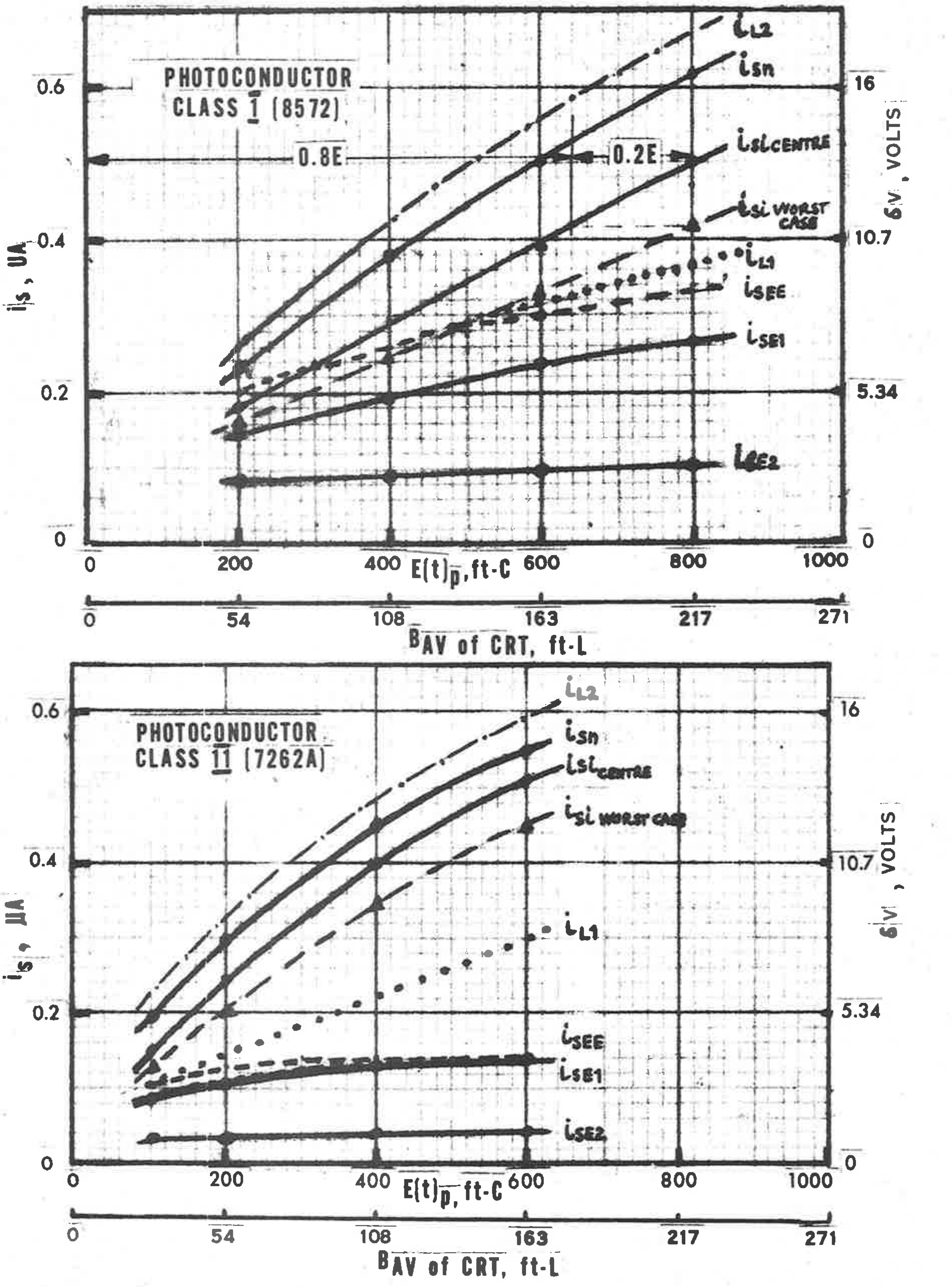


Figure 68. Output Signal 'i_s' vs. Peak Illumination "$E(t)_p$" Due to 'W' Phosphor TV-mode Excitation.

The reason for plotting $i_s(t) = m.i_p(t)$, rather than the photocurrent response, "$i_p(t)$" becomes apparent now. The output current signal is merely the mean of the area under the current buildup curves for each frame time interval as plotted in Figs.67(a),(b). From these the curves Figs. 68, 69 are plotted.

Hence from the means of these current buildup integrals (obtained by graphical approximations as analytic expressions, as mentioned previously, are difficult if not impossible to obtain), the output current signals "i_s", for the following conditions are obtained:

(i) the output current expected after new display information has been input - call this "i_{si}". This is proportional to the area of the first cycle of Figs.67

(ii) the output current expected after the display information has been displayed for some time, call this "i_{sn}". This is proportional to the area of the 3rd cycle in Figs.67.

(iii) the output current expected after the display information has been erased, due to remanent photocurrent existing - call this "i_{sei}". This is proportional to the area of the 4th cycle in Figs.67

It is clear from the Figs.67(a)(b) that

$$i_{se} < i_{si} < i_{sn} .$$

4.3.5 Vidicon Output Signals

Vidicon output signals are required to:

(1) provide the refresh information for the next frame by feeding this signal into the CRT.

(2) be available for processing by the CPU.

Clearly "i_{si}" and "i_{sn}" are these two signals; their amplitudes vary, yet the peak luminance required at the CRT at all frame times, which they initiate, are to

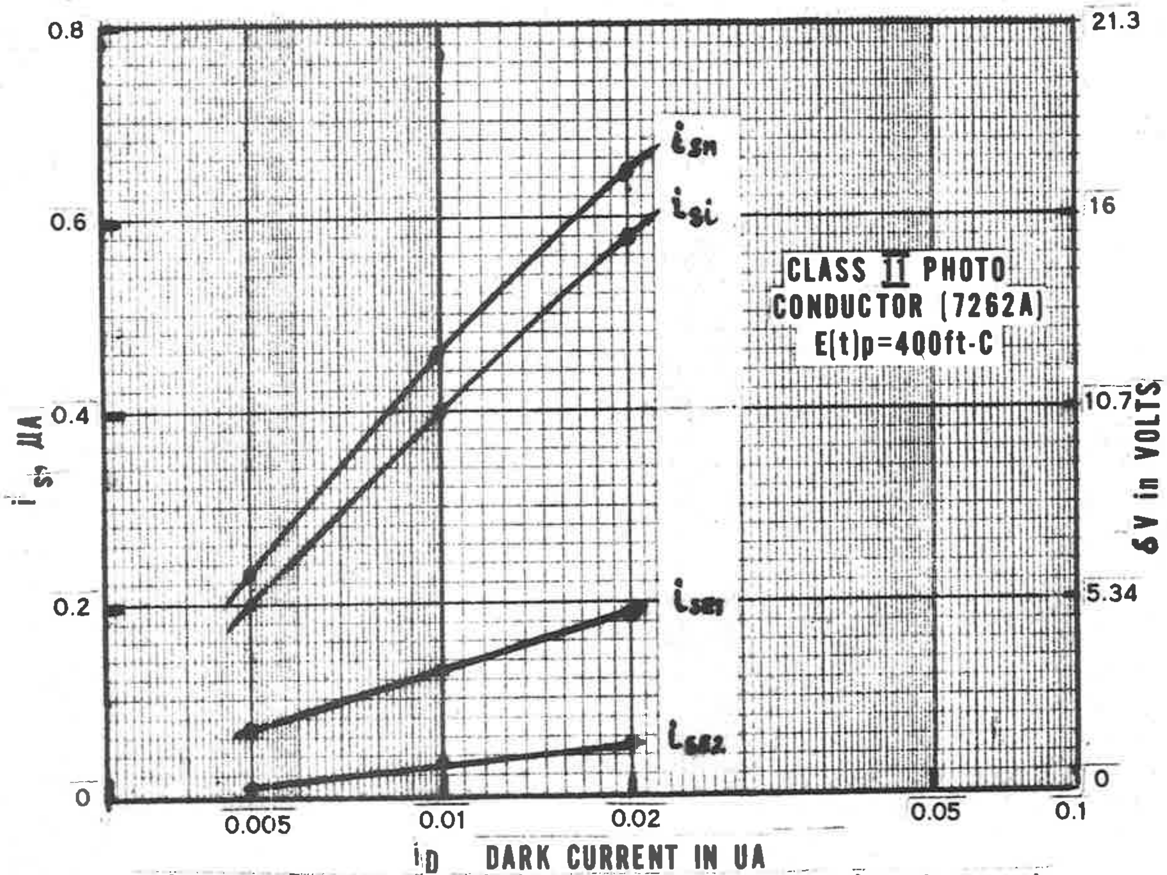


Figure 69. Output Signal i_s vs. Dark Current (and hence vs. Signal Plate Voltage).

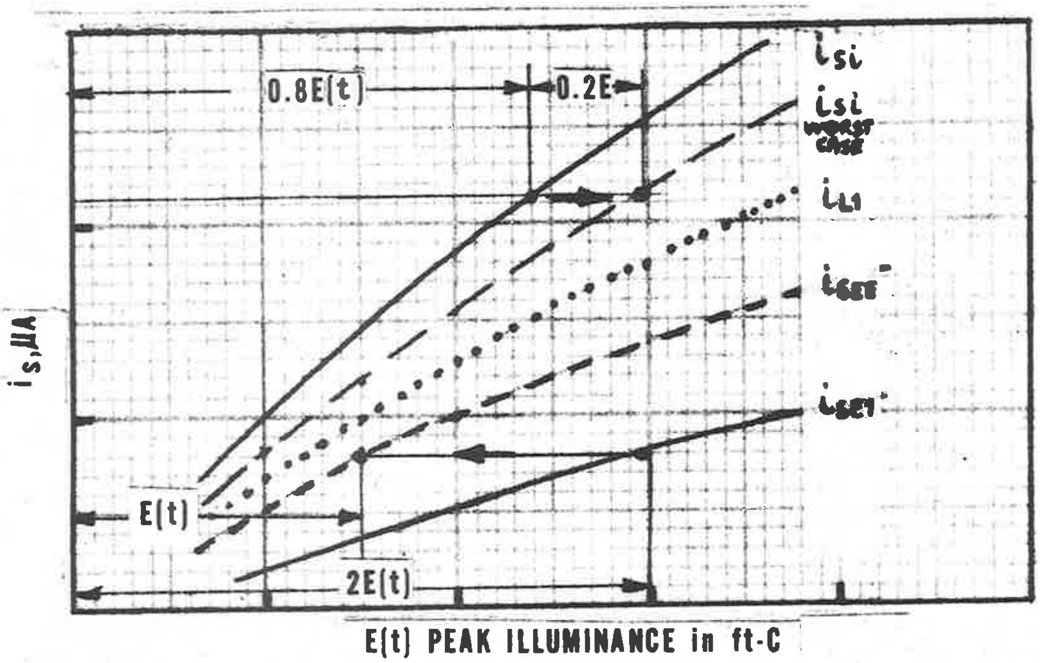


Figure 70. Method of Obtaining Worst -case Currents "i_{si} worst case" and "i_{see}".

be constant. The signal current when no illumination is present, "i_{sei}", is an unwanted signal and must not reinitiate the refresh cycle.

A Level Detecting Circuit performs both of these requirements. If the switching level "i_{L1}" is set so that

$$i_{sei} < i_{L1} < i_{si},\ i_{sn} \quad \ldots\ldots\ 4.21$$

then no output occurs for the unwanted signal "i_{sei}", and a constant output signal results for "i_{si}" and "i_{sn}".

Due to the variation in illumination across the Vidicon (section 4.2), and the reduction in illumination in the first frame time interval after display input (due to phosphor buildup effects - section 4.1.3), "i_{L1}" must be set to cater for the worst case signal.

Thus
$$\left.i_{se}\right]_{centre} < i_{L1} < \left.i_{si}\right]_{edge,\ first\ cycle.} \quad \ldots\ldots\ 4.22$$

Buildup effects in the phosphor contribute less than 10% of the luminance; thus "i_{si}" need be evaluated at 10% less than its nominal brightness value.

Edge illumination degradation is about 10% of that brightness value again.

Thus the worst case, "first frame time interval" current signal, at the edge, is due to an illumination of 80% of the nominal value. The resultant "$i_{si\ worst\ case}$" is plotted in Fig.68; the construction is self explanatory and given in Fig. 70.

The discrimination between the output current signals at various levels of illuminance can be obtained quite simply by normalizing these currents with respect to "i_{sn}", as "i_{sn}" is the usual steady case signal current.

In practice these curves in Figs.68-69 need be modified to some degree, allowing the actual discrimination between the various classes of signals to be determined. The output current signals are modified (invariably with the result that the discrimination between the required and unwanted signals is lowered) due to the following reasons:

(1) the incomplete discharge of the stored charge "Q" by the Vidicon scanning beam.

(2) the loss of scanning beam energy, the magnitude of which depends on the angle of deflection of the beam with respect to the tube axis.

(3) asymmetry of charge discharge due to the unilateral direction of travel of the scanning beam during the raster scan.

The resultant effect of these is described in the following chapter. The degree of signal current modification due to these various effects is left till then.

Modifying slightly the curves of Figs.68-69 makes them still of considerable use.

Equation 4.19 can be rewritten as

$$i_s = (m.c_m) \cdot \frac{\delta V_T}{T_F} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; .4.19(a)$$

and thus

$$\delta V_T = \frac{T_F}{m.c_m} i_s = \frac{T_F}{C} i_s \quad . \; . \; . \; . \; . \; . \; . \; . \; 4.23$$

where "δV_T" is the surface potential change associated with the output signal "i_s", rather than the surface potential "ΔV_T" of the photoconductor. "T_F", the frame time interval, equal to 40.10^{-3} seconds.

"C" is the Vidicon target capacitance and equal to about 1500 pF (and equal to $m.c_m$)

Hence evaluating,

$$\delta V_T = 26{\cdot}7 \times 10^6 . i_s \quad . . . . \quad 4.23(a)$$

This can be indicated on the R.H. ordinate axis of the curves of Figs.68-69.

The actual values of "δV_T" corresponding to any given ΔV_T (allowing for beam discharge effects), are read off from Fig.74. Consequently knowing "δV_T," the output signal currents "i_s" can be simply read off these curves. The operative values of "δV_T" under varying conditions is left till section 5.2.3.

4.3.6 Response to User Specified Inputs

A second set of current output signals is of relevence, namely those generated by the light pen during user-specified graphics input or user-indicated display features for CPU processing or for erasure.

For the inputting of graphic information, the illuminance must be such as to result in an output signal, labelled "i_{sui}" so that $i_{sui} > i_{L1}$, and hence become part of the display information. The spectral composition and time variation of luminance of the light source may be different to the CRT luminance. The form of the photo-current buildup may thus be different to that found above; the buildup and hence the expected output signal, will be left till section 6.6.

The second type of signal, resulting from pointing to displayed features, needs be differentiated from the above. A second Current Level Detector is used and enabled "ON" whenever these signals are required. Calling the signal from an indicated feature for CPU processing, "i_{sun}", while the signal from a feature to be erased, "i_{sue}", the second level detector when enables, must have its level "i_{L2}", such that

$$i_{sn}, i_{si} < i_{L2} < i_{sun}, i_{sue} \quad \ldots . \; 4.24$$

The signals "i_{sun}", "i_{sue}", are obtained by superposing the light-pen emitted luminance "$E_{PEN}(t)$" on the CRT generated luminance "$E_{CRT}(t)$" at the CRT screen. Clearly then the luminances add, to result in a combined illuminance,

$$E(t) = E_{CRT}(t)+E_{PEN}(t) \quad \ldots\ldots\ldots . \; 4.25$$

$$\text{Thus, as } E_{sun}, E_{sue} > E_{sui} \quad \ldots\ldots . \; 4.26$$

$$\text{then } i_{sun}, i_{sue} > i_{sui} \quad \ldots\ldots\ldots . \; 4.26(a)$$

As "i_{sui}" need be of the same order as "i_{sn}", "i_{si}", then as the illumination due to the light pen is constant for both "i_{sui}" and "i_{sun}", "i_{sue}", then

$$E_{PEN}(t) \gg E_{CRT}(t) \ldots\ldots\ldots\ldots . \; 4.27$$

From the above expression 4.25, the total illuminance $E_T(t)$ thus can be

$$E(t) \gg 2E_{CRT}(t) \ldots\ldots\ldots\ldots . \; 4.27$$

For the "Erase" signal in particular, the subsequent frame time CRT illimination ideally need be such that $E_{CRT} = 0$, while the remanent photocurrents, still flowing, generate an unwanted signal "i_{suee}". This signal, being

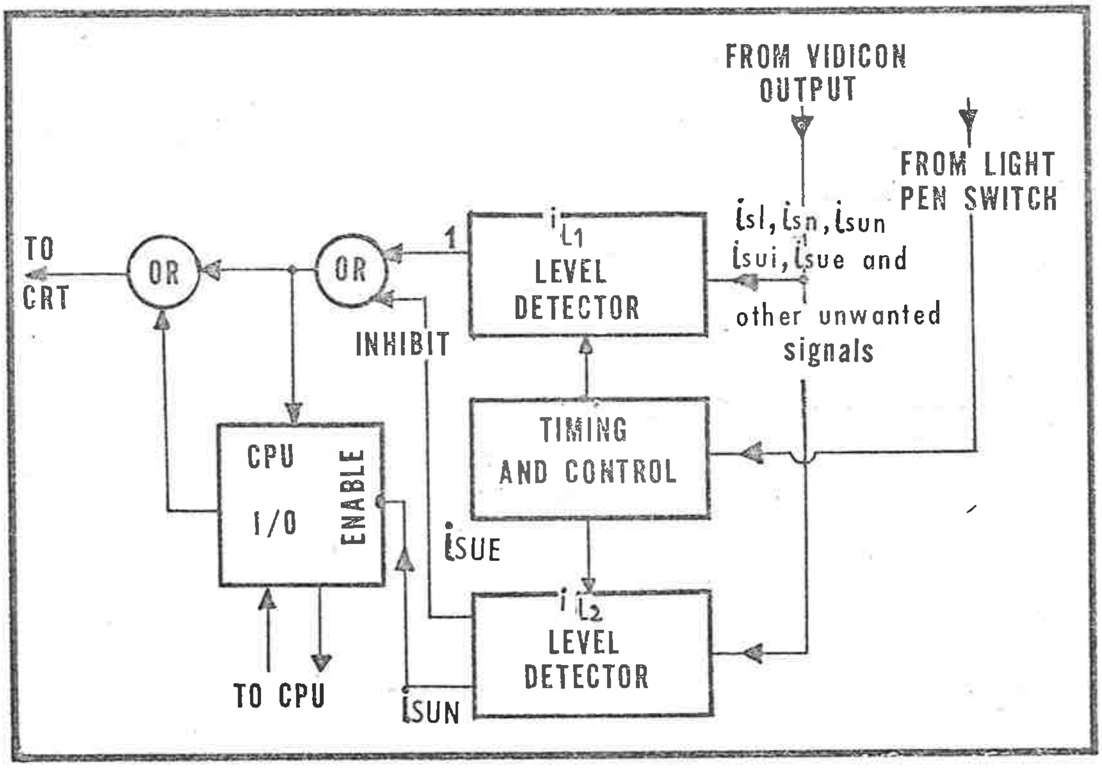


Figure 71. Logic for Vidicon Output Signal Processing.

TABLE 2

TYPES OF VIDICON CAMERA SIGNALS TO BE PROCESSED BY "i_{L1}" AND "i_{L2}" CURRENT LEVEL DETECTORS

	SIGNAL	REQUIREMENT	WANTED	EXPLANATION
CPU OR DISPLAY ORIGINATED SIGNALS	i_{si}	$i_{si} > i_{L1}$	yes	1st signal after CPU Input.
	i_{sn}	$i_{si} > i_{L1}$	yes	steady state signal after "n" refresh cycles.
	i_{sel}	$i_{sel} < i_{L1}$	no	1st signal after CPU specified erasure.
	i_{sei}	$i_{sei} < i_{L1}$	no	"nth"cycle signal after CPU specified erasure.
USER ORIGINATED SIGNALS	i_{sui}	$i_{sui} > i_{L1}$	yes	1st signal after User-Input.
	i_{sun}	$i_{sun} > i_{L2}$	yes	signal from a user indicated display location.
	i_{sue}	$i_{sue} > i_{L2}$	yes	signal from a user-indicated display location for erasure.
	i_{suee}	$i_{suee} < i_{L1}$	no	1st signal after user-specified erasure.

due to a much higher illumination than "i_{si}", "i_{sn}" may even be comparable in amplitude to "i_{si}", "i_{sn}" which are wanted signals.

The signal current "i_{see}" is plotted in each of the set of curves in Fig.68. It is merely "i_{se}", evaluated at 2E(t) but plotted at the illuminance E(t) (see the self-explanatory construction in Fig.70).

Clearly photoconductor Class I is unsuitable for our purpose as $i_{suee} \approx i_{si}$, leaving little or no discrimination for the Level Detector "i_{L1}".

Photoconductor Class II is still very suitable for our purpose. Since presumably during the time when display features are being pointed to, care is used in superposing the Pen over these display features and "writing" speed is reduced, then some means of reducing the light pen luminance source can be introduced during the time the pen is used in the pointing mode. When this light source is itself the CRT (or parts of the CRT screen), the control of light pen luminance can be accomplished at electronic speeds. This is further discussed in section 6.6.5 - 6.6.8.

Fig.71 illustrates the Signal Level Detecting logic.

Table 2 defines the major classes of signal outputs from the Vidicon camera and their relative amplitudes necessary to satisfy the intended requirements.

4.3.7 SUMMARY

(1) Within a frame time interval of 40ms, adequate signals must be generated in the Vidicon camera to be detected and to restart and maintain the display-refresh storage.

(2) The time constants governing signal buildup in Vidicons are significant compared with the frame time interval, except at high levels of illumination.

(3) The CRT "W" phosphor luminance is extremely suitable having the conditions of a very high illumination for high signal buildup at the beginning of the frame time and low signal output at the end of the frame.

(4) Expressions for the time constants governing the rise and fall times of the signal buildup have been derived, and in conjunction with the general expression for exponential buildup or decay, typical current signal output curves have been derived based on data readily obtainable from manufacturers' curves (Fig.67).

(5) From such curves the relative ratios of the output signals for various conditions can be obtained for various levels of peak illumination. The level of illumination required, and hence the required CRT, can be determined for a given photoconductor (Fig 68-69).

(6) Once having selected the levels of output currents, the luminance required from the light source supplying the user light pen can be specified. (Expression 4.27).

(7) The above are based on the assumption that complete charge erasure occurs with the electron scanning beam to generate the output signed; this in fact, is not quite true and the effect of the beam scanning on the amplitudes of the output signals is dealt with in the next chapter.

....

CHAPTER 5

BEAM DISCHARGE OF VIDICON PHOTOCONDUCTOR

5.1 INTRODUCTION

The curves in Figs.68-69, showing the expected output current signal for various starting conditions and levels of illumination, assumed that the discharge current provided by the Vidicon electron beam completely discharged the built up charge "Q" (giving rise to the potential "ΔV_T") during the beam dwell time "T_d", which is of the order 0.1µs. This assumes that the scanning beam is a perfect current source; in fact it is far from so, particularly at low values of stored charge. The result is incomplete stored-charge discharge during the initial scan, leading to output signal reduction, thus bringing the required signal "i_{si}" and the unwanted signals levels "i_{see}" closer together, reducing the discrimination between them. This signal reduction is also known as "beam discharge lag" or "capacitive lag" mentioned previously in section 4.3.1. This signal output reduction and any other factors contributing to output signal reductions need be investigated.

A second effect, due to scanning, results because the scanning beam is deflected across a finite target area of some 12·8 x 9·6mms on a flat target surface. The scanning beam thus does not land normally on the target at points away from the centre of the target. Again this has the effect of incompletely discharging the stored charges, the deviation from complete discharge becoming progressively larger as the deflection angle increases. The incomplete discharge can be predicted at any given landing angle and thus at any location on the target; thus it can be compensated for. Alternatively, "careful" Vidicon tube design, resulting in certain electric field distributions existing near the target and ensuring that the beam lands normally at all points on the target, is required.

A third effect, which is extremely difficult to calculate quantitately, is more selective yet in the output signal degradation. The direction of movement of the scanning beam is asymmetrical with respect to the Vidicon target centre. The beam sweeps, say from left to right and, more slowly, from top to bottom, that being the usual "raster scan". Now on the photoconductor target in the vicinity of the beam, a potential difference exists between the location just previously scanned and the location about to be scanned, resulting in an electric field in the direction of motion of the moving beam, giving a localized deflection of the beam (of significant magnitude) away from the normal; this appreciably changes the angle of the beam with respect to the normal to the target surface. The nominal angle of the scanning beam to the normal due to scanning varies from say "$+\varphi$" to "$-\varphi$" (see Fig.77). The localized electric field beam deflection shifts the beam by say "$+\alpha$" degrees unidirectionally - hence the angle of the beam at landing varies from $(\varphi+\alpha)$ to $(-\varphi+\alpha)$; this angle is asymmetrical, with the result that asymmetrical deviations from complete discharge occur.

The difficulty in predicting the magnitude of this effect is apparent; it varies with the initial stored charge (and thus with the illumination), the characteristics of the beam, and the resulting field configuration between the target and the accelerating mesh. Qualitative results however, can be predicted (253).

Thus three major effects lead to the degradation of the output signals. These are :

(i) the nature of the discharge beam itself.

(ii) the angle of the deflected beam (effects of which are predictable and hence may be compensated for easily).

(iii) the asymmetry of the scanning direction with respect to the photoconductor target and localized electric field effects in the vicinity of the beam landing locations.
Also variations in scanning velocity produce similar output signal defects.

It will be shown in the following sections that the magnitude of the degradation of the output signal is not very significant in our application.

However, because the literature on Vidicons mentions "beam discharge lag" and other output signal degrading factors as having considerable effect, the explanation of the causes and resultant magnitudes of signal variations need be given.
The degradation of Vidicon signal output may be (and is) certainly noticeable in low-level, live-scene Vidicon application, but in our case, where Current Level Detection is used, the degradation is not so serious enough.

5.2. BEAM DISCHARGE EFFECTS

5.2.1 Introduction

The electron beam of "i_b" amps originates from the Vidicon cathode, which is usually kept at ground potential (OV). After being accelerated by the final anode and mesh, both of which are at some +300V, it is retarded by the retarding electric field "$\underset{\sim}{E}_R$" existing between the mesh and the target potential distribution "ΔV_T" which may be up to +10-15V.

The separation between mesh and target is of the order of 2-3mms. This retarding field* "$\underset{\sim}{E}_R$" ensures that secondary emission is kept negligible and that the electron beam lands normally to the photoconductor surface. So long as $\Delta V_T > V_{CATHODE}$ (=0V), the beam lands on the target giving rise to the discharge or "target current", "i_T" where

$$i_T = i_b \quad \text{for} \quad \Delta V_T > 0 \; . \; . \; . \; . \; . \; . \; . \; . \; 5.1$$

This is called the "normal current range" (251,252,253).

However due to the electron velocity distribution of the beam,an "intrinsic current range" also occurs, which is of the form

$$i_T = i_b . \exp(a . \Delta V_T), \quad \Delta V_T < 0 \; . \; . \; . \; . \; . \; 5.2$$

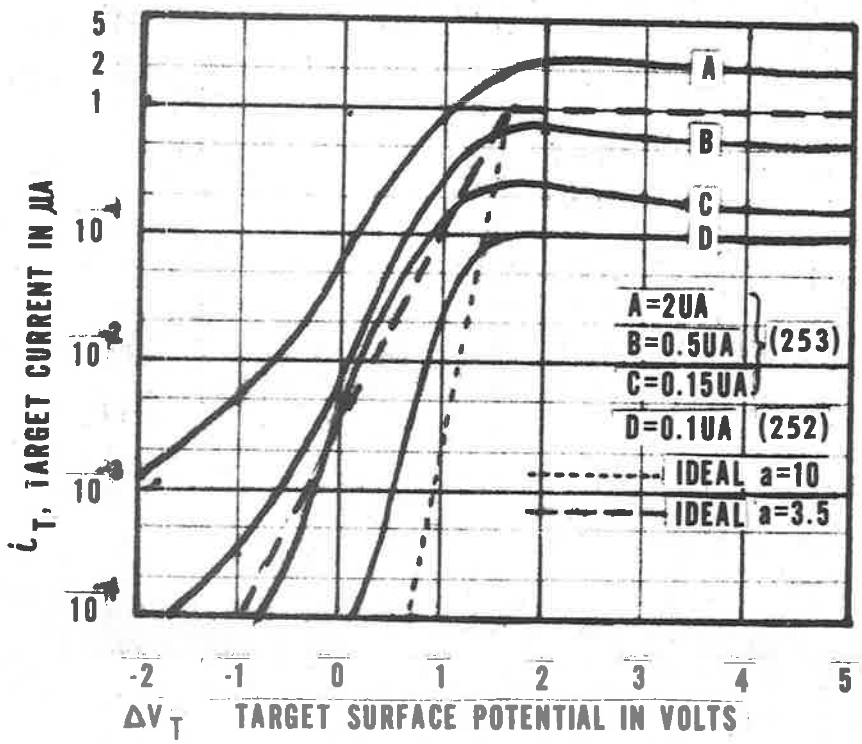
where "a" is a constant of the order of 10.

The "current vs. ΔV_T" curve over all ranges of "ΔV_T" is called the "beam acceptance" curve. Practical beam acceptance curves vary from the ideal curve described by expressions 5.1 and 5.2, due to:

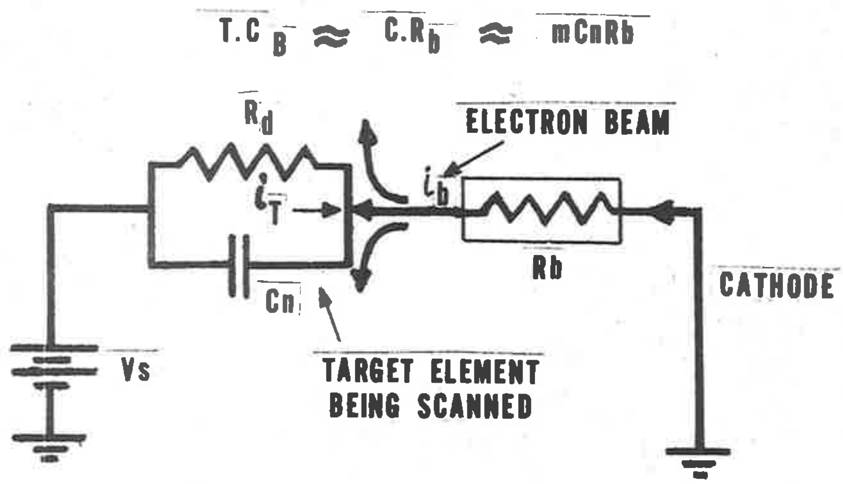
(1) a shift in the origin where the two curves meet, by some ΔV_C = 2V, due to a contact potential (see below).

(2) the slope of the curve in the "intrinsic range," defined by "a" being not 10 but some value below 10, is less steep than that predicted in expression 5.2.

Several curves, one ideal, the others derived from (251,252) are shown plotted in Fig.72(a).
The actual method of obtaining practical beam acceptance curves is to use "Vidicons" with the photoconductor layer omitted, and just the back-plate present at some "V_S"



(a) Typical Beam Acceptance Curves - theoretical and experimental (references cited)



(b) Equivalent circuit at beam discharge with beam-discharge time constant.

Figure 72. Beam Discharge and Beam Acceptance vs. Photoconductor Target Potential.

corresponding to "ΔV_T". These modified "Vidicons" have been shown to approximate the actual case (253).

It would appear at first sight that the presence of the intrinsic range is of no consequence as the signal plate voltage "V_S" (see Fig.62) is always positive, leading to a positive "ΔV_T" due to "dark current" flow, and any photocurrents flowing always lead to a positive "ΔV_T". However, a "contact potential" (see Appendix A.10.2) of some +1·8-2V exists between the photoconductor and the electron beam; the actual value depends on the type of photoconductor used. Electrons, whether from photons or beam electrons, must have a minimum energy of about +2eV to be injected into the photoconductor to generate, or become, carriers, a fact often forgotten or omitted in beam discharge effects. This has the effect of changing the "origin" of transition between the "normal" and the "intrinsic" current ranges.

Thus the above expressions now become:

$i_T = i_b$ .... ($\Delta V_T > 2V$). . 5.1(a)

and $i_T = i_b.\exp(a.\Delta V_T)$ .....($\Delta V_T < 2V$). . 5.2(a)

5.2.2. Beam Impedance

As a rough approximation, expression 5.2(a) can be differentiated, to result in an effective beam impedance "R_b" (see Appendix A.7.2), where it is found that $R_b = \frac{1}{a.i_T}$; this is of the order of 10^6-$10^7\Omega$.

It is further shown in Appendix A.7.2 that this impedence "R_b" leads to a Time Constant

$$T.C_B = R_bC = \frac{C}{a.i_T}$$

where "C" is the Vidicon target capacitance ($\approx$1500pF)
"a" the beam acceptance constant with a nominal value of 10, but in practice varying from 2 to 5 (252).
"i_T" is the target current.

At target currents of some 0·05µA, when "R_b" becomes operative, "$T.C_B$" has values of the order of 5-10ms. and progressively increases as "i_T" decreases.

5.2.3 Beam Discharge

During the discharge of ΔV_T by the beam current "i_b", during the dwell time $T_d \approx 0{\cdot}1$us, the target current is governed by the usual relation

$$-i_T = c_m \cdot \frac{d(\Delta V_T)}{dt}$$

where "c_m" is the capacitance of a single target element (and equal to about $\frac{1500}{m}$ pf $\approx 3{\cdot}3\text{x}10^{-15}$F)

Solving this expression in conjunction with 5.1(a) and 5.2(a) (see Appendix A.7.2) results in

$$\Delta V_T(t) = ib\frac{t}{c_m}, \text{ for } \Delta V_T > 2V \quad . .5.3$$

and

$$-i_b\frac{(t-to)}{c_m} = -\frac{1}{a}(\exp(-a.\Delta V(t) - \exp(-2a)).$$

$$\text{for } \Delta V_T < 2V \quad . . . . 5.4$$

where the symbols are as defined before and "t_o" is the time taken for $\Delta V_T(t)$ to reach to +2V from the time that the dwell time "T_d" begins.

These two expressions may be plotted for "$\Delta V_T(t)$

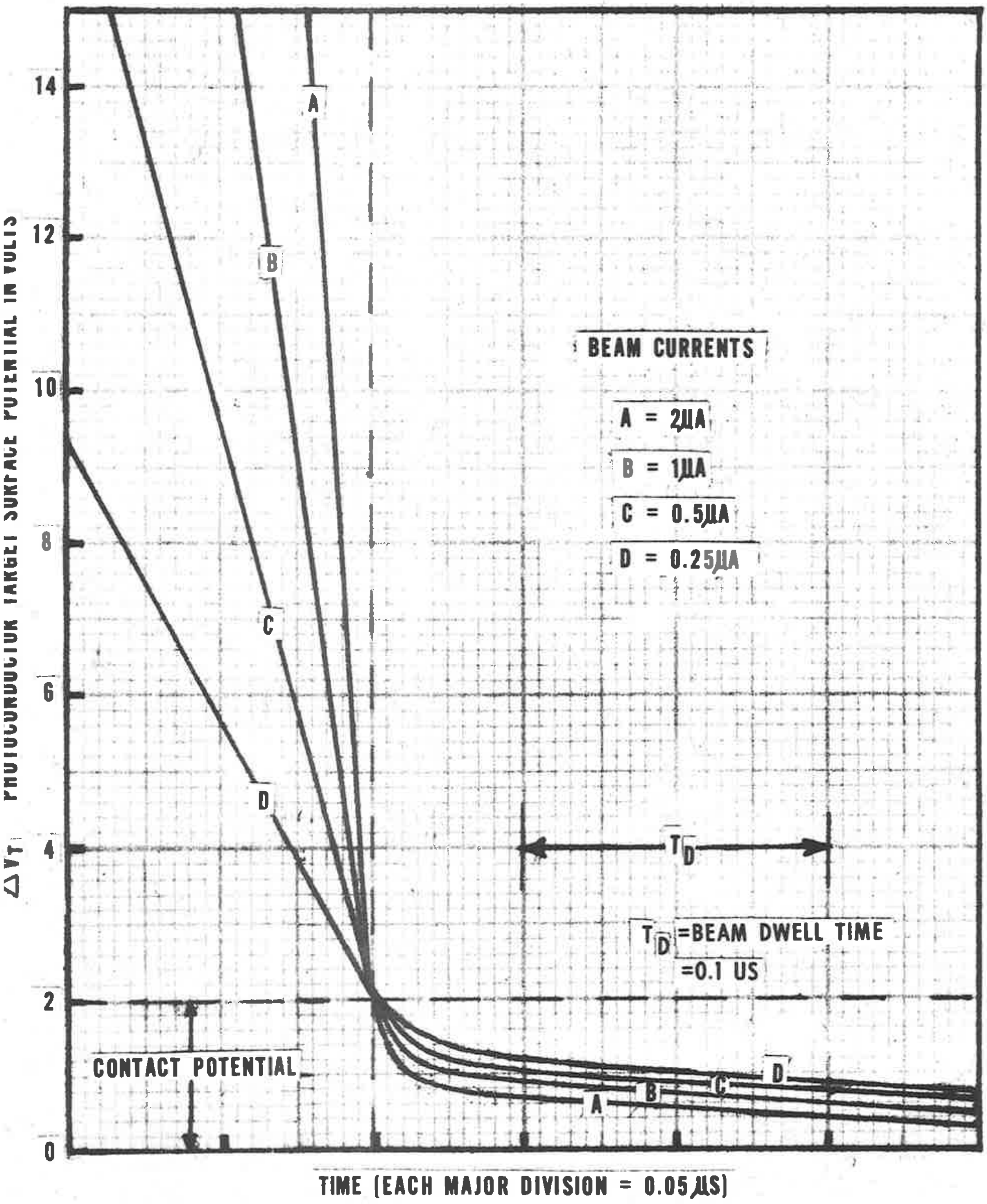


Figure 73. Ideal Vidicon Target Potential Change Curves vs. Dwell Time for Various Beam Currents (a= 3.5)

vs. Time" for several values of beam current "i_b" around a nominal value of i_b = 1uA. The actual expressions plotted are derived and given in Appendix A.7.4 ; values of $c_m = 3.3.10^{-15}$F, a = 3·5 and four values of "i_b", are used. The result is shown in Fig.73.

These are ideal curves in the sense that a constant value of a = 3·5 is used. In practice, as can be seen in Fig.72, "a" varies, with the result that such actual curves would exhibit some non-linearities around the value of $\Delta V_T(t) = +2V$.

Thus if "$\Delta V_T(t)$", the Vidicon target surface potential is known, then, "T_d" seconds later, (i.e. a "beam dwell time instant" later), the remaining $\Delta V_T(t)$, labelled $\Delta V_{TR}(t)$, can be found. The nett change in potential

$$\delta V_T(t) = \Delta V_T(t) - \Delta V_{TR}(t)$$

is thus the quantity contributing to the output signal "i_s", thus:

$$i_s = c_m . \frac{\delta V_T(t)}{T_d} \quad \ldots\ldots\ldots (\text{from } 4.19(a)).$$

As curves in Figs.68-69 have "$\delta V_T(t)$" also shown, the resultant signal output current can be read directly off Fig.68-69.

From the curves in Fig.73, a more useful set of curves can be obtained. For each value of 'ΔV_T' for a particular beam current "i_b", "$\delta V_T(t)$" can be obtained. Plotting "$\Delta V_T(t)$ vs $\delta V_T(t)$" for a dwell time T_d = 0.1us, results in Fig.74. From curves of Fig.74 and curves of Fig.68-69, actual output current signals allowing for beam discharge defects from the Vidicon can be obtained directly.

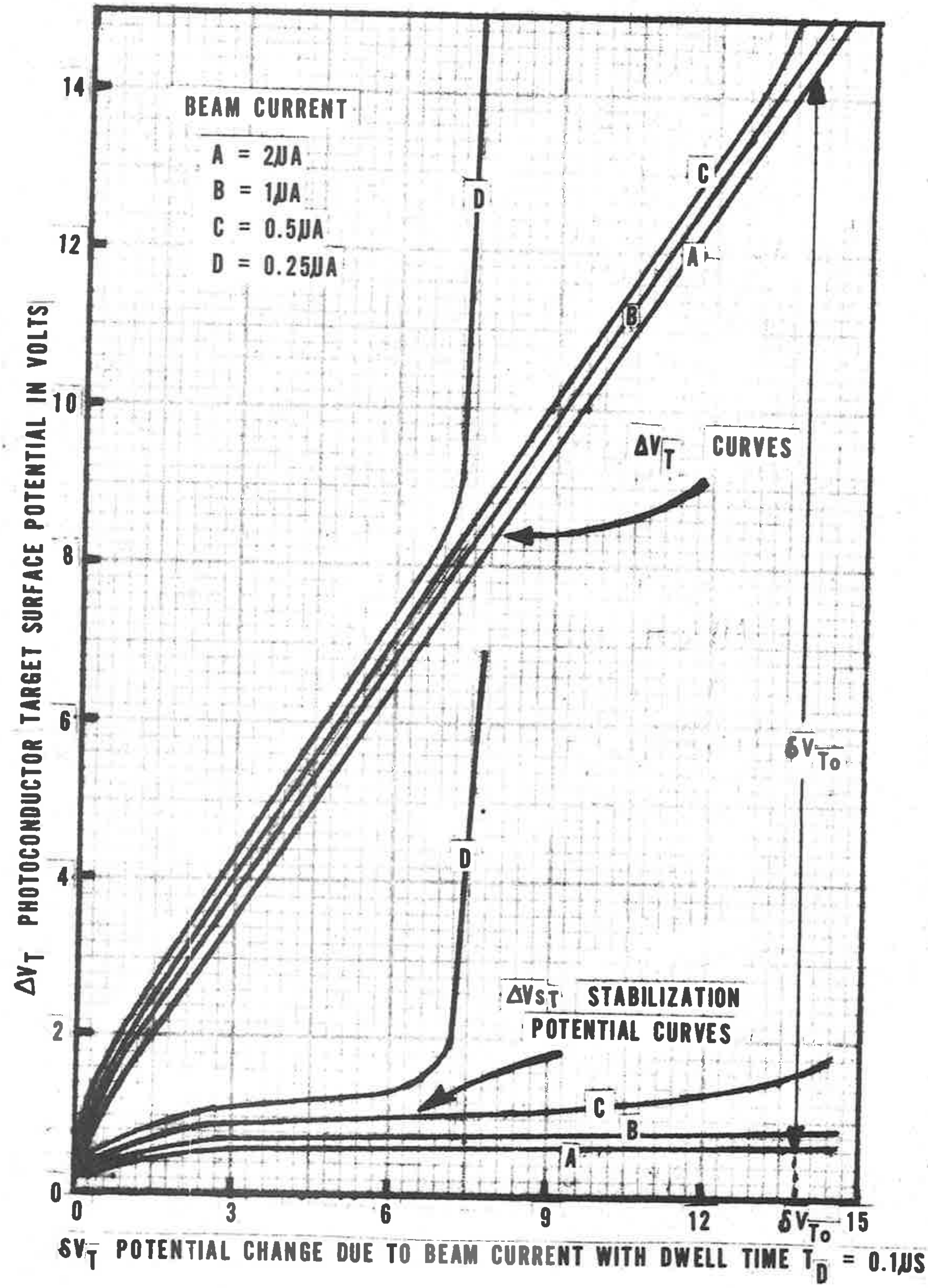


Figure 74. Ideal Vidicon Target Potential vs. Potential Change due to Beam Current Discharge.

The lower curve in Fig.74, being "$\delta V_T(t)$" units below the "ΔV_T" curve is called the "voltage stabilization curve, ΔV_{TS}."

5.3. PHOTOCONDUCTOR POTENTIAL STABILIZATION

5.3.1 Introduction

During any frame time interval, there is a charge buildup resulting in a resultant "ΔV_T" just prior to beam discharge; this buildup is due to either photocurrents or "dark currents". The steady state or equilibrium output signal clearly occurs where the nett potential rise during a frame time interval is equal to "$\delta V_T(t)$", the discharge potential difference. Any changes in illumination whether due to new display information, or to display erasure, imply some buildup or decay effect over several frame time intervals.

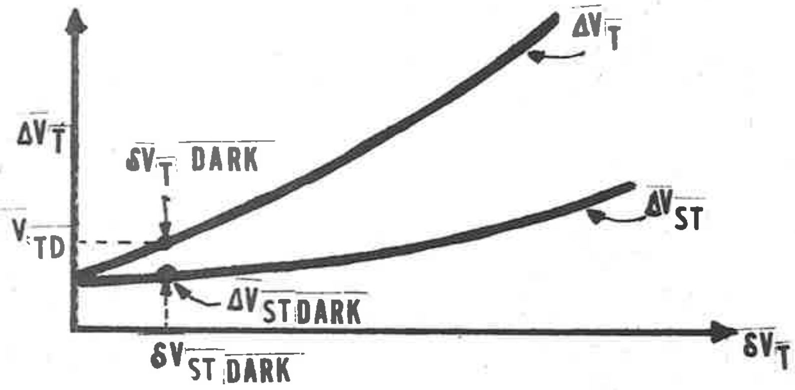
The two steady state conditions are clearly :

(i) no information displayed for at least several frame time intervals.

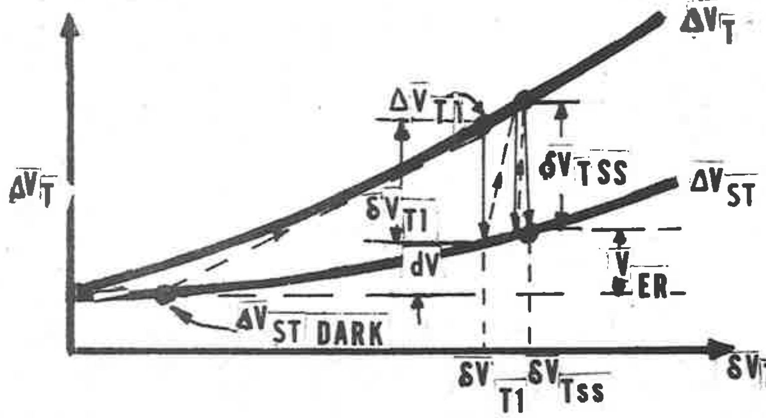
(ii) information displayed for at least several frame time intervals.

5.3.2 Dark Current Stabilizing Potential (Fig.75(a))

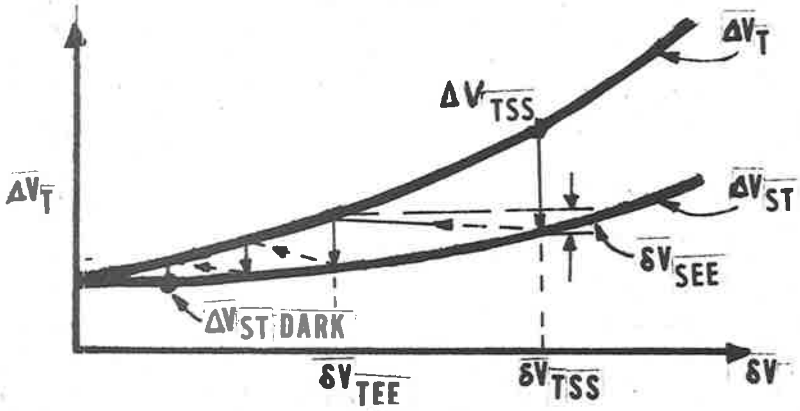
For no information displayed, the target current flow "i_T" is due to the "dark" current during the frame time interval; this is equivalent at the output to some current value of say 0·01uA, when the charge built up by the "dark" current is discharged during the dwell time "T_d". This output current being due to a nett discharge, the potential change associated with the dark current of 0·01µA can be read off from Fig.68. For a photoconductor class II (a Vidicon 7262A), this is due to a "δV_T" of about 0·3V. Call this $\delta V_{ST\ DARK}$ =0·3V.



(a) Dark current Stabilization Potential



(b) Buildup of new display information.



(c) Decay of erased display information.

Figure 75. Use of "ΔV_T","ΔV_{ST}" vs. "δV_T" Curves to Obtain Output Signal Amplitudes for Various Conditions

From Fig. 74, this gives a value of $\Delta V_{T\ DARK}$ of some 0·6-1·3V depending on the beam current, prior to discharge. The ordinate on the Voltage stabilization curve "ΔV_{STD}" corresponding to "SV_{STDARK}" is the "dark current" stabilization potential i.e. at locations where no display information occurs, this is the value of the surface potential immediately after beam scanning.

The above is shown in Fig.75(a).

5.3.3. Signal Buildup of New Display Information

Assume new display information is injected at some location. From Fig.75(b) this provides some nett additional charge resulting in "ΔV_{T1}". After the first scan discharge the surface potential drops by "δV_{T1}", leaving a net undischarged potential "dV" compared with "$\Delta V_{ST\ DARK}$", where

$$dV = \Delta V_{ST1} - \Delta V_{ST\ DARK}$$

In practice the maximum accumulated "dV", called "V_{ER}", can be seen from curves of Figs. 74,75(b) to be less than about 1V.

In actual cases, the upper curve is slightly steeper at higher values of "ΔV_T", thus allowing the steady state condition to be reached in several frame times. The maximum difference in the output signal between the initial signal out and the steady state value can be seen to be no larger than "V_{ER}" (see Fig.75(b)), and is of the order of a volt. This "V_{ER}" is relatively insignificant with the signal magnitudes in question. At low output signals encountered in TV-work this may be noticeable as a buildup effect in brightness.

The buildup process is shown on Fig.75(b).

5.3.4 Signal Lag after Erasure of Display Information

The remaining signals seen at successive scans after display information has been erased is shown in Fig. 75(c). From Fig.67(a) and 67(b) it is clear that photo-current still flows after illumination has been eliminated and the resultant unwanted output currents or rather equivalent charge buildup ΔV can be obtained from curves "i_{SE1}" and "i_{SEE}" of Fig.68. These resultant ΔV_T increases give rise to the increment, labelled "δV_{SEE}" in Fig.75(c) resulting in the nett "δV_{TEE}" discharge at the subsequent scan intervals, the photocurrent buildup is progressively smaller and so are the output signals.

5.3.5 Magnitude of Beam Discharge Lag or "Capacitive Lag"

It is seen that if "ΔV_{ST}," the stabilization voltage curve has zero slope then no delay and hence no output signal degradation occurs due to beam discharge lag. Mathematically this is shown in Appendix A.7.6(b).

In practice it is seen that the slope of "ΔV_{ST}" is small, giving a maximum "V_{ER}," between "δV_T" of 15V to "δV_T" of about 1V, of less than 1 Volt. Hence the effect of beam discharge lag can be, for our purpose anyway, neglected in comparison with the lag due to photocurrents flowing after illumination has been cut off. This could have been anticipated from the fact that $T.C_B$, the "beam discharge" Time Constant is of the order of 5ms, compared with the time constant of photocurrent decay at the end of the frame time interval, due to "W" phosphor, which is of the order of $\approx$ 25ms.

However, the "ΔV_T vs. δV_T and ΔV_{ST}" curves form a useful function in illustrating the actual beam discharge effect, arising from causes other than the nature of the beam itself. These effects are developed more fully in sections 5.4 and 5.5.

5.4. MODIFICATION OF PHOTOCONDUCTOR STABILIZATION POTENTIAL DUE TO DEFLECTION

The electron beam in the Vidicon tube is deflected by a time varying magnetic field superimposed on a long axial magnetic field of high intensity which provides beam focussing (see sec. 9.3.3) and also helps to ensure that the beam lands normally onto the photoconductor. The beam is emitted from a cathode at some potential "V_K" and accelerated by the final anode and mesh immediately in front of the photoconductor, which is at some potential 'V_A' (usually about +300V).

From Fig.76(a), the worst case angle at which the beam strikes the photoconductor (the angle deviation from the normal) (assuming axial magnetic field does not realign the beam after deflection - see below), is

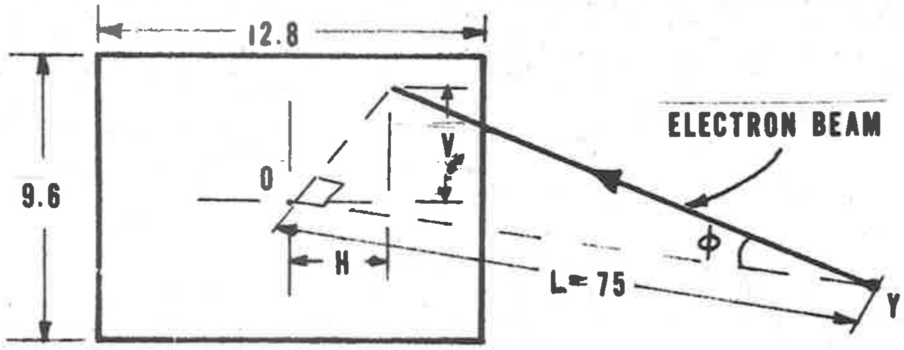
$$\varphi = \arctan \frac{\sqrt{H^2 + V^2}}{L} \quad \ldots\ldots\ldots \quad 5.5$$

where

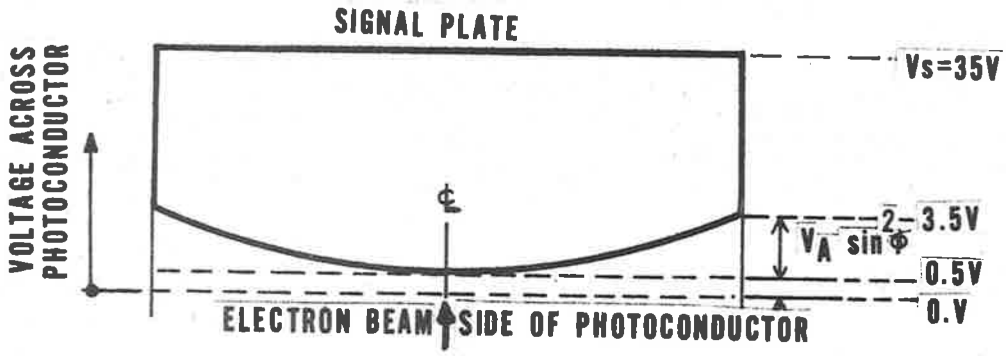
'H' and 'V' are the coordinates of the location where the beam strikes, from the central display axis (0,0),

and 'L' is the length of the region of deflection, approximately 75mms. in a 1" Vidicon.

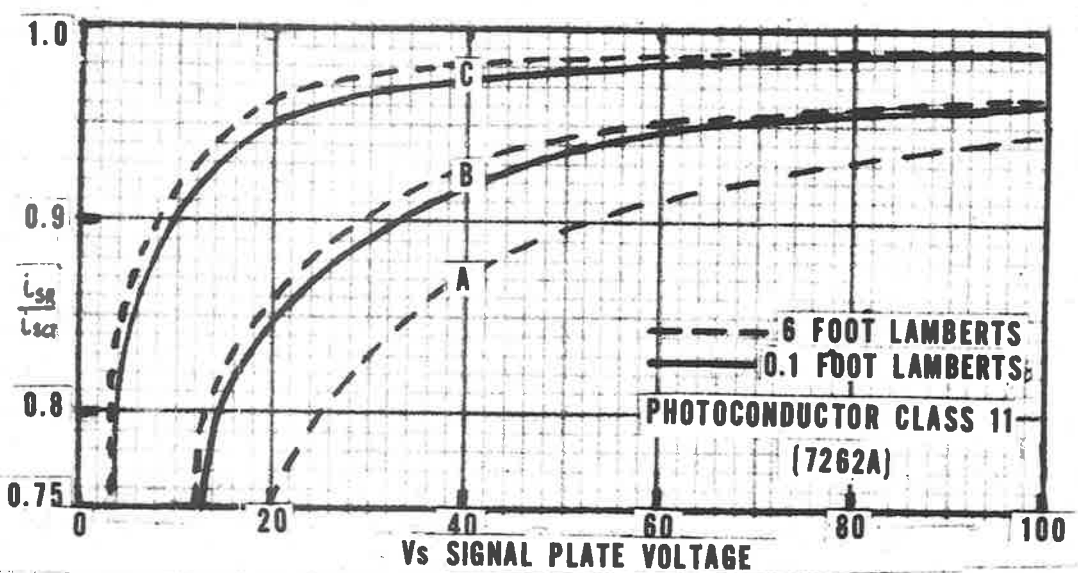
For 12·8 x 9·6mm photoconductive target, "φ_{max}" is of the order of $\pm$0·1 rads (about $\pm 6^{\circ}$).



(a) Geometry of deflection. (dimensions in mm.).



(b) Resultant voltage across photoconductor target at locations corresponding to the diagonal of scanned area.



(c) Limits of decrease of output current signal 'i_s' for areas within circles indicated in Figure 65(b).

Figure 76. Beam Deflection Effects on Output Current "is".

From section 5.3 above it is seen that the photoconductor surface just after scanning is "stabilized", or discharged to nominally cathode potential V_K(=0V). Due to contact potential, the intrinsic range of beam current landing, and the presence of a dark current, the stabilized voltage "ΔV_{ST}" is of the order of 0·5-1V ((V_K+0·5-1) Volts).

Now the energy relationship of electrons in an electron beam is given by equating the electric field energy with the resultant kinetic energy,

$$e(V_A-V_K) = \frac{1}{2} mv^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; 5.6$$

where "e" is the electron charge
"m" is the mass of the electron
"v" is the final electron velocity
"V_A" and "V_K" are as above.

If the beam is at some angle "φ" to the central axis of the scanned area, then

$$e(V_A-V_K) = \frac{1}{2} mv^2 Cos^2\varphi + \frac{1}{2} mv^2 Sin^2\varphi \quad . \; . \; 5.6(a)$$

Hence from expression 5.6,

$$e(V_A-V_K-(V_A-V_K) Sin^2\varphi) = \frac{1}{2} mv^2 Cos^2\varphi \quad . \; .5.6(b)$$

or

$$e(V_A-V_K') = \frac{1}{2} mv^2 Cos^2\varphi \quad . \; . \; . \; . \; . \; . \; . \; . \; 5.6(c)$$

where

$$V_K' = V_K + (V_A-V_K) Sin^2\varphi$$

$$= V_A Sin^2\varphi \qquad \text{for } V_K = 0$$

For the accelerated electron beam under deflections the "cathode" potential thus becomes V_K'.

The photoconductor surface thus becomes nominally stabilized at $V_K' = V_A \operatorname{Sin}^2\varphi$. With the contact potential operative, this stabilized potential "ΔV_{ST}" is "$V_A \sin^2\varphi + 0{\cdot}5$" Volts. For $V_A \approx +300V$ and $\varphi_{max} = 0{\cdot}1$, $\Delta V_{STmax} \approx 3{\cdot}5V$. The dark current flowing enables charge to leak away during the first few cycles after switch on until the surface potential reaches "$\Delta V'_{ST}$."

The upshot of this is that the nett voltage across the photoconductor is (V_S signal plate $- V_A \sin^2\varphi$); see Fig.76(b).

The voltage variation from the centre of the target, where $\varphi = 0$, to the corner of the display area where $V_A \sin^2\varphi = 3{\cdot}0V$, is then

$$\left(\frac{V_{S\ \text{Signal plate}}}{V_{S\ \text{signal plate}} - 3}\right) \text{Volts}$$

This has two effects on signal current levels:

(i) the signal current is reduced at locations away from the centre of the photoconductive target.

(ii) the dark current is also reduced at locations away from the centre of the target.

Ideally it can be shown that (Appendix **A.10.** 2)

$$i_s = K_S V_P^2 \quad \ldots\ldots\ldots\ldots\ldots 5.7$$

that is, the output signal current is proportional to the square of the voltage across the photoconductor, "V_P".

In practice, from the "Is vs E" curves on which several transfer curves at various "dark currents" are plotted, and from the "Dark Current vs. V_S" curves (Fig.66) (and hence "Dark Current vs. V_P", as the stabilization voltage "ΔV_{SI}" approaches zero), the actual "I_S vs. V_P" relationship can be found. Thus for low illumination, the above exponent in expression 5.7 is not "2", but about "1·7." At higher light levels it is about "1·5"; this is for a class II photoconductor (the RCA 7262A in particular).

Thus $$\frac{i_s(\varphi)\ \text{deflection}}{i_{s\ \text{centre}}} = \left(\frac{V_S - V_A \sin^2\varphi}{V_S}\right)^{1\cdot5\ -1\cdot7} \quad \ldots\ldots\ 5.8$$

Similar expressions have been derived in (256).

The reduction in output signal with respect to the nominal output at the centre of the target is given thus by expression 5.8 and plotted in Fig.76(c). Two values of "φ" are chosen corresponding to the circles labelled A,B,C in Fig.65(b).

For a photoconductor of class I, the exponent is somewhat higher, about "1·8 - 2·1." The change in the value of exponents cause a variation from the curves in Fig.76(c) of less than 5%.

In Vidicons used for normal TV-applications, the reduction of output signals due to this effect causes the "porthole" effect (256). The centre of the image appears at normal brightness, while towards the edges of the picture, brightness progressively becomes worse when viewed on a TV-CRT.

Similarly the relationship between the amplitude of the "dark current" and the voltage across the photoconductor is obtained directly from manufacturers' curves, Fig.66(a)

Thus $i_d = K_D V_P^{\beta}$ 5.9

where "β" varies from about 3 to 4.

The "dark current" being of the order of 0·01uA, any variation (at most about 50% at $V_S > 15V$) can be neglected.

In practice (256), the reduction in output signals "i_s" less than that predicted by expression 5.8. In earl Vidicon tubes this was mainly due to the lack of uniformity in photoconductor thickness, ensuring that some degree of correction resulted (see section 5.5.7), and also due to the long axial focussing field being present, reducing the angle "φ" at target landing. In present day Vidicon tubes, the latter is the reason for the output signal variation being less than predicted above.

The correction of this resultant non-constancy of output signal with deflection is simple and obvious. Since it is caused by the cathode potential V_K apparently being "$+V_A \sin^2\varphi$", then by feeding in a voltage of "$-V_A \sin^2\varphi$", derived and controlled from the deflection system, at the cathode, the resulting net "cathode voltage" is constant and zero. This is described in section 9.3.6.

Thus assuming that this correction circuit has been incorporated, the discharge curves in Fig.74. and the current output signals in Fig.68-69 need not be altered.

5.5 MODIFICATION OF PHOTOCONDUCTOR STABILIZATION POTENTIAL DUE TO ASYMMETRY OF SCANNING

5.5.1 Introduction

In the vicinity of the photoconductor target,

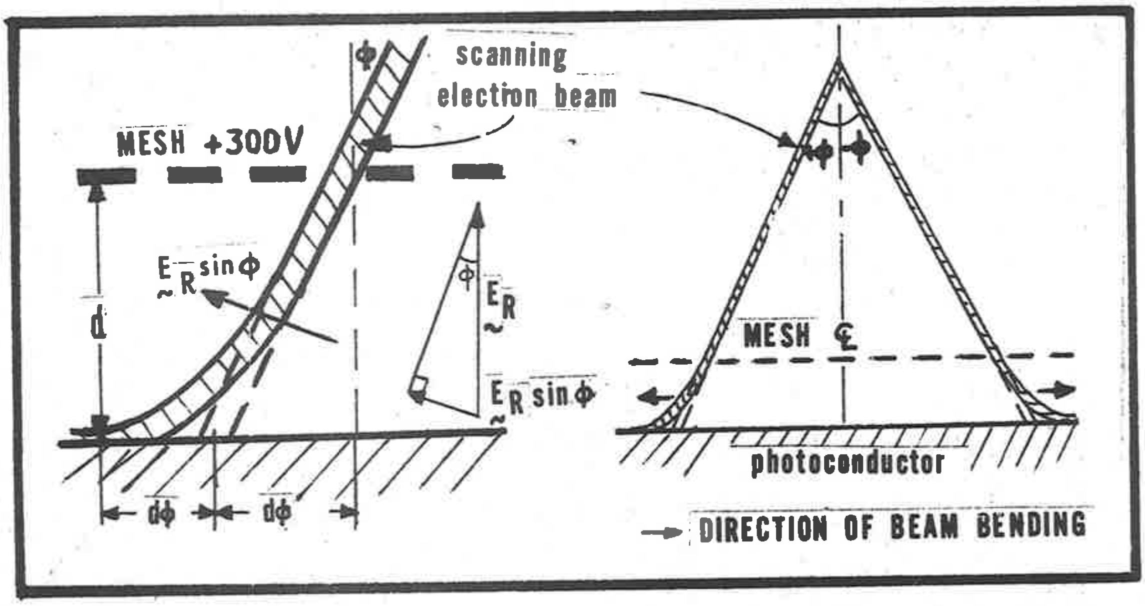


Figure 77. Beam Deflection due to Retarding Mesh Potential Field E_R Showing Symmetrical Effect About Central Axis of Scanned Area.

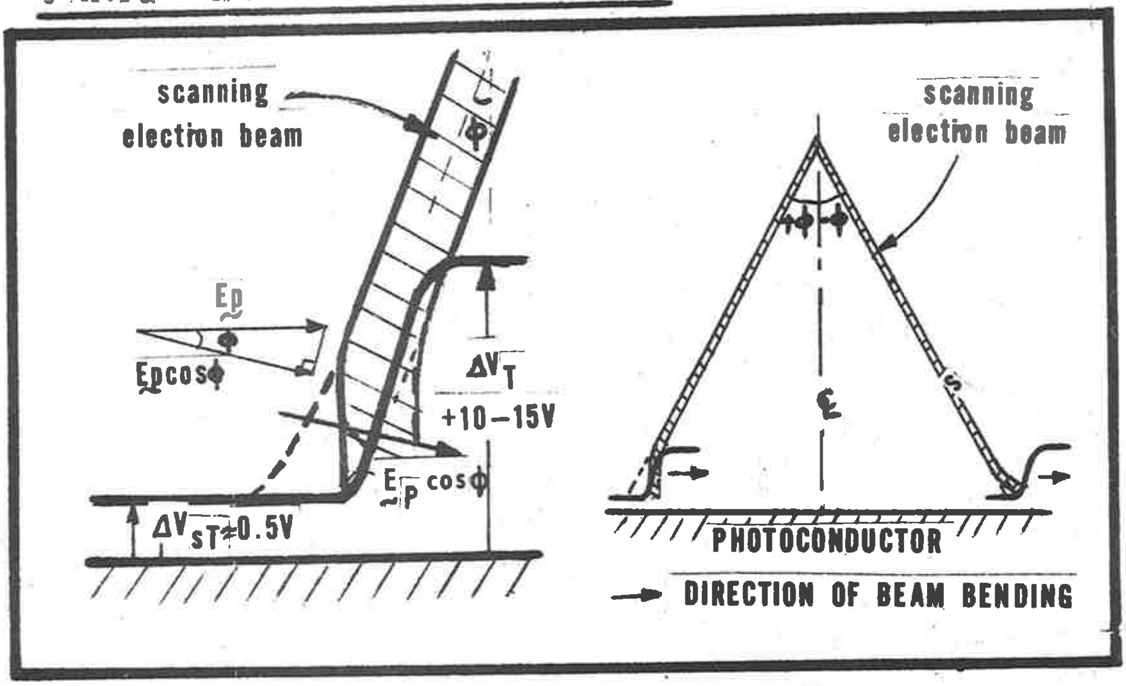


Figure 78. Beam Deflection due to Surface Potential Field E_P Adjacent to Beam, Showing Asymmetrical Effect About Central Axis of Scanned Area.

and on the target itself, potentials exist, either due to the retarding mesh adjacent to the target, at some +300v, or due to the charge accumulations on the target. Associated with these potentials are electric fields which have components orthogonal to the electron beam; thus opportunity exists for beam deflection by these electric field components. Any beam bending is equivalent, as shown above in section 5.4, to raising the cathode potential and hence raising the target stabilization potential; this in turn affects the effective voltage across the photoconductor, hence the sensitivity, and hence the magnitude of the output current signal "i_s". Many of these electric fields, and hence the degradation in the output signals, have asymmetry with respect to the centre of the Vidicon target, the main cause being the unidirectional scan of the electron beam from left to right and from top to bottom of the scanned image.

Although the cumulative effect of all of these defects is smaller than the discrimination intervals between the Level Detector switching levels and the largest unwanted signal "i_{see}", an explanation and indication of the amplitude of these defects is necessary. The defects resulting due to these effects become significant only in Vidicon applications such as in live-or film-pickup applications.

5.5.2 Beam Deflection due to Retarding Mesh Field

The mesh, in-between the cathode and the photoconductor and adjacent to it, is at some +300V and some 2mms. distant from the target (although the actual values may vary from these nominal values). Consequently a retarding field "$\underset{\sim}{E}_R$", normal to the photoconductor surface exists, and is of the order of $1{\cdot}5 \times 10^3$ Volts/cm, as the surface potential of the photoconductor is, at most, some +10 -15V.

During scanning the electron beam passes through the mesh at some deflection angle "φ" (given by expression 5.5). An electric field component equal to "$\underset{\sim}{E}_R \sin\varphi$" exists, orthogonal to the beam, exerting a force on it and deflecting it (see Fig.77). The added deflection tends to increase the angle of beam landing away from the direction normal to the photoconductor surface (see Appendix A.7.5). Due to the non-normal beam landing, electrons, which would normally land on the target, are deflected and captured by the mesh; the stabilization potential "ΔV_{ST}" thus rises.

However, a secondary effect is present. The spot size on a Vidicon target of area 12·8 x 9·6mms in a 625-line system, with about 580 active display lines, is about 2.10^{-3} cms. square; the beam diameter is assumed to be of about the same dimensions.

In the immediate vicinity of the beam and the photoconductor, the stabilized potential "ΔV_{ST}" just behind the beam is 0·5-1V say, while the potential of the area just to be scanned is, say, at some +10V. Within the beam-width dimensions, an electric field "$\underset{\sim}{E}_p$" of some $\frac{9}{2.10^{-3}}$ = $4{\cdot}5 \times 10^3$ Volts/cm. exists, tangential and parallel to the target surface. The component of this field orthogonal to a beam approaching at some angle "φ" to the normal, is $\underset{\sim}{E}_p \cos\varphi \approx \underset{\sim}{E}_p$, for small "$\varphi$", and its direction is such that it deflects or bends the beam towards the unscanned area; i.e. beam-bending is in the scanning direction. This is shown in Fig.78.

This then is a unidirectional beam bending effect as distinct from the previous beam bending effect.

The nett resultant beam bending is the result of the two fields, the retarding field "$\underset{\sim}{E}_R$" of about $1\cdot5.10^3$ V cm., and the localized surface potential field "$\underset{\sim}{E}_P$", acting on a beam approaching the suface at an angular deviation "φ" from normal approach, as in the greater part of the beam retarding region between mesh and photoconductor, only "$\underset{\sim}{E}_R$" is operative.

The two fields oppose in the Left-hand half of the Vidicon target area and add in the Right-hand half, the resultant being smallest in the extreme Left-hand of the target surface and largest at the Right-hand or end of the horizontal line scan. Thus the stabilized voltage "ΔV_{ST}" is lowest at the left hand edge and greatest at the right hand edge.
Call these stabilized Voltages "$\Delta V_{ST\ R-H}$" and "$\Delta V_{ST\ L-H}$" respectively.

The nett voltage across the photoconductor thus varies from $V_S - \Delta V_{ST\ R-H}$ to $V_S - \Delta V_{ST\ L-H}$

with $V_S - \Delta V_{ST\ R-H} < V_S - \Delta V_{ST\ L-H}$. . .5.10

where "V_S" is the signal plate voltage.

From "Dark Current vs. Photoconductor Voltage" curves and "Signal Current vs. Dark Current" relationships (Figs.66) and for similar reasons as explained leading to expression 5.8, this implies that the dark current and signal current are greatest at the left hand side of the Vidicon scan area (i.e. near the beginning of the scan line.

The actual magnitude of the beam deflection causing this signal amplitude variation is difficult to calculate since

(a) the nett resultant electric field varies across the finite beam cross section, causing differential beam deflection.
(b) the current density distribution is not constant across the beam and is not always determinate.
(c) the potential step difference between scanned and unscanned areas differs from point to point depending on the incident illumination. Also, the potential difference across the beam is not a step but varies gradually.

Reference (254) mentions such a calculation for resultant beam deflection (or rather resultant stabilized potential) but being computer solved, and then under extremely simplifying conditions, only qualitative results, already predicted above, are reported.

These beam landing variations help to explain two assymmetrical defects often seen in Vidicons:

(i) The uneveness in current signal, particularly in the dark current level, from some relatively high level at the beginning of the scanning line to a relatively low level at the end of scanning line (see Fig.80(c)), known as "shading effects".
(ii) edge "flare" or "flicker", best described by the presence at the scanned area edge, corresponding to the beginning of the line, of a "rippling" or "waterfall" effect. Continuously rippling striations of varying and sometimes intense

amplitude are seen even at low intensity illumination, when the result is viewed on a CRT.

5.5.3 Dark Current Asymmetry

In Vidicons with no compensating cathode circuits to correct for beam landing errors due to scanning deflection (section 5.4), the photoconductor surface is stabilized at some voltage $\Delta V_{ST} = (V_A \sin^2\varphi + 0{\cdot}5)$ Volts, which at the edges of the scanned area is in the order of 3-4 volts. The unsymmetrical beam deflection near the photoconductor may lower the stabilized potential to say about 2V at the L.H. edge, 3V at the centre and 5-6V at the R.H. edge.

For a signal plate voltage "V_S" of some + 35V, and noting that $i_d \propto V_P^{3.8}$ (from expression 5.9), then the ratios of dark current at the L.H. edge, centre of scanned area and R.H. edge are:

$$\left(\frac{V_S - 2}{V_S - 3}\right)^{3.8} : \left(\frac{V_S - 3}{V_S - 3}\right)^{3.8} : \left(\frac{V_S - 5}{V_S - 3}\right)^{3.8} \quad \ldots 5.11$$

Evaluating,

$$1.12\Big]_{\text{L.H.side}} : 1\Big]_{\text{centre}} : 0.77\Big]_{\text{R.H.side}}$$

For a RCA 7262A, the dark current for V_S = 32 volts is between 0·01uA and 0·12uA (259).

The variation between L.H. and R.H. edges may thus be, in the worst case, 0·05uA which, although not critical considering the switching current level detector level, is significant.

For the output signal current "i_S" variation, $i_S \propto V_P^{1.6}$ (from expression 5.8). Thus

$$\left.i_S\right]_{R.H\ edge} : \left.i_S\right]_{centre} : \left.i_S\right]_{R.H.\ edge}$$

is

$$\left(\frac{V_S-2}{V_S-3}\right)^{1.6} : \left(\frac{V_S-3}{V_S-3}\right)^{1.6} : \left(\frac{V_S-5}{V_S-3}\right)^{1.6} \quad \ldots . \; 5.12$$

giving

$$\left.1{\cdot}05\right]_{L.H.\ side} : \left.1\right]_{centre} : \left.0{\cdot}93\right]_{R.H\ side}$$

The 7% or thereabouts decrease at the extreme R.H.edge may thus be neglected, since adequate discrimination between the Current Level Detector switching level and "i_S" is provided.

5.5.4 Edge Ripple and Flicker

Since the "ripple" or "flicker" effect is visible on a CRT to an observer when the Vidicon camera output is displayed, it implies a cumulative effect over at least two frame time intervals (and hence two beam scans), and thus possibly is also associated with effects over alternate or interlaced fields of a frame (otherwise if the effect was over one frame time interval or less ($<$40ms) it would not be detected by the observer's eye).

The degree by which the beam is bent or deflected before reaching the photoconductor depends greatly on the field produced by the potential difference between the scanned and unscanned section of the photoconductor adjacent to the beam. This in turn depends on the charge

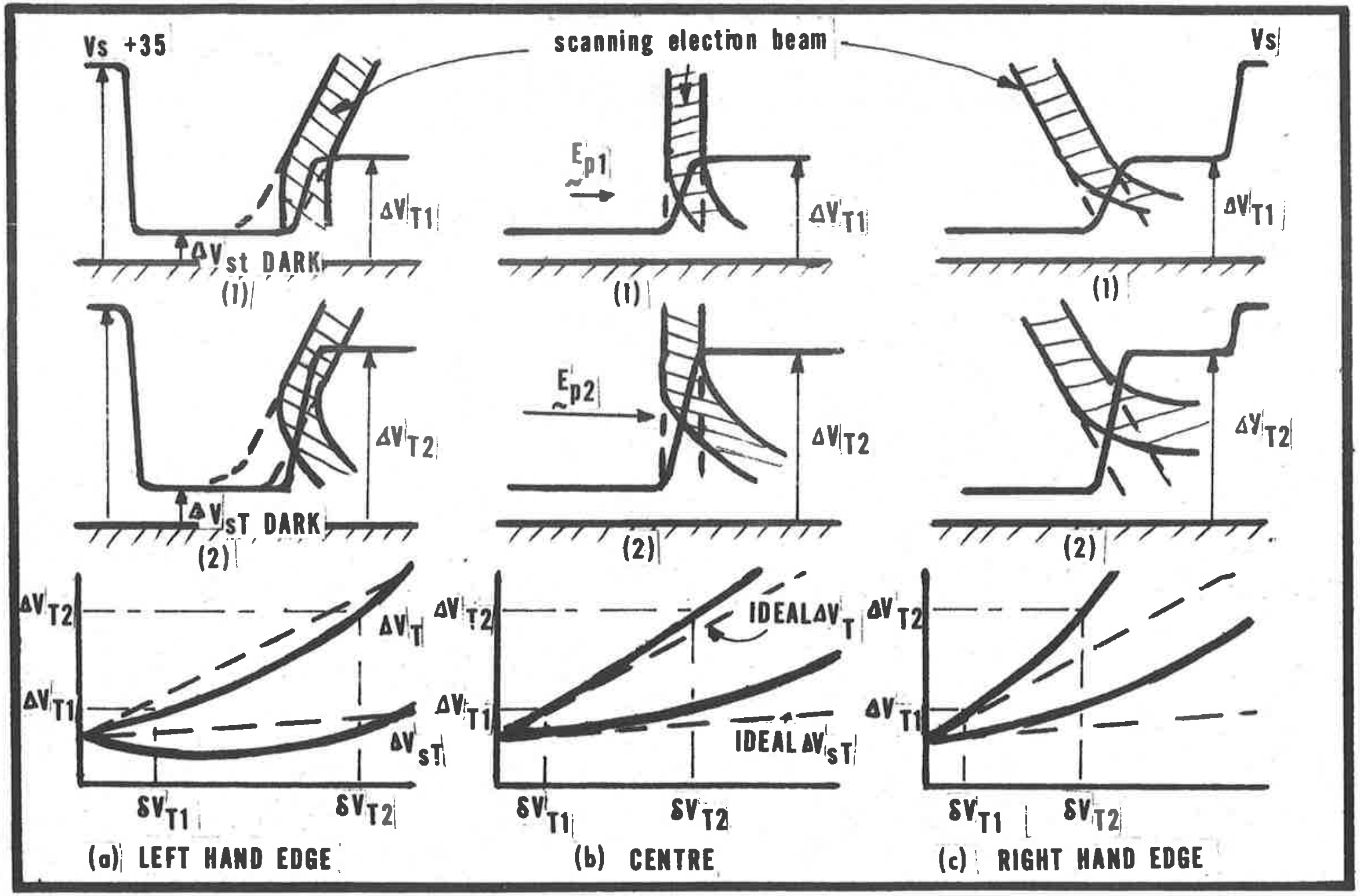


Figure 79. Effect on Stabilization Potential ΔV_{ST} due to Surface Potential Amplitude and Position on Scanned Area, Explaining R.H.Edge Ripple and Flicker.

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"Q" built up at the individual display locations, either due to incident illumination or to the dark current leakage due to the signal plate voltage "V_S"; and also on the angle of the beam incident onto the photoconductor target i.e. on the beam location on the scanned area. The beam bending lowers the stabilization potential "ΔV_{ST}" where the two beam deflections oppose and cancel out. However at locations with high built up charges "Q", resulting in high target potentials "ΔV_{T1}" prior to discharge, the resulting nett beam deflecting field "$\underset{\sim}{E}_P$" may be such as to not only cancel this retarding mesh and primary beam bending, but introduce some beam bending in the opposite direction, raising the stabilization potential anew. Fig.79(a.2) illustrates this. The stabilization potential "ΔV_{ST}" may thus have an initial negative slope at low "δV_T" and a positive slope at higher "δV_T".

At other sections of the Vidicon target, away from the left-hand side, beam bending becomes unidirectional for all "δV_T" and hence for all output signal current amplitudes. The voltage stabilization curve has a positive slope within those regions.

It is this negative stabilization voltage slope that causes the "edge rippling". Intuitively one can see that from the curves in Fig.79 some "strange" effects would occur, as negative slopes in device characteristics invariably imply instability and/or oscillations. In this case the "oscillations" are variations in the output discharge potential "δV_T" and hence variations in output signals, manifesting themselves as visible "ripples" of varying intensity when viewed on a CRT. In Appendix **A.7.6** it is shown that for a negative slope of the stabilization voltage curve, "δV_T" (and hence "i_s") is oscillatory over several frame times, either as overdamped oscillations or regenerated damped oscillations. The derivation and calculations are a further development of work reported in (254).

The effect of edge ripple is to have dark current levels near the extreme L.H. edge at up to twice the amplitude otherwise predicted, due to a cumulative build-up effect. Consequently the dark current level "i_d" need be kept low to say less than 0·03uA, otherwise it may be detected by the Current Level Detector in the worst case of (i_{see} + i_d) being greater than "I_{L1}", and be displayed as a legitimate display location.

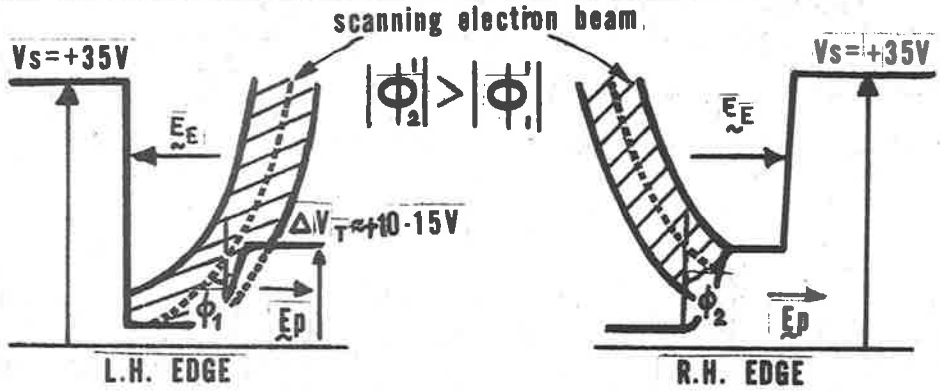
5.5.5. Scanned Area Edge Effects

The scanned area of 12·8 x 9·6 mms is located centrally on a circular surface of some 25mm diameter. The electron scanning beam accesses only the scanned area and discharges it with the result that the remainder of the surrounding photoconductor from the beam side is at a potential of "V_S", the signal plate voltage. Consequently at the edges of the scanned area, there are large potential differences of the order of "$V_S - \Delta V_T$".

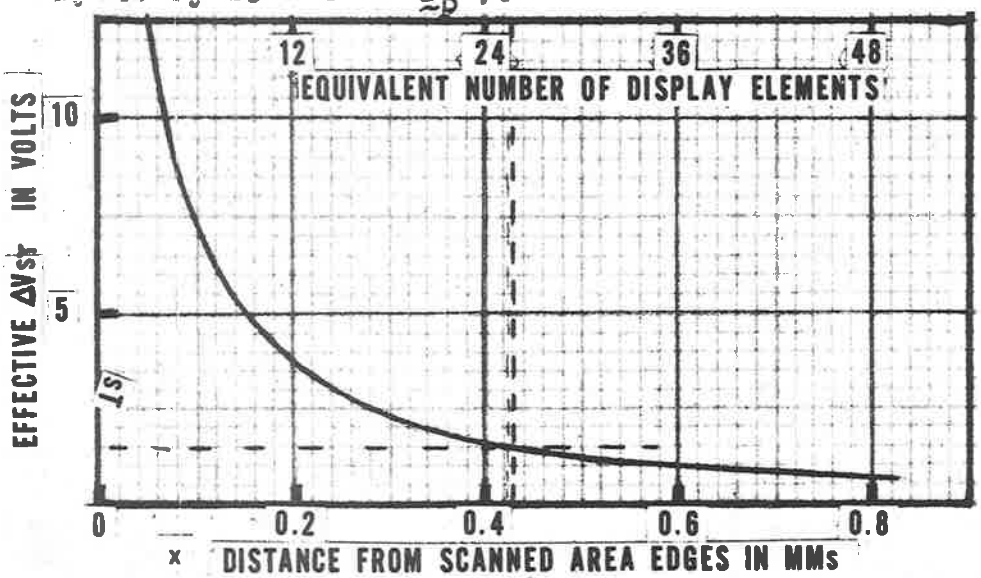
If "V_S" is say +35V and "$\Delta V_{T\,max}$" about +10-15V under high illuminance, electric fields of the order of

$$\frac{30}{3 \times 2.10^{-3}} = 5.10^3 V/cm$$

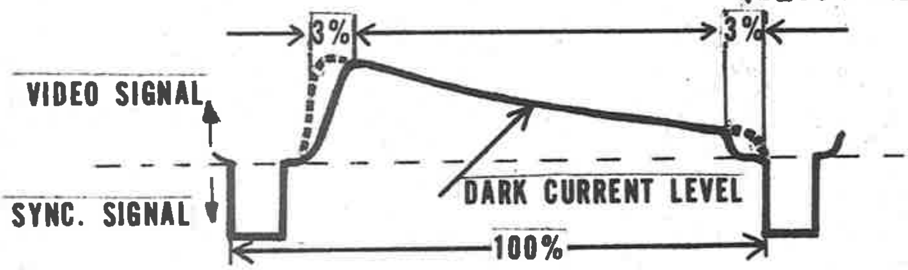
exist, some 0·06mm or 3 locations away from the edge of the scanned area. The direction of the resultant beam deflection is towards the edge and thus symmetrical around the centre of the scanned area and additive to the primary beam bending effects due to scanning. The effect in the <u>immediate</u> vicinity of the scanned area edges is a higher stabilizating potential



(a) Beam deflection due to scanned edge potential field E_E showing symmetrical effect. (The non-symmetry is due to E_p).



(b) Increase of Stabilization Potential ΔV_{ST} vs. distance from edge of scanned area. (based on [254])



(c) Resultant effect on output video signal.

Figure 80. Scanned Area Edge Effects on Vidicon Signals.

"ΔV_{ST}" and hence lower sensitivity and lower output signal. This is shown in Fig.80(a).

Van Polder (254) has measured the effect of this edge electric field for a "Plumbicon", a tube very similar to a Vidicon in application and construction, except for the different type of photoconductor used. Dimensions of the target, mesh size etc, and mesh and anode potentials are similar, and thus his results serve as good guide for the Vidicon.

An experimentally derived curve for the stabilizing potential "ΔV_{ST}" as a function of distance from the edge of the scanned area and other factors, given by him, is

$$\Delta V_{ST} = \frac{V_S}{1+63\left(\frac{V_A \cdot x}{300\ d}\right) + 225\left(\frac{V_A \cdot x}{300\ d}\right)^2} \quad \ldots\ldots 5.13$$

where " ΔV_{ST} " is the stabilizing potential
" V_S " is the signal plate voltage (say + 35V in our case)
" V_A " is the anode accelerating voltage (+300V in our case).
" x " is the distance from the edge of the scanned area, where "ΔV_{ST}" is measured.
" d " is the mesh to photoconductor spacing (2mm in our case).

A simple calculation shows that for the values of the constants inserted, "ΔV_{ST}" (eliminating other effects), is kept below +1·5V for distantces greater than 0.42mms from the scanned area sides. Thus for the 12·8 x 9·6mms. scanned area, some 14% of this area has a $\Delta V_{ST} > 1{\cdot}5$V due to edge effects. As this edge degradation effect cannot (or rather does not warrant) be corrected for, the effective useful scanned area is reduced to some 85-90% of its nominal area. "ΔV_{ST}"nominal"vs.*" is shown plotted in Fig. 80(b).

The very large increases in "ΔV_{ST}" greatly reduce the signal, particularly the dark current.(according to expressions 5.8 and 5.9), in the first few percent of line lengths at the beginning and end of each scanning line and almost the whole first few and last few scanning lines. This is shown in Fig.80(c) for a typical Vidicon output signal.

5.5.6 Non-Linearities in Scanning Waveforms

For magnetic beam deflection, a current waveform, nominally sawtooth-shaped, drives the deflection coils located around the Vidicon tube, producing a time varying magnetic field which controls the deflection of the beam and hence the sequence of scanning and the discharge of the charge "Q" at the display locations.

Any non-linearities in the scanning current waveform not only cause geometrical distortion in the image as observed on a CRT, but because they determine the "speed" of beam deflection, they also determine for how long the dwell time "T_d" is for each location, and hence the amount of charge capable of being supplied by the beam at each such location. Thus far it has been assumed that the dwell time "T_d" has been constant for each location i.e. that the "scanning velocity" of the beam has been constant.

Ideally the electron beam should travel such that equal distance increments "Δs" on the photoconductor should be scanned in equal intervals of time "Δt"; hence

$$\frac{\Delta s}{\Delta t} = K \text{ cms-sec, the scanning velocity.} \quad 5.14$$

where K = a constant

It can be shown (see Appendix A.6.4) that for low velocity electron beams (accelerated by some potentials of the order of say + 300V) superimposed on a strong axial magnetic field to give focussing and good beam-landing properties, the beam deflection "S" is very nearly equal to "L tan φ" where "L" is the length of the deflecting field, taken as an approximation as the distance between the final beam aperture and the target, and is of the order of 75mm, while "φ" is the deflection angle (see Fig.76(a)). Also it can be shown that

$$\tan \varphi = k.i(t) \quad .5.15$$

where "i(t)" is the driving current for the deflection coils

"K" is a constant.

For $\varphi < \pm 6^{\circ}$, $\varphi \approx \tan\varphi$ differing by less than 0·5%. Hence,

$$S = L.\varphi \approx L.k.i(t) \quad 5.16$$

For a nominally linear sawtooth current waveform

$$i(t) = c.t$$

"c" being the slope of the current waveform, resulting in

$$S = L.k.c.t \quad 5.17$$

or

$$\frac{\Delta S}{\Delta t} = L.k.c, \text{ a constant} \quad 5.14(a)$$

In section 5.5.2 it was mentioned that a beam approaching the retarding mesh at some "φ" is acted upon by the component of the retarding field orthogonal to the deflected beam to give added beam deflection. This added deflection can be shown to be approximately equal to "d.φ.", where "d" is the mesh to photoconductor spacing and about 2mm. The actual deflection distance "S" on the photoconductor becomes

$$S = L\varphi + d\varphi = (L + d)\varphi$$ which still gives a constant scanning velocity

$$\frac{\Delta S}{\Delta t} = (L + d)k.c$$

Actual scanning current waveforms are (in commercial TV cameras at least) non-linear to a greater or lesser degree. From expression 5.17

$$\frac{\Delta s}{\Delta t} = L.k.\frac{\Delta i(t)}{\Delta t} \quad \ldots\ldots\ldots\ldots 5.14(b)$$

gives the scanning velocity as a function of the slope of the sawtooth current. The dwell time "T_d" per element is clearly

$$T_d = \frac{\text{element dimension, } \Delta s}{\text{scanning velocity}} = \frac{\Delta s}{\Delta S/\Delta t}$$

$$= K \frac{1}{i(t)/\Delta t} \quad \ldots\ldots\ldots\ldots 5.18$$

From Fig.73 it is clear that the larger "T_d" the lower is the stabilization potential "ΔV_{ST}" for a given beam current and thus the higher the sensitivity and the larger the output current signal, particularly the "dark" current "i_d".

Significant variations in dwell time, (and if the scanning waveform is approximated by a section of an exponential discharge, such variations may be of the order of ± 15% off the nominal value of "T_d"), give significant variations in "δV_T" and "ΔV_{ST}" for very low beam currents (and thus for highly focussed beams such as required in film pickup applications). Even then the effect is mainly apparent as variations in the level of the dark current.

During intervals when the scanning velocity is higher and hence the display is more distorted (apparent by the "stretching" or elongating of objects sideways when viewed on a CRT), the smaller is the beam dwell time "T_d", the higher is "ΔV_{ST}", and the lower is the dark current and, if noticeable, the less bright is that part of the display. Conversely, "side compressed" distorted sections of a display indicate slower than nominal scanning velocities, and hence brighter and higher level dark currents.

Any localized non-linearities in the scanning current waveforms, such as transient ripples near the beginning of the horizontal scanning lines, may give localized variations in $\frac{\Delta i(t)}{\Delta t}$ of 2:1 or more. These can be clearly seen on a CRT display as brightness "ripples" or rather stationary vertical bars of varying width and decreasing intensity away from the Left-hand edge of the image display.

Since, as seen later (Chapter 7) , very linear scanning current waveforms are required, it is assumed signal current degradation due to this effect does not occur; and hence typical variations of dark current under these conditions need not be calculated.

5.5.7 Thickness Variations in Photoconductor Target

The sensitivity of the photoconductor has been assumed (and stated thus in manufacturers' data sheets) to be a function of the voltage across it - nominally the signal plate voltage, "V_S". In actual fact (see Appendix A.10.3), the sensitivity is a function of the electric field strength across the photoconductor. Using the voltage, rather than electric field strength, is valid if the photoconductor thickness is constant. If the photoconductor has a thickness at its centre of "W",

$$\text{then} \quad i_S,\ i_d \approx f\left(\frac{V_s}{W}\right)$$

Normalized to the nominal thickness "W",

$$i_S\ ,\ i_d \approx f\left(\frac{V_s.W}{W}\right) \approx f\left(V_s\right)$$

For a thickness of "W + ΔW"

$$i_S,\ i_d \approx f\left(\frac{V_s.W}{W+\Delta W}\right) \approx f\left(V_s(1-\frac{\Delta W}{W})\right). \quad . \quad . \quad . \quad 5.19$$

Early manufacturing processes of Vidicon targets resulted in the thickness being much thinner at the edges of the target (and thus "ΔW" is negative) (256,257). Hence this had the effect of apparently increasing the signal plate voltage to $V_S(1 + \frac{\Delta W}{W})$, thus increasing the sensitivity and the signal and dark currents. This compensated for the reduction in sensitivity due to beam landing errors due to primary beam deflections and the decrease of illumination due to the "$\text{Cos}^4\varphi$ Law" (expression 4.9) At very high "V_S", giving dark currents of the order 0·1-0·2uA, the added sensitivity resulted in "Edge Flare", a high intensity halation of the image as viewed on the CRT, and quite significant Left-Hand edge "flicker" or ripple due to the beam bending of the high resultant potentials at the scanned area edge (section 5.5.5)

Present day manufacturing processes ensure a uniform thickness over the whole target area (256,257) thus giving nominally equal sensitivity over the whole scanned area. Variations in thickness occur from tube to tube and are in the range of 2-3:1, but within the one tube, the film thickness is constant. (The Vidicon in the camera purchased has a uniform thickness in the range of "3-6 microns"). The thickness variation can be seen from manufacturers' data in the "dark current" characteristics; any given "dark current" value lies in a range of backplate voltages "V_S" of approximately 2:1 spread, Fig.66(a).

Since the thickness affects the capacitance also by a factor of say 2:1, ($C \propto \frac{1}{W}$), then expressions involving "C", the photoconductor target capacitance (particularly the expression for the time constant of photocurrent rise time and decay in expressions 3.15 and 3.16) also may vary by a factor of 2:1. This is indeed the case as seen from published data giving signal-output decay spread e.g. RCA 7735B, RCA 8134 data sheets (259)).

Localized variations in the photoconductor may still occur (see for example photos of Vidicon photoconductor cross-section thicknesses in (258)) or else localized surface contamination may be present, say on the signal plate conducting film, giving rise to some different contact potential. These blemishes manifest themselves as "dark spots" i.e. locations where signal currents are lower than at other locations, indicating either contamination and contact potential voltage drops, or else localized increased thicknesses.

The quality and grade of the Vidicon tube (and hence the price!) determines the number, size and location of these dark spots on the image area (say within or outside the marked circles as in Fig.65(b)) (270). The number of these faults is small (several at the most) and the resultant change is output signal current

amplitudes is such as to be noticeable and "objectionable" on high quality CRTs and in critical applications.
The signal amplitude variation is such that with the switching current levels operable, these effects (or rather defects) can be neglected.

5.6 REMARKS

The deviations from ideal scanning are principally due to non-normal beam landing, either due to:-

(i) "primary", non-normal beam landing, due to beam deflection.

(ii) "secondary", non-normal beam landing due to localized electric fields in the immediate vicinity of the photoconductive surface.

"Primary" beam-landing errors are significant while the "secondary" beam-landing errors, while causing output signal variations, are of no consequence for our application since the discrimination between the switching level and the worst case unwanted signal "i_{see}" is larger than their cumulative effect, particularly in photoconductors of class II (see Fig.68).
However the different classes of signal variation, causes and expected output signal variations need be mentioned, particularly as little of this work is available in the literature, and what there is, is usually descriptive (252,253,254,255,256). The effect of these signal variations unless explained, may be thought to be significant particularly as the resultant defects are amplified and appear more significant than in fact they are, because when observed on a CRT, they are enhanced by the "gamma" of the CRT transfer characteristic being larger than unity (usually gamma is about 2). What the observer sees is

the square ("gamma" = 2) of the signal defects rather than the signal defects themselves.

The only significant secondary beam-landing error occurs around the edges of the scanned area of the Vidicon target, reducing the useful (for our purpose) scanned area by some 10-15%.

The magnitude of these secondary effects is based on the assumption that the scanning beam approaches the retarding mesh and the photoconductive target at the deflection angle "φ", to the normal. In fact current modern Vidicon design have features ensuring near-normal beam landing. The main design approach to this is firstly to use a "separate mesh" connection whereby the retarding mesh is separated from the focussing cylindrical electrode and at some higher potential than it, and secondly, shaping the focussing electrode etc (258). Simultaneously the focussing and hence the resolution is improved; non-orthogonal beam landing means a greater cross-sectional area of the beam striking the target hence a reduction in the resolution.

5.7 SIGNAL - TO - NOISE IN VIDICONS

5.7.1 Introduction

Signal-to-noise in Vidicon output signals need be considered here, as noise causes signal deviations from the nominal values and hence the possibility of Current Level Detection exists when no required signals are present, resulting in false display locations being generated.

There are two main noise sources:

(1) the input noise due to the fluctuations in the illumination.

(2) the noise injected by the tube and by the associated output video signal amplifiers.

5.7.2 Noise Due to Illumination

Photons in the incident illumination have a Poisson distribution (261) as regards their arrival at the photoconductor. The root-mean-square fluctuation "N" of the number of photon arrivals (giving rise to noise) is given by

$$N = \sqrt{n}$$

where "n" is the average number of photons reaching the Vidicon element area (calculated in Appendix 8.2.3) and thus contributing to "S", the signal which results in the photocurrents producing the output current signals.

The Quantum Efficiency "Q" is defined as

$$\text{" } \frac{\text{Number of the photons used to produce the signal}}{\text{Number of photons reaching the photo conductor}} \text{ "}$$

thus $$Q = \frac{S}{n}$$

or $$S = nQ$$

In Vidicons, "Q" is of the order of 1% (see Appendix A.10.1). Clearly the required Signal to Noise Ratio is

$$\frac{S}{N} = \frac{nQ}{\sqrt{nQ}} = \sqrt{nQ} \quad \ldots\ldots\ldots\ldots \quad 5.20$$

In Appendix 8.2.3 it is shown that 1ft-candle of Tungsten Filament illumination at 2870°K is equivalent to about $2{\cdot}6 \times 10^{13}$ photons per second falling on an area of $12{\cdot}8 \times 9{\cdot}6\text{mm}^2$. Average illumination in TV applications is about 5 ft-candles.(This is approximately equal to the "steady state" illumination in our case, given by "total luminance" within a frame time interval, divided by 40ms).

The period of illumination is one frame time interval of about 40ms, and there being $4 \cdot 5 \times 10^5$ elements in a Vidicon target area, then

$$nQ = \frac{5 \times 2 \cdot 6 \times 10^{13} \times 40 \cdot 10^{-3}}{4 \cdot 5 \times 10^5} \times 0 \cdot 01 \quad \text{per frame time per element.}$$

Hence $\frac{S}{N} = \sqrt{nQ} = 340 : 1$ . . . . 5.20(a)

which is of the order quoted in the literature, usually stated to be 300 : 1 (262).

This noise due to illumination manifests itself as input noise to the first stage of the Video amplifier at the output of the Vidicon photoconductor target.

5.7.3 Nett S-N At Output

It is shown (262) that for a TV video-bandwidth amplifier, usually of 4•5Mhz, this input noise current to the first stage amplifier is of the order of 2nA. The usual Vidicon output signal amplitudes of 0•3-0•5uA were aimed for, to give $\frac{S}{N}$ ratios of about 100:1 (262), by appropriatly selecting the beam current, tube size, photoconductor thickness etc.

It is considered that a visual S-N of about 30:1 (that is, the $\frac{S}{N}$ fluctuations as perceived by the viewer on a CRT screen) is needed before any noise becomes visible on a CRT as "graininess" etc (263). Using expressions 5.20, 5.20(a), such a $\frac{S}{N}$ ratio equal to 30 occurs at a photon arrival rate corresponding to about 0•05 ft-candles;

this illumination is often the limit on the E-axis of the "I vs E" curves supplied by the manufacturers. A minimum operating $\frac{S}{N}$ ratio at the Vidicon camera output greater than 30:1 can thus be considered to be operative.

5.7.4 Fault-Free Operating Interval

It is shown in Appendix **A.7.7** that

(i) with a worst case signal "i_{SEE}" of about 0.15uA

(ii) a normal minimum desired signal "i_{si}" of about 0.35uA

(iii) a switching level in the current level detector of "i_{L1}" of 0.25uA

then for a fault-free period of 8 hours of continuous operation (a fault being defined as an unwanted signal being detected as a wanted signal), the requirement is that

$$\frac{S}{N} \approx 32$$

These requirements are easily met with the minimum usual $\frac{S}{N} > 30$. Thus fault-free periods are much longer than the above stated requirement of 8 hours fault-free operation.

5. 8. SUMMARY

(1) The actual output current signal from a Vidicon is due to the scanning electron beam depositing adequate charge at charge depleted locations during the beam dwell time, "T_d"; the output signal is the charge-restoring capacitive current. The output signal amplitude depends on

   (i) the initial charge leaked away (due to the photocurrent-section 4.3).

   (ii) the effectiveness of the electron beam in restoring this charge.

(2) The effectiveness of the beam in restoring this charge is affected by

(i) the magnitude of the beam current, usually of the order of 0·5 -1uA at photoconductor target approach.

(ii) the presence of a contact potential of about + 2V, charging up the photoconductor target to the "stabilization potential", "ΔV_{ST}" of about 0·5 - 1V.

(3) The "beam acceptance characteristic" is such that when the beam electron energy expressed in volts approaches the contact potential (about 2V), the beam exhibits an impedance of some $10^7 \Omega$, which in conjunction with the photoconductor target capacitance, results in a time constant, the "beam discharge time constant", of the order of 5 - 10ms and causes "beam discharge lag". This occurs at signal levels of the order of 0·05uA or less. Hence with expected output signals in our case of some 0·3 - 0·4uA, beam discharge lag causes no great problems.

(4) Fig.73 shows the "Potential Difference ΔV_T due to Charge Buildup' vs Time" for several beam currents. From these curves are derived curves in Fig.74 which give the expected output potential changes "δV_T vs Initial potentials ΔV_T" on the photoconductor, for several beam currents. Negligible variation occurs between the various beam currents, except at low beam currents. The lower curve "ΔV_{ST}" is called the "Voltage Stabilization Curve"; variations in this curve cause

the secondary signal variation effects.
The expected output current signals can be obtained by the "δV_T" amplitude read off from the Fig.74 and seeing what the output current "i_S" is from Figs.68-69. Although the above curves are for ideal cases, actual deviations from real and ideal cases is significant only at low values of "δV_T" and hence not detected, as current Level Detection is used.

(5) The primary deflection of the scanning beam over the scanned area causes, in the worst case, non-orthogonal approach of the beam to the photoconductor target, which is equivalent to a rise in the stabilization potential "ΔV_{ST}" of the target, this increase being a function of the angle deviation away from the normal. This in turn decreases the output signal amplitude in the worst case by up to 10 - 15% of the nominal value at the centre of the target, for signal plate voltages "V_S" of about 30V.

In practice the decelerating mesh and its structure near the photoconductor target ensure that the beam landing is more normal to the target than described above, particularly when "separate mesh" Vidicons are used.

Since the signal current decrease, whether for the "worst case" or in the partially compensated "separate mesh" connection, is symmetrical about the target axis, and determinate, it can be compensated for by certain waveforms, derived from the scanning waveforms, fed at the cathode. This is described later in section 9.3.6 .

(6) Several secondary effects are present, mainly causing asymmetrical signal decrease or increase at the edges of the scanned area. These are described in sections 5.5. Their effect is very apparent in normal usage of Vidicons (i.e where continuous level signals are used corresponding to the grey shades of still or live scenes), particularly when viewed on a CRT, which tends to accentuate these defects. The Current Level Detectors ensures that they do not cause spurious signals.
The only significant defect occurs near the immediate edges of the scanned area, leading, in the worse case, to a reduction of the usable scanned area by about 10 - 15%.

(7) Signal to Noise in Vidicons and the associated video amplifiers is more than adequate to ensure that noise does not generate unwanted signals or causes unwanted signal erasures.

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CHAPTER 6

THE OPTICAL SYSTEM IN "VIDIOGRAPHIC" : DISPLAY, USER — INPUT AND LIGHT PEN

6.1 INTRODUCTION

The luminance generated on the CRT screen is not only for the purpose of illuminating the Vidicon photoconductor target to maintain the display refresh cycle, but must be available to the user for viewing whatever is displayed on the CRT screen. An "optics system" is required to extract sufficiant CRT luminance for this purpose, without unduly reducing the luminance reaching the Vidicon or even directly interfering in the Vidicon-CRT line of sight; a screen on which this display information is projected for user viewing is also required.

Similarly, to enable the user to directly input graphics information or to enable him to be able to point to, or select, any display graphic feature, provision must be made to firstly have a light emitting device in the form of a hand held device such as a pen or probe, and secondly, to have an optical system (since a light-emitting pen is used) to project this information onto the Vidicon photoconductor target. Thus an "User-Display Optics System" is required as well as a "User-Graphics Input Optics System". These two optics systems cannot be treated completely independently of each other.

The CRT generated luminance is projected onto a viewing screen. The user utilizes this image on the screen as his reference system for pointing to, or inputting, new information by projecting light on the screen with his pen; being light-transmittive, the screen permits this light to be projected back towards the direction of the CRT.

This light pen luminance must be superimposed on the appropriate display location and must be imaged such that for the Vidicon, it appears as though this luminance originates for the CRT. Optically then, the user-originated light signals and the CRT screen luminance must be superimposed, for acceptance by the Vidicon. The Superposition Optics thus link the User-Display and User-Graphics Input Optics Systems; the two systems are thus intimately linked together.

Only the light pen and its light source can be treated independently to a certain degree. However, their spectral characteristics, amplitude, and persistance characteristics must match the CRT "W" phosphor characteristics and yet still be capable of being differentiated by Level Current Detectors of differing switching levels. (see section 3.2. 6.3.).

6.2 THE USER-DISPLAY INTERFACE (U.D.I)

6.2.1 Requirements of the User-Display Interface (U.D.I)

In section 2.2.2.2 the minimum brightness requirements of a user display are given as approximately 5ft-L minimum for viewing, with 10ft-L being quite adequate. The contrast ratio is to be better than 5:1. The display area is to be of the order of about 10" x 10" or more and its viewing position to be such as to allow for comfortable viewing; it is to be so located as to allow comfortable access by a hand holding a light pen - i.e. at about chest and eye level, some 20" away from the user. The display brightness is "B_{AV}", the average brightness; and as

$$B_{peak} \approx 63\ B_{AV} \quad \ldots\ldots\ldots\ 4.4$$

the peak viewing-brightnesses required are from some 300 - 600ft-Lamberts (peak), for 5 - 10 ft-L screen brightness.

The primary aim of the User-Display Optics System is to generate a display on the user-viewing screen of the above brightness and size parameters.

6.2.2 Luminance Requirements for the User-Display Interface U.D.I

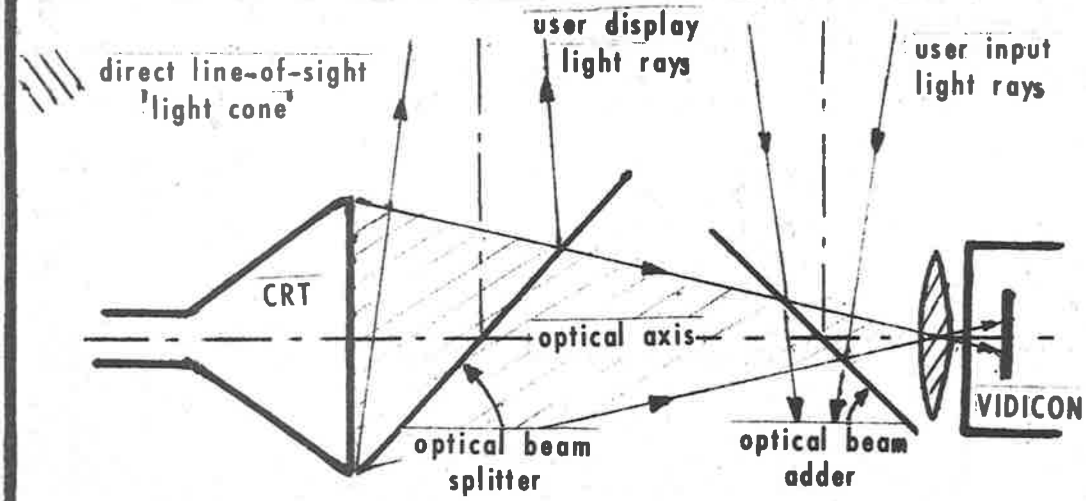
The CRT screen is very nearly a perfectly diffusing luminance source (a "Lambert radiator")(267), that is, its luminance appears approximately constant whatever the viewing angle from the front of the screen (unlike a directed beam or parallel light source which can only be viewed from certain directions).

Some of this omni-directional luminance is intercepted by the Vidicon camera lens, when it is placed in a direct line-of-sight with the CRT, the two tube axis being collinear (to enable 1:1 display spatial relationship). To extract luminous flux for screen projection, either one of two methods is required. These are shown in Figure 81:

(i) either luminous flux is extracted from this direct line of sight "light cone" by an optical beam-splitter (a semi-silvered mirror), requiring a beam-adder later in the same light cone to enable user-graphics input.

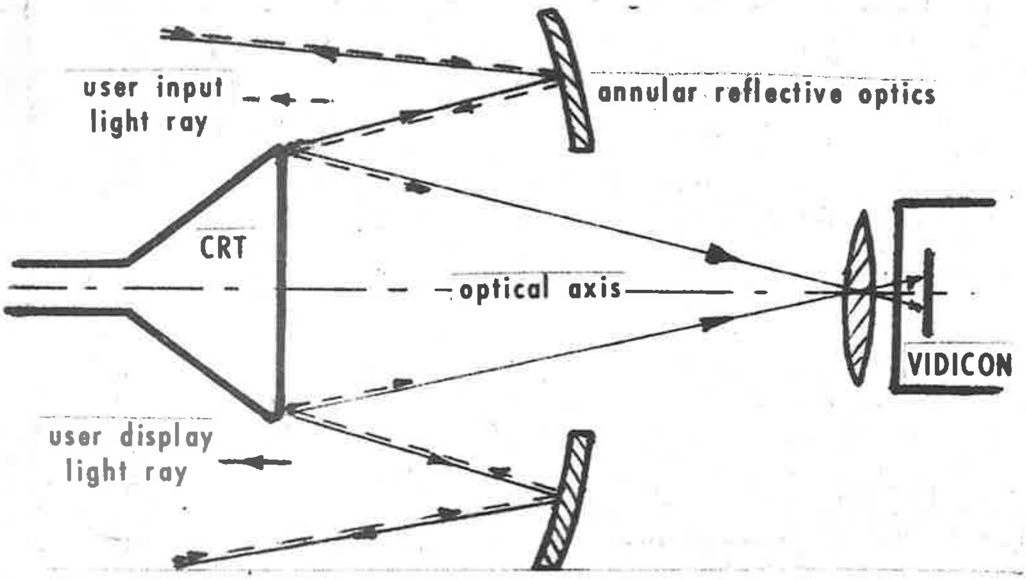
(ii) or else luminous flux is collected from the annular region outside the cone of light incident on the Vidicon camera lens. This could feasibly be by means of a large annular lens or an annular reflecting spherical mirror. For practical reasons of optical quality, mounting problems and cost, the annular lens concept will not be explored further.

It will be seen that the optimum solution will be



The direct line-of-sight luminous flux in the shaded "light cone" is shared between the Vidicon and the Display Screen. Added losses to the CRT luminous flux are due to reflections from the Beam Adder.

(a) Light Division using a Beam Splitter.



Luminous flux is gathered from mutually exclusive regions. Direct "optical superposition" is enabled by the CRT screen being a "reflective-diffusing" surface (a Lambert Surface).

(b) Light Division with Spherical Mirror Optics.

Figure 81. CRT Luminance Utilization for Vidicon and Display Screen.

based on a variation of annular reflecting spherical mirrors, or the Schmidt Optical System as it is known.

The apparently "obvious" solution of line-of-sight beam splitting, with a simple reflecting mirror, without a viewing screen is not permissable. The requirement is that a real image of the CRT display be obtained with fixed size and fixed position on a screen, on which points etc. may be positioned with a light pen and detected therefrom. The formation of such a real image requires the presence of some form of an imaging optical system, such as convergent lenses or convergent reflecting spherical mirrors. A simple mirror with a beam-splitter viewing system with no lens imaging-optics, means that the resultant viewed image of the CRT display, is a virtual image on the eye's retina, the observer's eye being now part of the optical system. The CRT display would appear in an optical "tunnel", its size and viewability depending on the position of the viewer's eye. Of course, light-pen beam projection would be impossible in attempting to input graphic information.

The selection of one of the two optic systems, "Transmissive Lens-optics with Beam Splitter and Adders," or "Reflective Spherical Mirror Optics", will depend on efficiency, cost and linearity and superposition performance. It will be seen that the "reflective optics" is by far the more superior, on all counts, of the two systems.

6.2.3. Transmissive Lens Projector Optics

6.2.3.1 Lens Projection Optics System

A possible configuration is shown in Fig.82, in which are included the projective optics, beam splitter

Facing p.222

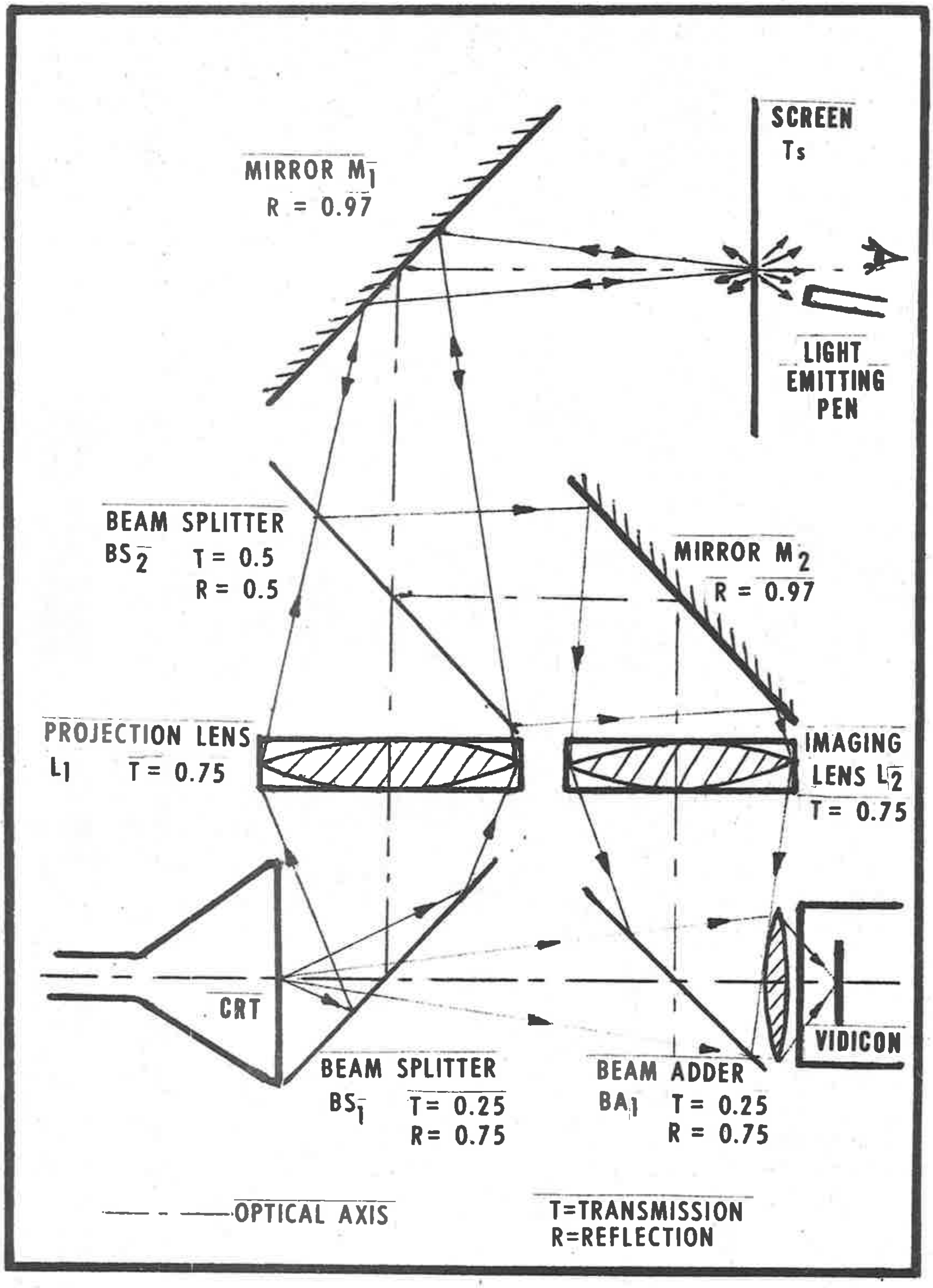


Figure 82. Transmissive Lens Projection Optics Syst... with User-graphics Input System Included.

and graphics input optics. It can be easily verified that the screen image and superimposed image onto the Vidicon have correct orientation. The luminous flux in the cone contributing to the Vidicon illumination is intercepted by a beam-splitter "BS_1", which ideally transmits say 50% of the incident flux and reflects 50% of it (in practice these ratios may be varied; losses i.e."absorption" losses are also invariably present). The reflected rays are gathered by a lens system "L_1" and projected onto screen "S", via a front surface mirror "M_1".

User graphics-input is enabled by the projected light beam being reflected by "M_1", beam-split by "BS_2", front surface reflected by mirror "M_2", and focussed and projected by a lens system "L_2", and thence beam-added by "BA_1", to be incident onto the Vidicon target. Typical Transmission "T", and Reflection "R" Coefficiants are marked next to the optical lens or mirror. Merely on the basis of the resultant losses and beam splitting, the fraction of light "T_{SCRT}" reaching the Screen from the CRT reaching the Vidicon from the user light-pen "T_{V-LP}", and reaching the Vidicon from the CRT L_{V-CRT}", are as follows:

(i) <u>T_{S-CRT}, CRT to Screen Transmission Coefficient</u>

$$T_{S-CRT} = R_{BS1} \cdot T_{L1} \cdot T_{BS2} \cdot R_{M1} \cdot T_S \quad \ldots 6.1$$

$$= 0{\cdot}75.\ 0{\cdot}75.\ 0{\cdot}5.\ 0{\cdot}95.T_S$$

$$= 0{\cdot}267\ T_S \quad \ldots\ldots\ldots\ldots 6.1(a)$$

where "T_S" is the Screen Transmission (see section 6.4.3)

(ii) <u>T_{V-LP}, Light pen-to-Vidicon Transmission Coefficiant.</u>

$$T_{V-LP} = T_S \cdot R_{M1} \cdot R_{BS2} \cdot R_{M2} \cdot T_{L2} \cdot R_{BA1} \cdot T_V \quad \ldots 6.2$$

$$= T_S.0{\cdot}95.\ 0{\cdot}50.\ 0{\cdot}95.\ 0{\cdot}75.\ 0{\cdot}75.\ 0{\cdot}75.$$

$$= 0{\cdot}19T_S \quad \ldots\ldots\ldots\ldots 6.2(a)$$

(iii) T_{V-CRT} CRT to Vidicon Transmission Coefficiant

$$T_{V-CRT} = T_{BS1}.T_{BA1}.T_V . . . . 6.3$$

$$= 0{\cdot}25.\ 0{\cdot}25.\ 0{\cdot}75$$

$$= 0{\cdot}047 . . . . 6.3(a)$$

Clearly the transmission coefficiants are very low due to the number of beam-splitters, lens systems etc. In practice they would be lower still due to losses in the beam splitters and adders.

6.2.3.2. Lens-projection Optical Efficiency

The light utilization efficiency of the projection lens system is very low also. Only one TV-system was available commercially some years ago, using lens optics, due to this poor efficiency (268). This used a 5" diameter by 6" 'long-lens' assembly in conjunction with a 4"x 3" screen area CRT. The projection length was such as to result in an image magnification of 4, resulting in a screen image of 16" x 12". The lens "F"-number (see section 4.2) was 1•9.

Using expression 4.9, the resultant illumination on the screen is, with this commercially available optics system:

$$E(t) = \frac{T_{S-CRT}.B(t).\ Cos^4\varphi}{4F^2\ (1 + M)^2} . . . . 4.9$$

where $T_{S-CRT} = 0{\cdot}27\ T_S$ (from expression 6.1(a))
$M = 4$
$F = 1{\cdot}9$

with the variation of illumination over the screen being neglected.

Evaluating this results in

$$E(t) = 0{\cdot}00074.B(t).T_S \quad \ldots\ldots\ldots\ldots \quad 6.4$$

A "directive" screen is used (see below section 6.4.3.2) which results in a $T_S \approx 3\text{-}4$.

hence $$E(t) \approx 0{\cdot}0025.B(t). \quad \ldots\ldots\ldots\ldots \quad 6.4(a)$$

Thus for every 1000ft-L of CRT illumination only 2•5ft-L are resultant on the user-screen. Thus $B_{AV} \geqslant$ 2000ft-L is required for satisfactory viewer conditions.

The resultant illumination on the Vidicon is given

by $$E(t)_V = \frac{T_{V\text{-}CRT} \cdot B(t)\cos^4\varphi}{4F^2\,(1+M)^2} \quad \ldots\ldots\ldots\ldots \quad 4.9$$

where $T_{V\text{-}CRT} = 0{\cdot}047$ (from expression 6.3(a)).

$F = 1.9$

$M = \dfrac{9{\cdot}6}{3 \times 25{\cdot}4} = 126$ (see Fig.65(a)).

and the variation due to $\cos^4\varphi$ can be neglected.

Evaluating this expression results in

$$E(t)_V = 0{\cdot}00256\ B(t). \quad \ldots\ldots\ldots\ldots \quad 6.5$$

If $B_{AV} \geqslant$ 2000ft-L

then $E(t)_{Vpeak} \geqslant 2000.\ 0{\cdot}00256.\ 63$

as $B(t)_{peak} = 63B_{AV}$ (from expression 4.4)

Hence $E(t)_{Vpeak} \geqslant$ 320ft-candles . . . . 6.5(a)

From Fig.68, this illumination is certainly adequate for the system to operate successfully.

6.2.3.3. Lens-Projection Disadvantages

Although apparently feasible (from a light flux quantity viewpoint anyway) this scheme has serious disadvantages:

(i) A large lens (5" diameter) has significant spherical aberrations, distortion and various other defects causing loss of picture quality. It is heavy and poses mounting problems.

(ii) The overall system of the several beam-adders and splitters implies several transmittive-reflective planes, which because they have finite thickness, may give rise to double images (one each from each surface of the plane) leading to contrast degradation and possibly spurious signals. To reduce these effects, very thin films and planes need be used, further creating problems of fragility, mounting etc.

(iii) The superposition of two images by two lens systems to enable user-graphics input causes problems in alignment, and more importantly,due to different distortion of the lenses, it greatly increases the problem of ensuring that 1:1 spatial relationships are maintained in the CRT and Vidicon display areas .

(iv) Overall cost (the lens optics being relatively expensive) and relatively poor light utilization, in addition to the above points,preclude this approach.

6.2.4 Reflective Mirror TV-Projection Optics

The advantages of reflective spherical mirror optics over the transmissive lens optics are many-fold and briefly are as follows :

(i) The light gathering and utilization efficiency is much higher, due to the "F"-number being several times smaller than for an equivalent focal length lens.

(ii) The aberrations and resultant image defects (including "double image" effects) are almost absent in reflective optics. Image quality is high for wide-aperture converging spherical mirrors.

(iii) Beam splitters (and beam adders) need not be used because luminous flux is gathered (for projection) outside the direct line of sight light cone between CRT and Vidicon. The "Principle of Optical Conjugacy" between real image and object planes enables superposition to be made directly on the viewing screen (the real image plane) and on the CRT screen (the real object plane). Hence problems of alignment, different distortion due to two separate lens systems etc, as above, do not enter.

Overall light utilization is increased because light for the Vidicon and viewing screen is gathered from different areas.

(iv) Projection TV-Units using spherical surface reflective optics (called "Schmidt Projection Optics") have been commercially available for over 20 years. These techniques are well known and developed to a fine art. Cost and implementation is very economical- several hundreds of dollars including CRT and viewing screen .

(v) With projection TV, high luminance CRTs are used, which is exactly the requirement for the purposes of generating and maintaining the display in the CRT-Vidicon loop.

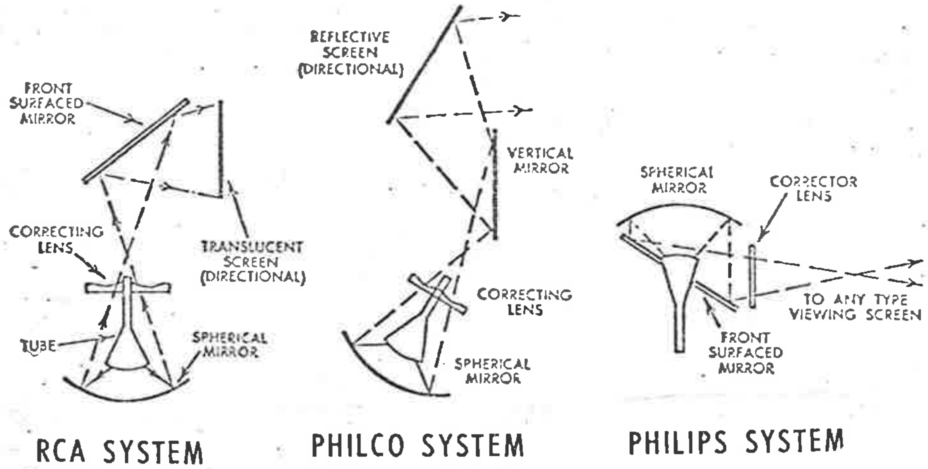
All in all, from the viewpoint of performance, efficiency and cost, the Schmidt TV-Projection Optics is ideal.

6.3. SCHMIDT TV PROJECTION OPTICS

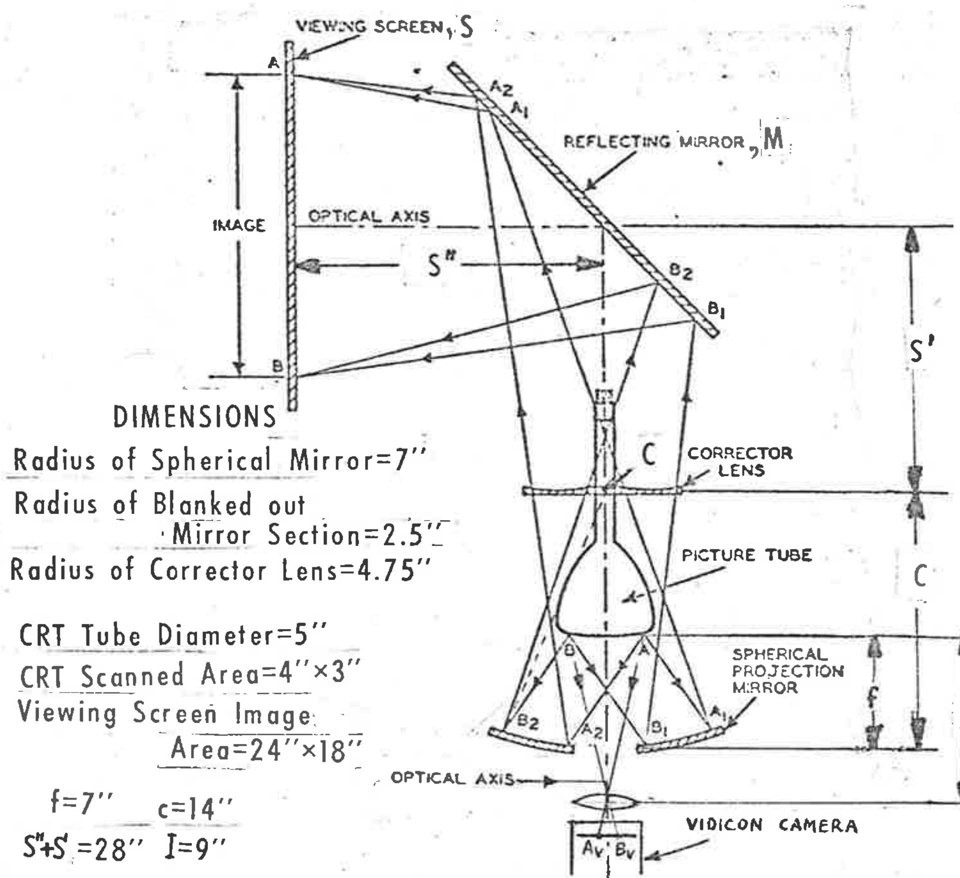
6.3.1 Introduction

Projection TV based on Schmidt Optics was developed some 25-30 years ago to provide adequately large displays (15" x 20", say) capable of being viewed by at least several people (270). The then current direct-viewing TV sets were small in size (9" diameter screens at the most), as difficulty was experienced in manufacturing larger direct-viewing CRTs. As these problems were overcome, the Projection TV-units were phased out. Units are still produced commercially, almost exclusively for closed-circuit audience viewing, or theatre TV viewing; they also have military application in group-viewing of displays particularly where "overlays" (e.g. map grids etc) need be superimposed.

To minimize costs of implementation, one of the commercially available TV-units need be used, of which there are three main types, shown in Fig.83(a). The Philco System (272) is unsuitable because it has not got a suitable transmission viewing screen enabling user-graphics input, while the Phillips System (245,271) has too small a CRT screen leading to focussing difficulties in the Vidicon camera lenses. The RCA System (243,270) satisfies most of the requirements for VIDIOGRAPHIC, from screen properties and adequate CRT size and luminance, and even, to the presence of a shaped central ring in the spherical mirror surface providing direct line of sight between CRT and Vidicon. A slight modification required is ensuring that the CRT phosphor ("P4" - USA usage) has the



(a) The three available commercial TV projection systems.



(b) RCA system showing Principal Rays and Vidicon camera position.

Figure 83. Schmidt TV Projection Optics

time-persistance properties of Phillips-type "W" phosphor shown in Fig.64. - the dimensions of a Phillips "MW13-38" (269) are such that a direct substitution for a "RCA 5N P4" can be made. Fig.83(b) shows the layout and dimensions of the major components in this system.

The literature on Schmidt TV projection optics, both general, and of individual systems, is very comprehensive and readily available (243,244,245,270); therefore no great depth of theory and details are necessary here. The basic laws of Reflective Mirror Optics can be found in any elementary physics or optics textbook.

6.3.2 Schmidt Optics System Operation

Very briefly, referring to Fig.83(b), the CRT screen, the object plane, is at the focal plane of the spherical mirror. Light rays emitted from point "B" say, are reflected at the spherical surface (some of these are incident on the Vidicon photoconductive target), the normal to which (i.e. radius of the spherical mirror) passes throught the centre of the sphere of which the mirror is a segment of. At this centre is a "corrector lens"; rays reflected off the mirror pass through this lens and are slightly refracted to correct for spherical aberration. These corrected rays are reflected from a front surface mirror "M" and focussed on the image plane, where a transmissive viewing screen is located. The mirror reorients the projected image in the correct orientation to compensate for the spherical mirror inversion.

The effective aperture, and hence effective "F-number on which depends the light gathering efficiency of the system, is determined by the aperture or diameter of the corrector lens, which in turn depends on the diameter of the reflecting spherical mirror.

At first sight it may appear that as objects other than the object plane are in the field of view and field of projection, these will also be imaged and visible on the projection screen. However only the objects on the focal "plane" are imaged and focussed on the screen; other objects, such as mountings, leads etc,not being at the focal plane are immediately defocussed (this focussing being very critical) and hence not registered on the screen. Further, the fact that the object at the focal plane is not a point source but a source of area 4" x 3" on a 5" diameter CRT, with deflection coils, mountings etc (see Fig.63(b)), implies that a portion of the reflected light from the mirror is blocked from reaching the screen, by a CRT tube and associated mountings. This light blockage implies that a central darker spot appears on the projection screen,as less light emitted from the central locations on the CRT screen reaches the projection screen (analogous, although of opposite effect, to the "porthole effect" in Vidicons, section 5.4.). Also, the possibility of multiple reflections between the CRT screen glass faceplate and the spherical mirror is present, introducing stray signals and hence loss of contrast.

For this reason, the central part of the spherical mirror, approximately of a radius equal to the radius of the CRT screen, is blacked out (i.e. made non-reflecting) as in the Philips system, or as in the RCA system, drilled out. Contrast is improved,but resultant screen image brightness is reduced.

This drilled aperture allows the direct line-of-sight incident illumination between CRT and Vidicon.

6.3.3. Advantages of Schmidt Optics

The two **major** advantages are:

(i) The prime advantage of the Schmidt Optics over Lens Optics is due to the fact that only one reflecting surface is present, with a simple mathematically defined surface. Production methods are thus relatively simple with resultant low costs.
Because only simple reflection and not refraction occurs, chromatic aberation, that is wavelength-dependent light ray bending, with resultant picture defects ("coloured edging") is absent.

(ii) A major class of image defects occur with lenses and reflection convergent mirrors, called "3rd-order aberations", which are due to, and whose magnitude depends on, the distance of a refracted (or reflected) ray from the principal optics axis of the system.
These aberations cause element distortion, defocussing and geometrical displacement of the whole image.

Since in a spherical reflecting surface, there is no preferred optical axis as all incident rays are reflected about the normal to the surface, and all of these normals pass through the centre of curvature of the mirror and are thus "principal rays", most of these 3rd-order aberations are ideally absent. In practice two aberrations,(out of a total of 5 recognised 3rd-order aberrations) remain:

(1) Spherical aberration (as this is still present even for principal rays), where rays from the periphery of the reflecting mirror are brought to a different focus that those from the centre of the object plane. However, the spherical aberration is about $\frac{1}{8}$ of that present in an equivalent sized lens.

(2) Distortion, which is due to the fact that the magnification is not constant for all points in the field of view. The result is an image distorted by "pincushion distortion", at least in the Schmidt Optics used for TV projection.

Because of the lack of optical defects, high quality images result (compared with Lens Optics) even for large mirrors; the aperture of the mirror of course governs the light gathering efficiency, and enables such bright images to be obtained with these reflective optics.

To correct for spherical aberration, a correcting lens is placed at the centre of curvature. This has the effect also of introducing an optical axis into the system,and hence 3-rd order aberrations,which however still are negligible. The correcting lens also effectively defines an aperture for corrected, focussed light rays. The aperture of the lens is chosen compatable with the diameter of the reflecting mirror.

The optical relationships (analogous to the lens optical relationships given in Fig.65(a)) of the Schmidt optical system, and of the equivalent lens system,are given in Fig.84(a).

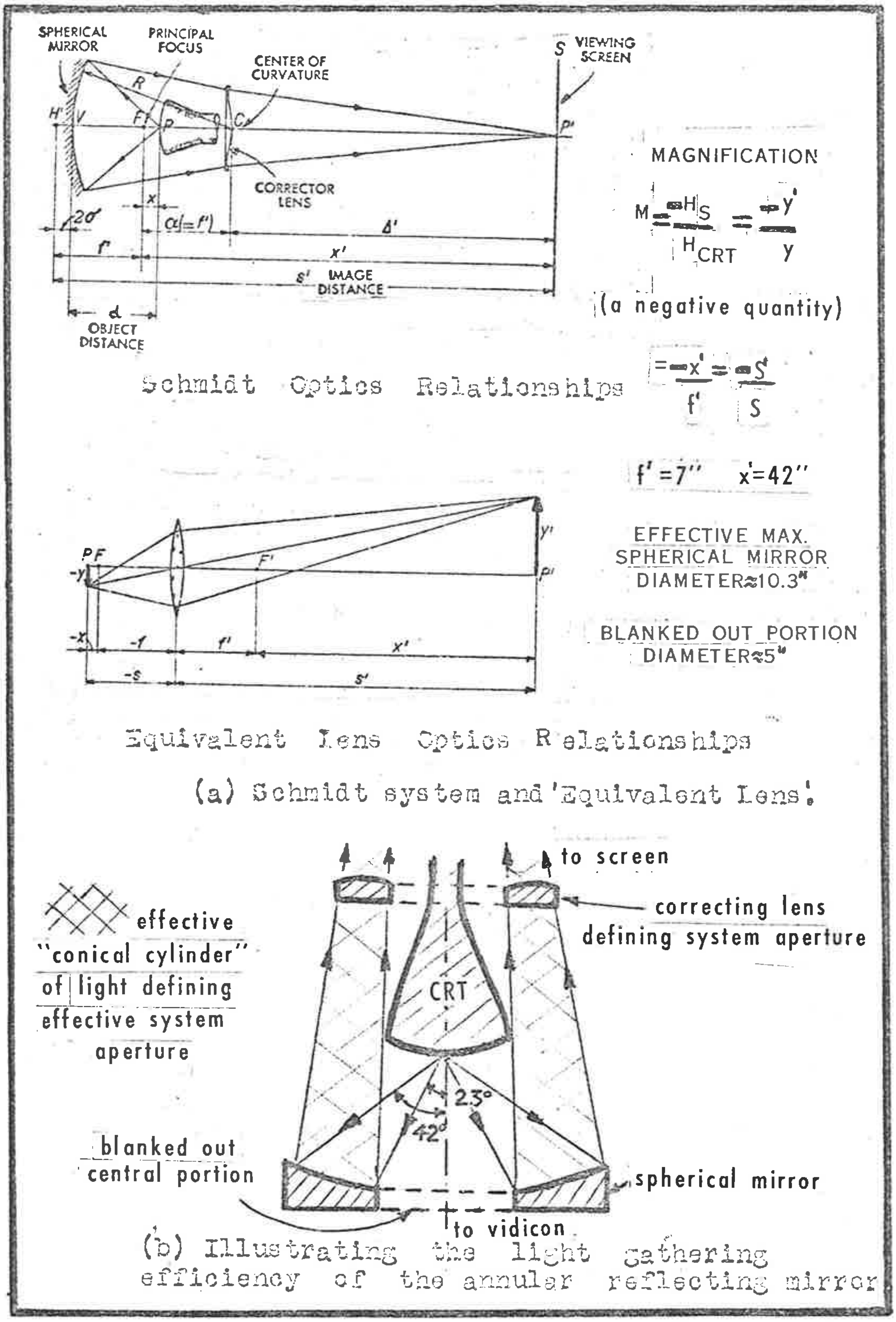


Figure 84. Schmidt TV Projection Optics Relationships.

It is found that the correcting lens has the effect of shifting the "principal" surface, i.e. the apparent surface at which reflected rays appear to be symmetrical about, (and which nominally is the mirror surface), is shifted by some $2\sigma \approx 0{\cdot}04R$ behind the front surface. The focal plane is also shifted forward by some $0{\cdot}02R$.

The focal length is $f' = \frac{1{\cdot}04R}{2}$, where "R" is the radius of the spherical mirror.

6.3.4 Disadvantages of Schmidt Optics.

(i) Unlike Lens Optics where variable image size is possible by shifting the lens relative to object plane, a given spherical mirror with a particular correcting lens has a fixed focussed image size. Different image sizes require different correcting lenses. Their shape is very critical for different image magnification due to their large aperture. They are relatively easy to produce being either of gelatin on glass (245) or moulded out of a plastic material called "Lucite" (243).

The RCA system has a fixed magnification producing an image on the screen of 24" x 18" in size.

(ii) Spherical mirrors can be made to almost any size but beyond diamters of some 10-12"(245) their own weight begins to introduce surface distortions resulting in non-ideal spherical surface, and thus image defects. Extra strengthening and rigidity is not warranted by the extra cost.

(iii) Adjustments for optimum focussability and image linearity are fairly critical, particularly the lateral or sideway displacement of the correcting lens so that its centre is not coincident with with the optic axis. On each TV projection unit, special adjustment screws etc are provided, which when used with a special alignment lamp, quickly align the CRT and the correcting lens with respect to the mirror and screen (270).

(iv) An extra disadvantage, perhaps even danger, is the presence of X-rays generated from the high-intensity luminance CRT, which has final anode accelerating potentials of the order of 25KV or more. The CRT and mirror is enclosed in a metal "barrel" with the CRT (pointed away from the viewers towards the ground); any X-rays are thus directed towards the floor, or absorbed by the metal barrel.

6.3.5 Optical Efficiency of Schmidt Optical System

The expression 4.9 giving the luminance on the optic axis at the image plane is valid for convergent mirror systems as well as lens; the only difference being that the magnification in a mirror reflection system is defined as negative i.e.

$$M = -\frac{\text{image size}}{\text{object size}} = \frac{-f'}{x'} \quad \ldots \ldots \; 6.6$$

The effective F-number in expression 4.9 can be found from the correcting lens aperture and the exact focal length dimensions.

This and the above data is not always supplied and thus this formula cannot be readily used.
What is given are the effective angles subtended by the point on the optical axis, at the boundaries of the mirror and the blanked out area (see Figure 84(b)); these are 42^o and 23^o respectively.

It is shown in Appendix 8.3.1 that for a circular planar diffusing illuminating source of brightness "B(t)" which subtends a semiangle "φ" at some point, the illumination "E(t)" at that point is given by

$$E(t) = B(t).\mathrm{Sin}^2\varphi \quad . . . . 6.7$$

Conversely if the brightness at that point is "B(t)", the illuminance within that area subtended by a semiangle of "φ" is given by the same expression.

The net illuminance on the spherical mirror is thus

$$E(t) = B(t)_{CRT}\,(\mathrm{Sin}^2(42^o) - \mathrm{Sin}^2(23^o) \quad ....6.8$$

since the circular area of semi-angle $\varphi=23^o$ is blanked out and does not contribute to the illuminance. This illuminance being imaged onto a screen, is fully utilized but is further reduced by reflection and transmission losses at the mirror surfaces and the correcting lens, and by the image/object magnification. The area of each element on the image is increased by "M^2" over the object size; hence illuminance on the screen is decreased by the same factor, "M^2".

Thus the screen illuminance $E(t)_S$ is given by

$$E(t)_S = \frac{B(t)_{CRT}(\mathrm{Sin}^2(42^o) - \mathrm{Sin}^2(23^o))\,T_S.T_{ML}(1-L)}{M^2} \quad . . . . .6.9$$

where "$B(t)_{CRT}$" is the luminance of the CRT screen

"T_S" is the screen transmission

"M" is the projection system magnification and equal to "6"

"T_{ML}" = $R_{MC} \cdot R_M \cdot T_{CL}$ where "R_{MC}", "R_M" are the reflections coefficiant of the two mirror surfaces, say 0·975 each and "R_M" is the transmission factor of the correcting lens equal to about 0•9(244)

" L" is the added loss due to blockage by the mounting, leads etc, and is of the order of 5 - 10%.

Evaluating for these values results in

$$E(t)_S = 0{\cdot}0065 . B(t)_{CRT} . TS \quad \ldots\ldots\ldots \quad 6.9(a)$$

With a directive screen, as mentioned in section 6.2.3.2 with T_S = 4.

$$E(t) = 0{\cdot}026\ B(t)_{CRT} \quad \ldots\ldots\ldots\ldots \quad 6.9(b)$$

This is to be compared with expression 6.4(a) for the illuminance incident on the screen due to a lens imaging system - an improvement by a factor of 10 in illuminance using Schmidt optics over that obtained using lens optics.

Hence with

$$B(t)_{CRT-AV} = 350 \text{ ft-L.}$$

$E(t)_S$ = 9ft-C, giving a screen brightness of 9ft-L. From section 2.2.2.2, this is just adequate for user comfort.

6.3.6 ILLUMINATION INCIDENT WITH VIDICON IN SCHMIDT OPTICS SYSTEM

Using expression $B_{peak} = 63B_{AV}$, and expression 4.9, the peak illumination on the Vidicon evaluates to (for F = 1·9).

$$E(t)_{peak\ V} \approx 905 \text{ ft-candles.}$$

This, from Fig.68, is too high a peak illumination, giving rise to too large a signal current with the possibility of Vidicon overdrive and photoconductor breakdown. Reducing the Vidicon lens aperture to an F = 2·8, reduces $E(t)_{peak\ V}$ to 420 ft-candles, which is eminently suitable from Vidicon considerations.

6.4 THE USER - VIEWING DISPLAY SCREEN

6.4.1 Introduction

The function of the user-display screen is to accept incident illumination "$E(t)_{CRT}$" from the projection CRT via the Schmidt Projection Optics and re-radiate this illumination as a visible image of brightness "$B_S(t)$". Simultaneously it accepts user-initiated illumination "$E_L(t)$" from the light emitting pen and reradiates this as visual brightness "$B_L(t)$" back onto the CRT and thence onto the Vidicon Photoconductor target.

The screen is thus required to be bi-directional, capable of accepting and transmitting light from both directions. For screens this is an unusual requirement, light flux acceptance being required from only one direction; but since in TV projection, rear-projection screens are used, which thus require to be transmitting, the requirement of bidirectionality is inherently met.

The parameters of interest are the transmission coefficiants of the screen linking the incident CRT illumination "$E_{CRT}(t)$" with the output brightness "$B_S(t)$",

$$B_S(t) = T_{S1} \cdot E_{CRT}(t) \quad \ldots\ldots\ldots\ldots \quad 6.10$$

and similarly, linking the light pen illumination $E_L(t)$ with the brightness incident on the CRT and Vidicon $B_L(t)$

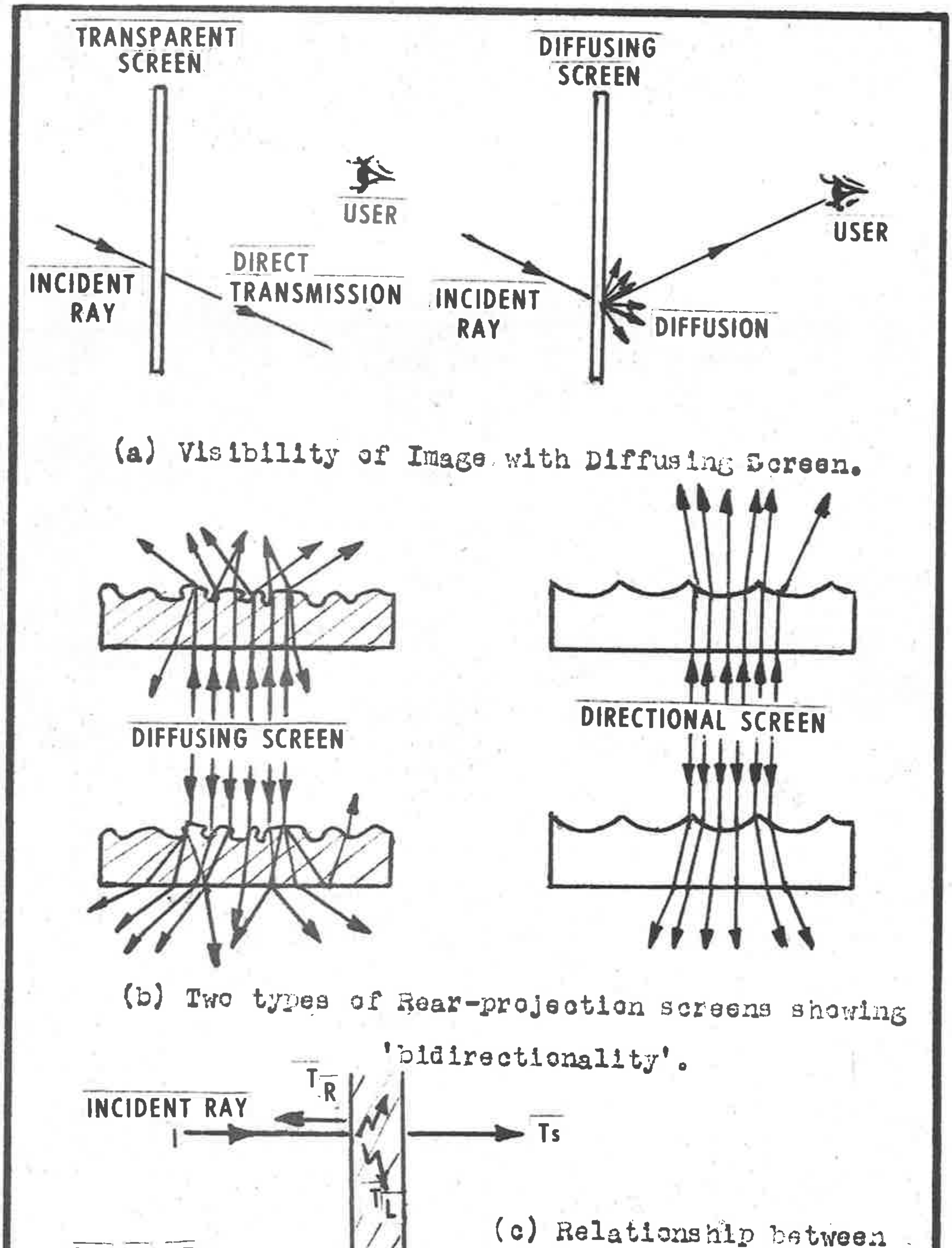
$$B_L(t) = T_{S2} . E_L(t) \qquad 6.11$$

Associated with the transmission coefficiants are the reflection and loss coefficiants, which vary with the direction of light incidence.

Such data is not readily available, not only in the general literature but also is difficult to obtain from the manufacturers; the nomenclature and performance parameters, and even theory of screen performance are not well developed or standardized (274).

The derivation of these parameters is not a trivial exercise; it is a necessary one. Efficient transmission and high resultant image brightness determine the requirement for the CRT screen brightness and simultaneously determine the incident illumination on the Vidicon. The resultant light-pen illumination on the CRT is determined by the screen and its light source, which in our case, will be shown to be also the CRT screen. All of these requirements are interdependent and must be evaluated to determine compatability.

The requirements for a screen are maximum transmission and minimum reflection and absorption. The transmitted light flux is to be distributed in such a manner as to be optimally utilized by the viewer; similarly light-pen emitted light flux is to be optimally utilized by the CRT-VIdicon system.



(a) Visibility of Image with Diffusing Screen.

(b) Two types of Rear-projection screens showing 'bidirectionality'.

(c) Relationship between Transmission, Reflection, and Loss Coefficiants.

Figure 85. Rear Projection Screen Concepts.

6.4.2 Requirement of Display Screen

The Schmidt Projection Optics forms a real image of the CRT screen display at the plane where the screen is located. If a completely transparent "screen" was used, the light ray directions would be unaffected. Unless the user's eye was in the direct line-of-sight of such a ray, he will not "see" it (see Fig.85(a)).

For the image to be visible on the screen from one fixed eye position, the screen must bend by refraction or "diffussion", a certain amount of the incident illumination in the direction of the user's eye (see Fig.85(a). This, in the simplest case, is by "roughening up" a glass screen surface (e.g. "ground glass" surface). The surface then may be likened to a collection of small lenses of varying radius of curvature, and hence of varying resultant direction of refracted rays. Since these "lenses" are randomly oriented and of random "focal lengths", there is no preferred direction of refraction. An incident light ray on such a surface is thus visible, by virtue of this omni-directional refraction, from all positions above this surface (see Fig. 85(b)). Such a resultant "screen" has very nearly complete light diffusing properties and is a good approximation to a ideal Lambert radiator. Practical losses by reflection and absorption are less than 15%; thus about 85% of the incident illumination is transmitted and re-radiated (274).

Alternatively, surface deviations from optical flatness can be made regular, resulting in light refraction in preferred directions, the preferred direction being where the viewer is expected, or supposed, to be. Such directional re-radiation gives rise to high luminance in these directions, much higher than would be expected in a Lambert radiator (see Fig. 85(b)). This gives rise to "screen gain" associated with such "directional screens."

In projection TV, the viewing audience sits at some 6'- 8' directly in front, with the screen at eye level; the required direction of the screen luminance is well defined and the screen surfaces are appropriately shaped to given this directional beaming of luminance. Similarly, in our application, the user is expected to have his eyes at some 20 - 24" away from the screen, to allow for comfortable arm movements in accessing screen locations with the pen. For the RCA screen dimensions of 24" x 18", this gives a maximum viewing semi-cone angle (at a corner) of some 35^o. This can be reduced to almost zero degrees by small head movements, not necessitating seating movement. Such movements may be necessary to reduce the luminous flux requirements of the system (see Fig.86, 88) Movements to reduce the semi-cone angle are not unreasonable to expect or demand, as the user invariably, when wishing to examine some portions of the display, invariably will "have a closer look". Particularly when positioning graphic input or selecting displayed data, he will "exercise care"; in other words he will reduce the semi-cone angle to eliminate expected parallax or alignment error. It is thus assumed that the screen-to-viewer semi-cone-angle is effectively 0^o.

6.4.3 Screen Performance and Transmission Gain

6.4.3.1 Introduction

Of the light incident on the screen, a fraction "T_S" is transmitted, a fraction "T_R" is reflected and a fraction "T_L" is absorbed (or "lost"). Thus

$$T_S + T_R + T_L = 1 \quad . . . . 6.12$$

The available transmitted light is thus $(1 - T_R - T_L)$ and this needs be maximized. $(T_R + T_L)$, in addition to reducing useful luminous flux, reduces contrast and hence image quality. The reflected fraction "T_R", enables the incident illumination to be visible from the projection side. Usually "T_R" is of the order of 0·1 - 0·2, while "T_L" is of the order of 0·05 or less (unless special "dark glass" is used) (275).

6.4.3.2 <u>Transmission Gain Coefficiant</u>

An ideal transmitting/diffusing screen (Lambert surface screen) radiates 1ft-L of luminance for each 1ft-candle of illumination. If the screen transmission "T_S" for some given angle of observation "β", is defined as (274)

$$T_S(\beta) = \frac{\text{Resultant luminance in ft-L}}{\text{Incident illumination in ft-C}}$$

then clearly, for an ideal Lambert surface, $T_S = 1$, for all viewing angles, as the luminance for such a surface is independent of the viewing angle. Tracing paper, ground glass etc. tend to approach this condition.

"Directional screens " have the property that $T_S(\beta) > 1$ for some angles of observation, resulting in "screen gain"; values of up to 10 or more have been obtained (274,276).

However, a screen, being a passive device, cannot add luminous energy. Any increase in luminous flux in a preferred direction, resulting in "gain", must be at the expense of decreased luminance at other directions.

A directional screen thus exhibits a directional luminance pattern, in many ways analogous to a polar plot of antenna directivity (275)(see Figs.86,90). The axis of this directional lobe should ideally be directed towards

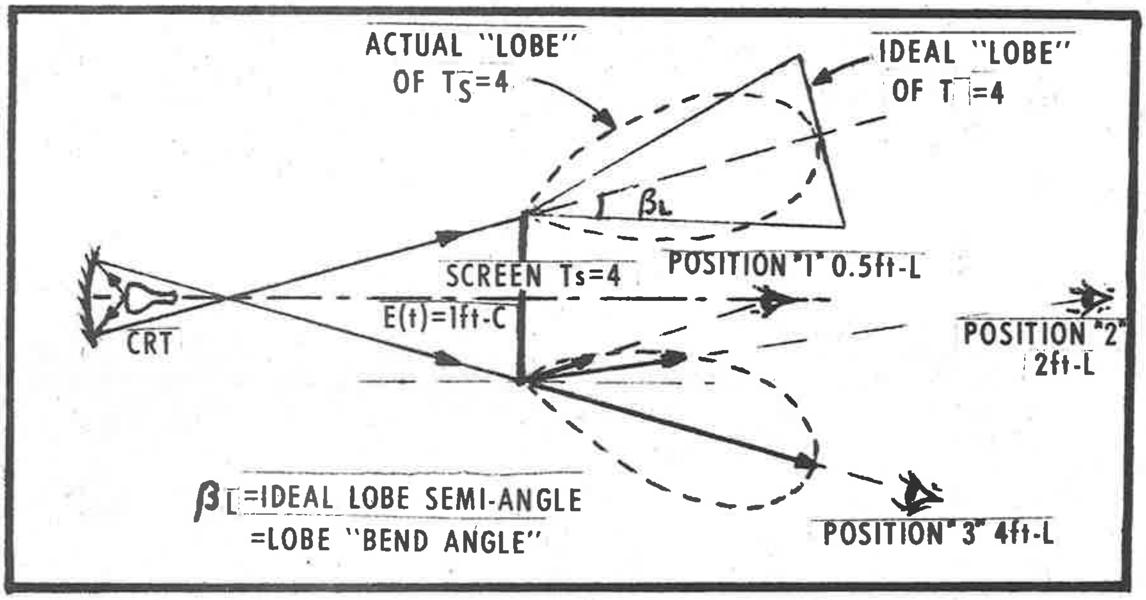


Figure 86. Effect of Viewing a Directional Screen of Transmission Gain 4 from Different Positions.

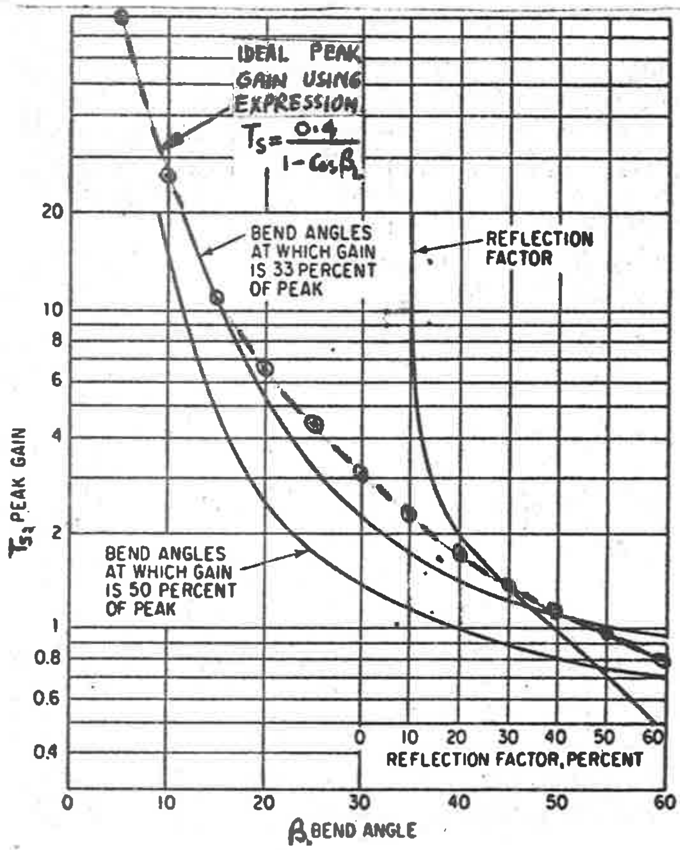


Figure 87. Average Rear Projection Screen Parameters with Ideal Curve of Maximum Gain (from [274])

the viewer.

Now a luminance of 1 candela/sq. ft. (or π ft-C) radiates π lumens into a hemisphere of 2π steradians if the surface is perfectly diffusing; in this case, by the definition, $T_S(\beta) = 1$. If however the screen is directional and luminance is confined to a lobe semiangle "β_L" ("the lobe bend angle"), the solid angle subtended by the lobe can be found by simple integration to be

$$\Omega_L = 2\pi(1 - \text{Cos}\ \beta\ )\ \text{steradians} \quad . . . . 6.13$$

As the total available luminous flux "F" is π lumens, the resultant luminance is $B(t) = \frac{F}{\Omega}$

i.e. $$B(t) = \frac{\pi}{2\pi(1 - \text{Cos}\ \beta_L)} \quad \text{(ft-L)} . . . . .6.14$$

As for a perfectly diffusing surface $\beta(t) = 1$ ft-L, the directive screen surface results in an effective ideal

$$T_S(\beta) = \frac{1}{2(1 - \text{Cos}\beta_L)} \quad . . . . .6.15$$

Since only a fraction $(1 - T_R - T_L) \approx 0{\cdot}8$ of incident luminance is transmitted, the actual gain within this resultant lobe of max. bend-angle or lobe semi-angle "β_{L1}" is

$$T_S\,\beta = \frac{1 - T_R - T_L}{2(1 - \text{Cos}(\beta_L))} = \frac{0{\cdot}4}{1 - \cos(\beta_L)} \quad ...6.15(a)$$

This is plotted on Fig. 87, (dotted curve).
In the RCA projection system, the worst case projection beam incidence, occuring at the corners, is incident to the screen at 37° (calculated from the screen directions and CRT distances). Assuming an ideal screen giving equal directive properties over the screen area, and the user to be able to observe these corner locations when

centrally placed w.r. to the screen 20" away, requires a lobe width of lobe bend angle" $\beta_{L\,max}$"

$$\beta_{L\,max} \geq 19^{0} + \alpha \geq 56^{0} \qquad \text{as} \quad \alpha = 37$$

This gives a potentially maximum screen Transmission Gain of 0·9. Allowing for head movements results in $\beta_{OPT} \approx 19^{0}$. Evaluating expression 6.15(a) for this, gives a sreen transmission gain of 7·2.

Hence small head movements increase the user screen luminance by a factor of ideally by a maximum of 8.

6.4.3.3 Actual Screen Transmission Gain.

It is found in practice (274) that for the majority of rear-projection screens, a certain empirical relationship appears to hold linking

(a) the maximum gain
(b) the lobe width
(c) the refledtion coefficiant.

This is shown in Fig. 87 reproduced from (274). The actual relationship is not stated but for comparison our derived expression 6.15(a) is also plotted. The form of both expressions is very similar except for the scaling. This is to be expected as at higher bend angles the reflection and losses increase. From the experimental curves, for a max.bend angle of 19° at the corners, a maximum gain of 6 can be expected with the luminance at the corners being about 3 times less bright than that observed at the centre.

An average Transmission Gain $T_S = 4$ is thus assumed over most of the display screen. This was the value used in section 6.3.5.

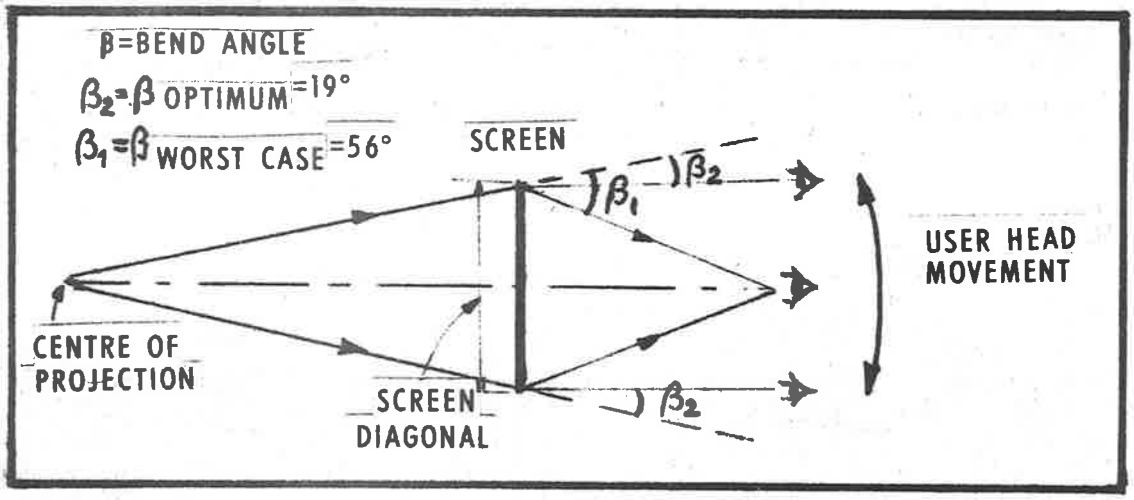


Figure 88. Reduction of Bend Angle by Head Movement.

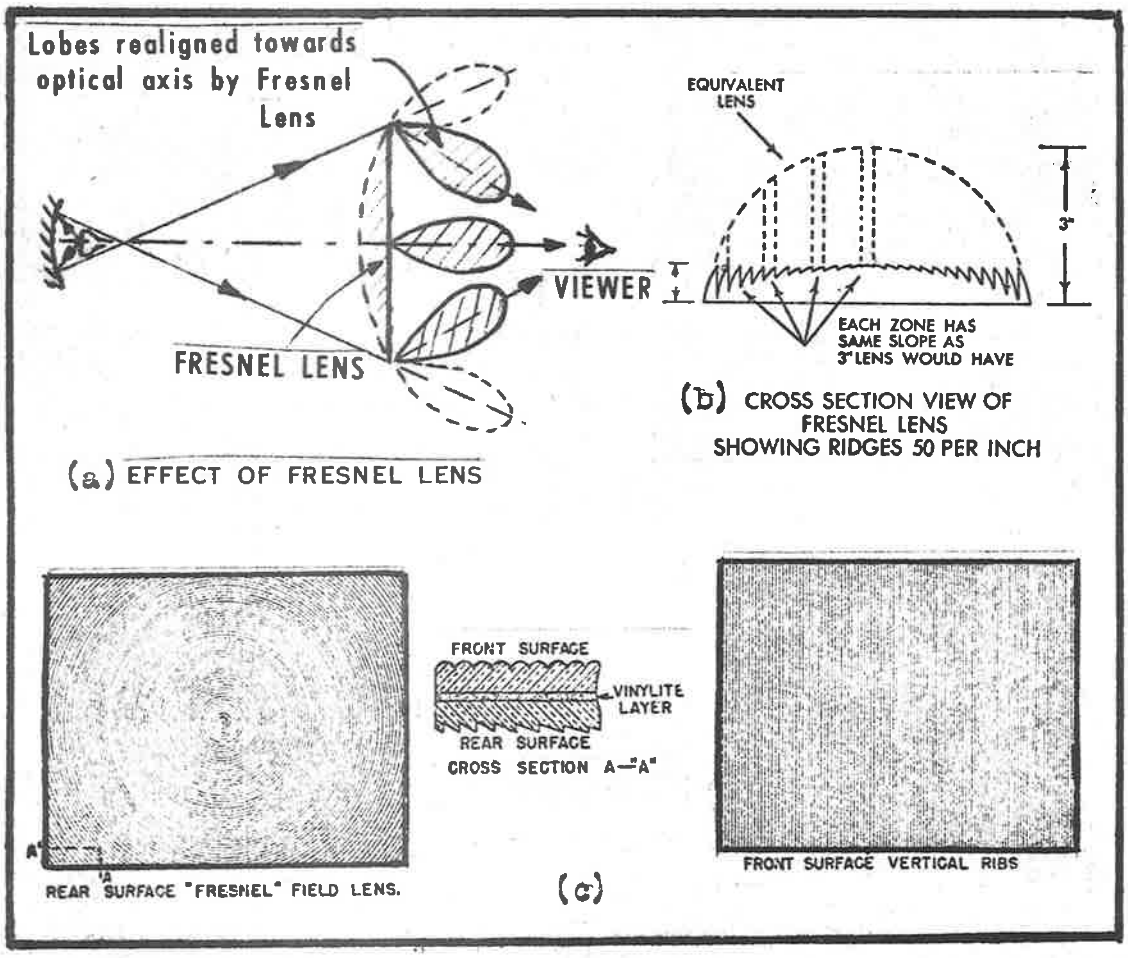


Figure 89. RCA Rear Projection Screen with Fresnel Lens.

An average reflection of about 12% is present; and including losses of about 5%, about 80-83% of the incident illumination is utilized.
The value of these curves is significant. For most rear-projection screens the expected luminance for a given illumination can be directly found at any angle of observation between the viewer and the projection axis of the observed screen location.

6.4.4. RCA Projection Unit Screen.

Two particular screens are of interest:

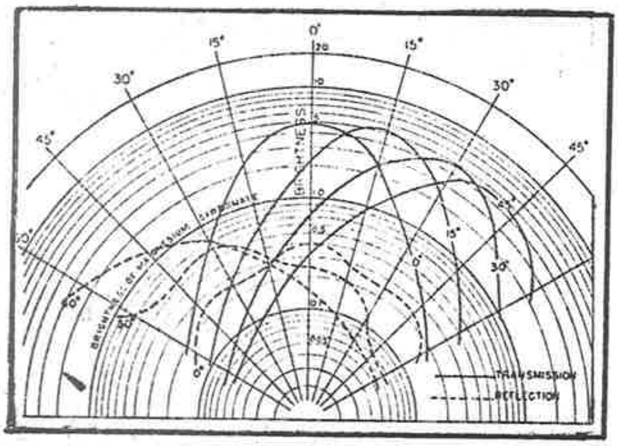
(a) that provided with the RCA Projection TV which will be shown to have most advantages and hence be the most suitable.

(b) a simple plastic rear projection screen for comparison.

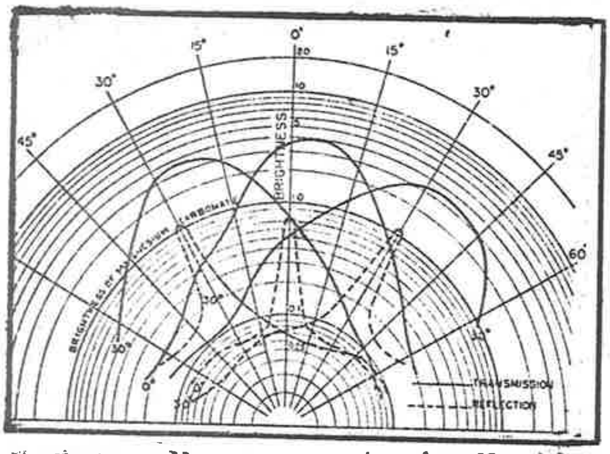
The RCA screen (277) is a complex three layer screen (Fig 89), optimized for viewers with a small bend angle between them and the extreme locations on the screen . With small head movements by the user, (see Fig 88) a small bend angle also results in our application.

The major component of the RCA projection screen is a "Fresnel Lens" which is a circularly grooved lens whose grooves ensure the same slope as a full 3" thick lens would have. Its effect is to effectively refract the Projection CRT-incident beam towards the observer by some 25° to 30° at the corners (see Fig.89(a)).

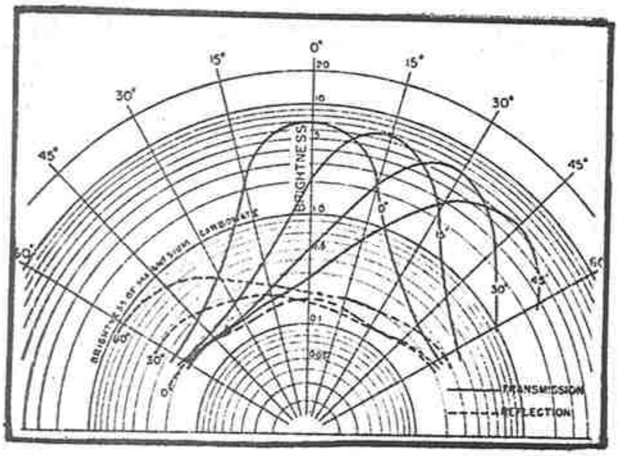
Consequently with little of head movements, the user is apparently in line with the lobe axis - i.e. the bend angle is very near zero and full maximum screen transmission gain is available.



(a) RCA Screen- Measurements in Horizontal Plane at centre.



(b) RCA Screen- Measurements in Vertical Plane at edge.



(c) Plastic Rear Projection Screen.

Figure 90. Experimental Rear Projection Screen Transmission Parameters. (from [275]).

The outside screen layer consists of vertical ribs, approximately 100/inch. This "biases" the viewing angle towards a narrower vertical viewing angle - in fact of some $\pm 10^{o}$ max. useful bend angle. A slightly diffusing, opaque middle layer (causing a large reflection and absorption factor ($T_L + T_R$) of about 0·3) reduces the interferance effects ("Moire Fringes") between the Fresnel Lens "corrugations" and the vertical ribs. A reported Maximum useful Transmission Gain of 7·5 over a field of view of $\pm 10^{o}$ Vertical and $\pm 25^{o}$ horizontal is reported. Actual tests ("objective evaluation") reported in (275) and shown in Fig.90(a) indicate gains of 4·5. For the screen performance at the edge of the screen, Fig.90(b), the curves are displaced by some 7^{o} towards the centre of the optical axis indicating that the Fresnel lens has refracted the light rays by some $(19 + 7)^{o} \approx 26^{o}$ towards the viewer.

The relatively large reflections ("specular" i.e mirror-type reflections) refer to reflections from the user side of the screen and are pronounced due to the vertical ribbed structure of the front screen section. However the total reflected luminous flux is small - compare the reflection lobe width with the transmitted lobe width.

For comparison, the performance of simple plastic screen is shown in Fig.90(c). A serviceable, transmission gain of about 1·3 occurs at $\beta_{OPT} \approx 19^{o}$. However having a peak gain of about 7, visible and probably annoying "porthole" effects or "hot spots" would be visible by the viewer.

For this reason, and for excessive head movements, and for the reason in section 6.4.5 below, this and most other screens are unsuitable. Where the projection distance and screen size ratios are greater i.e. where smaller maximum bend angles occur, other screens are very useful; but in this RCA projection scheme with a fixed CRT to screen bend-angle, a Fresnel Lens is most necessary.

A Transmission Gain coefficiant $T_S = 4$ is thus assumed for the screen and the RCA screen is most eminently suitable for our application.

6.4.5 Quality of Projection Screen Image due to Schmidt Optics.

An objective report (273) described the image contrast, linearity and quality of a TV projection system; this was the Phillips system but generalities can be extended to the RCA system. The test reported "excellent picture" with "good linearity" (presumably at least as good or better than with direct-view receivers), with "picture detail as good as in directly viewed tubes".

6.5. THE USER-GRAPHICS INPUT SYSTEM

6.5.1 Screen Requirements for user Light-Pen Input

In a luminous flux-transmitting screen such as a rear-projection screen, the direction of light rays can be reversed (The "Principle of Reversability") (278)

By this Principle, it can be taken that ~~what is true~~ for a CRT- generated incident screen illumination and resultant viewer side screen luminance, is true for the User-generated screen illumination from the light-pen and the resultant screen luminance on the CRT-side of the screen; such a luminous spot then becomes, as explained in more detail in section 6.5.2, the object generating an image on the CRT screen and hence will be reflected back onto the Vidicon photoconductive target.

The light beam at the exit-pupil of the light pen must be held in a direction such that its optical axis are aligned with the apparent optical axis, or rather lobe axis of the screen luminance, for the above transmission gain coefficiant $T_S = 4$ to be valid. At other directions, the directivity pattern will have the effect that a significant fraction will be radiated in directions not intercepted by the CRT projection optics and hence wasted; in fact stray light will be generated and cause loss of contrast. The pen light beam direction is thus fairly critical!

Not only does a particular user's angle of pen grip vary from time to time, but the axis along which the pen should be aligned with (the direction of the light-pen projected beam with the screen) varies over the screen . Variations of incident illumination on the CRT due to the light pen should not vary by more that 2:1 at the worst case, otherwise false signals may be generated. The plastic rear-projection screen provides a variation of luminance of about 3→4:1 over the screen (unless excessive head movements, and thus pen directions, are used) - if for no other reason then, this is sufficient to disqualify this type of screen for use.

The RCA screen on the other hand, by its Fresnel lens, ensures that exit-ing CRT generated beams have maximum intensity (and thus the lobe axis) nearly perpendicular to the screen surface over the whole screen (actually near the edge they converge at some 7^0 towards the central screen optical axis (see Fig.90(b); this is of negligible significance). Consequently for efficient pen utilization, the only requirement is that the light pen be held vertical to the screen surface - and if the user is centrally placed, he will always, even when the pen is "perpendicular" to the screen, give a slight pen holding bias in his direction - i.e. towards the screen optical axis, aligning the pen even more closely to the slightly convergent lobe axis due to the Fresnel Lens action. Provision thus should be made in the pen for ensuring it has a preferred mode of operation when it is normal to the screen surface. Then the Transmission Gain coefficiant $T_{(S)} = 4$ can be fully justified when used.

6.5.2 Optical Image Superposition

In an optics system where real images are formed from real objects (such as in systems with convergent lenses or convergent spherical mirrors, which can result in real images which can be projected or intercepted by screens), the two planes, the object plane corresponding to the CRT screen, and the resultant image plane, corresponding to the projection screen, are called "conjugate planes". This means that light emanating from either plane will be brought to a focus at the other plane (278).

Thus the resultant luminous light spot appearing on the CRT-side of the projection screen, caused by the emitting light-pen, becomes the object in the Schmidt Optical system, and is imaged and focussed at its conjugate plane, the CRT screen, which now becomes the image plane! This, of course, is valid in concurrence with the CRT screen being simultaneously the object plane for its own emitting luminance for the user display screen.

Thus by "optical conjugacy" of real objects and real images, images can be projected simultaneously on both CRT and projection screen by both the CRT and the user's pen, and it is this Principle which enables user-graphics to be inserted into VIDIOGRAPHIC (hence the acronym component Optical).

6.5.3 The CRT screen as an Reflecting surface.

The CRT screen itself is a very good diffusing reflecting surface ("Lambert" radiator) whether for cathodoluminescent originating light flux or whether for reflection of incident projected light (267)! It is not quite an ideal Lambert reflecting surface (having preferred reflection/diffusion for certain wavelengths - the "colour" of the CRT being not "white"), and thus has a certain degree of absorption. Its effective transmittance is nearly zero, as an aluminized backing layer is present which reflects back specularly (i.e. mirror-type reflection), any luminous flux which is being transmitted. For the incident luminous flux expression 6.12 holds

i.e. $$T_S + T_R + T_L = 1 \quad \ldots\ldots\ldots\ldots \quad 6.12$$

where "T_S" is the transmittance ≈ 0

"T_L" is the loss due to absorption, say 0·4 resulting in "T_R", the reflection coefficiant, being equal to 0·6.

Thus 0·6 of the incident luminous flux on the CRT screen is reflected back and rediffussed over a solid angle of 2π steradians. A fraction of this luminance is intercepted by the Vidicon lens and inserted into the CRT- Vidicon loop for storage refresh.

Ideally then, the incident illumination on the Vidicon photoconductor shows no differentiation between CRT cathodoluminescence and light-pen originated reflected illuminescence, assuming the spectral energy distribution of the light pen illumination is no different to the "W" phosphor spectrum; this is the case if the CRT is the light source for the light pen.

6.5.4 CRT screen illumination due to light pen.

For a screen of dimensions 18" x 24", and a 625 line TV-system of about 580 active lines, the display element dimensions are approximately 0·03" x 0·03".

Assume that the light pen has an exit aperture of d" x d", and a focussing lens which, when in optimum proximity to the screen, has a resultant illuminating spot section equal to say 0·045 x 0·045" (the reason for the light-pen illuminating spot being larger than an element is explained in section 9.3.)

If the illumination at the exit pupil is $E_L(t)$ ft-Cs, then the illumination on the screen (as illumination is $\propto \frac{1}{\text{Area}}$) is, $E_L\ (t) \left(\frac{d}{0\cdot045}\right)^2$ ft-Cs.

With the screen Transmission Gain coefficiant $T_S = 4$ (which includes in it the loss and reflection factors), the resultant brightness or luminance on the CRT side of the screen is

$$B(t) = T_S .\ E_L(t) \cdot \left(\frac{d}{0\cdot045}\right)^2 \quad \ldots\ldots \quad 6.16$$

$$= 4 \left(\frac{d}{0\cdot045}\right)^2 .\ E_L(t) \quad \ldots\ldots\ldots \quad 6.16(a)$$

This luminance is intercepted by the Schmidt Optical System and imaged onto the CRT screen, resulting in a CRT screen illumination $E_{L-CRT}(t)$.

An expression analogous to 4.9 and 6.9 is used,

$$E_{L-CRT}(t) = \frac{B_L(t)\ (\mathrm{Sin}^2\varphi_2 - \mathrm{Sin}^2\varphi_1)\ T_{CRT}.T_{ML}.(1-L)\mathrm{Cos}^4\beta}{(1+M)^2} \quad \ldots\ldots 6.17$$

where "$E_{L-CRT}(t)$", "$B_L(t)$" are as defined previously,

"T_{CRT}" is the transmission factor of the CRT screen, 0·7

"T_{ML}" = $R_{MC}.R_M.T_{CL}$, the losses due to reflection and transmission of the mirrors and correction lenses $\approx$ 0·85.

"L" = 0·05, the loss due to blockage by leads, mountings etc.

"M" = $\frac{1}{6}$, the magnification

"φ_2" is the semi-cone angle formed by the reflecting mirror at the centre of the CRT screen and equal to 42°.

"φ_1" is the semi-cone angle formed by the blocked out section of the mirror, at the centre of the CRT screen and equal to 23°.

"β" is the angle between the optic axis and locations lying on the CRT screen on the circle corresponding to circle "B" of Fig.65(b). Within this circle $\mathrm{Cos}^4\beta > 0{\cdot}85$

Hence

$$E_{L-CRT}(t) = 4\left(\frac{d}{0{\cdot}045}\right)^2 . E_L(t).(\mathrm{Sin}^2(42°) - \mathrm{Sin}^2(23°)) \times \frac{1}{(1{\cdot}67)^2} \times 0{\cdot}7.0{\cdot}85.0{\cdot}95.0{\cdot}85 \quad \ldots\ldots 6.17(a)$$

Evaluating,

$$E_{L-CRT}(t) = 0{\cdot}43\left(\frac{d}{0{\cdot}045}\right)^2 . E_L(t) \text{ ..ft-C...} \quad 6.17(b)$$

This then is the incident illumination on the CRT screen due to an light pen exit pupil illumination $E_1(t)$".
Assuming a Reflection Factor $T_{R\ CRT} \approx 0{\cdot}6$, 60% of this illuminance is reflected and rediffused back over 2π steradians. The resultant CRT screen brightness thus becomes

$$B_{L-CRT}(t) = 0{\cdot}6\ E_{L-CRT} \ldots \text{ft-L} \ldots \quad 6.18$$

and substituting for "$E_{L-CRT}(t)$",

$$B_{L-CRT}(t) = 0{\cdot}25 \left(\frac{d}{0{\cdot}045}\right)^2 . E_L(t) \ldots \text{ft-L} \ldots \quad 6.18(a)$$

For this CRT screen luminance to be indistinguishable from the CRT cathodoluminescene it must have the same amplitude-time relationship as "W" type phosphor and result in some 400-500 ft-Candles of peak illumination on the Vidicon photoconductor or, from Fig.68, there must be a effective equivalent average CRT brightness of some $B_{AV} \approx 100 - 140$ ft-L.

6.5.5 CRT Screen Reflections

6.5.5.1 Internal Reflections and Loss of Contrast.

Of interest is the possiblility of stray reflections etc occuring on the projection CRT screen due to the light-emitting pen projected illumination. If present, these may cause :

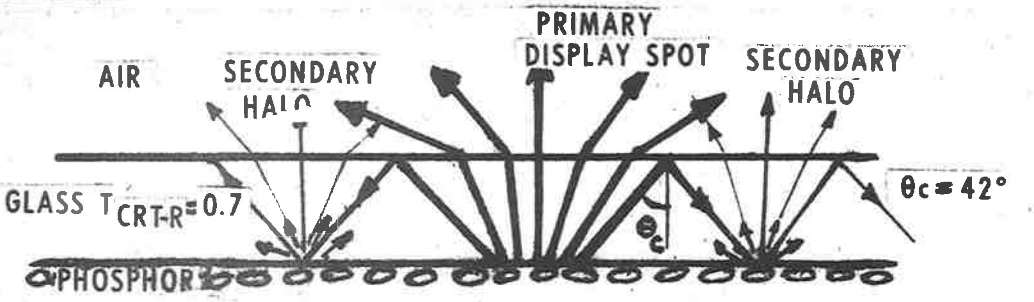
(a) loss of useful luminance

(b) generation of stray reflections leading to:

(i) possible erroneous signals injected into the CRT-Vidicon loop generating unwanted display features.

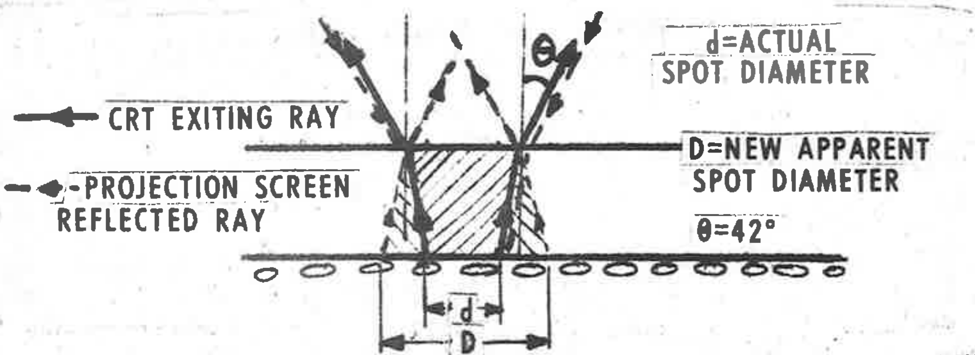
(ii) reflection back onto the rear-projection screen, causing loss of contrast and stray unwanted display features.

The phosphor CRT surface is effectively a Lambert radiator radiating luminous flux, whether cathodoluminescent-originating luminous flux or reflected light-pen originating luminous flux,in all directions outward from the screen - i.e. in a "cone" of 2π sterads. (see Fig.91(a)). Incident rays striking the upper surface (or glass face-air interface) of the glass faceplate at angles greater than the "critical angle" for glass, (which is of the order of $41-42^{\circ}$ from the normal to the screen,for this type of glass) will be internally reflected, and being incident on the phosphor screen again, will be reflected and rescattered. Thus, around a primary luminous flux radiating display location, secondary radiating sources appear due to these internal reflections. Since the primary source radiates equally well in all directions, these secondary sources are located "equally well" around it and make their appearance as "halos" around the primary sources. These secondary sources in turn give rise to further reflections; the result is a primary source surrounded by well defined "halos"of increasing diameter and decreasing luminance amplitudes. Photographs of these are quite common in the literature (see for example in (267). The presence of these halos clearly indicates the reflecting diffusing property of luminous flux of the CRT screen phosphor!
Because a fraction of the luminance originating from the primary location is used to generate these unwanted signals, not only is the primary source luminance (the "signal") decreased, but this fraction also generates unwanted signals ("noise"); the contract then decreases sharply,as does the useful luminance.

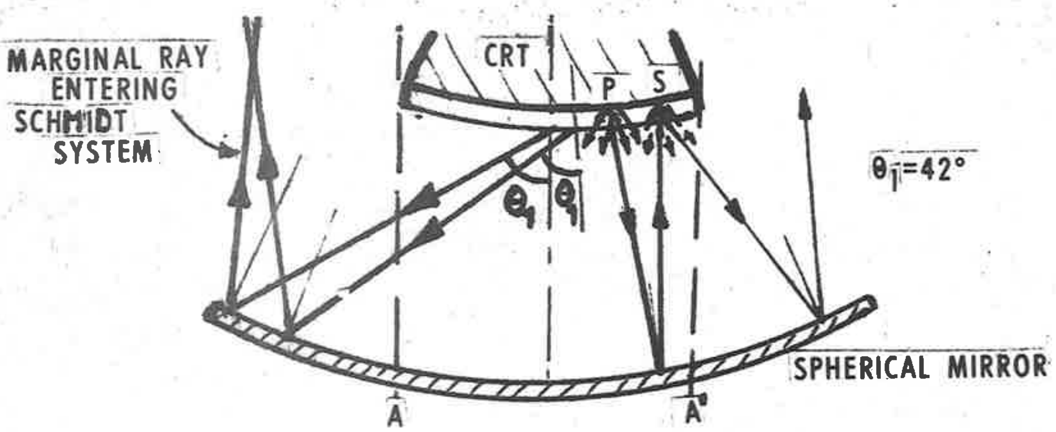


The low transmission glass faceplate greatly attenuates the secondary halos due to the longer optical path between the origin and the exit.

(a) Total internal reflections causing secondary halos and reducing contrast.



(b) Effect of rear-projection screen reflection coefficiant "T_{RS}" causing an apparent increase in spot size, due to glass faceplate reflection at large cone semi-angles (⩾42-43°).



(c) Occurrence of stray reflections 'S' originating from some spot 'P' when central regionAA' is present.

Figure 91. Stray Reflections in Schmidt TV Projection Optics.

The halation is reduced or nearly eliminated by having the glass face made of low transimittance or "absorbing" material with a transmission coefficiant $T_S \approx 0\cdot5 - 0\cdot7$ (267).

From the Fig.91(a), it can be seen that for the primary halo, rays need to traverse at least three glass screen thicknesses (allowing for ray refraction, this is more like 4 screen thicknesses) compared with one screen thickness for the primary ray. With the phosphor Reflection/diffusion Factor "$T_{R\,CRT}$" of say 0·6, the primary halo is reduced (for a glass screen. $T_S \approx 0\cdot7$) to $(0\cdot7)^3 \times 0\cdot6 \approx 0\cdot2$ of its previous value. The primary luminance is reduced to 0·7 of its previous value when normal glass faceplates are used, indicating that contrast has improved by about 4, at the cost of reduction of luminance.
In practice, with lower "T_S", contrast improvement by factors of 6 to 18 has been reported (267)

Similarly any external incident illumination at an angle $< 41^\circ$-42° to the normal, will travel at least two screen glass thicknesses before being reflected/diffused and emitted again, compared with the CRT phosphor-emitted luminance travelling through one glass thickness. For the light pen originating luminance off the CRT screen, a factor $T_{CRT} \approx 0\cdot7$ was allowed for, in expression 6.17.

6.5.5.2 Schmidt Optics Dimensionsand Contrast Improvement.

Some of the dimensions and parameters of the Schmidt Optics system may now be explained. The size of the aperture lens in both the RCA and the Phillips system,

both of which use rear-projection screens, is such as to allow a maximum semi-cone angle from the centre of the CRT screen to the mirror of 42° (in the Phillips system, 38°).
Presumably the reason is as follows. Rays reflected off the mirror and incident on the rear-projection screen have a certain fraction "T_{RS}" reflected back (or rather reflected/diffused) making that ray visible when viewed from the rear of the screen. Part of this reflected luminous flux travels along the same direction, but in the reverse direction as the original incident ray. It is reflected off the mirror and incident on the screen. If the angle of incidence is $\geqslant 42^{\circ}$ or thereabouts (the critical angle for reflection for glass), a sizeable fraction is specularly reflected off the glass faceplate to be incident on the mirror and reflected back onto the glass faceplate again. However because of finite glass faceplate thickness and refraction effects, its apparent origin on the CRT phosphor screen is not the original location but some adjacent location (see Fig.91(b)).

The result is CRT spot sizes of apparently larger diameter with defocussed or diffused spot boundaries. Hence a loss of resolution results.
If a thick faceplate is present, double images may even become visible.

Clearly making the effective mirror aperture such that the exit angle at the glass/air interface is less than 42° ensures that the image defects and loss of resolution do not occur. Reflected rays of angular incidence which result in grazing or shallow travel paths in the glass faceplate are quickly attenuated due to the Transmission of the glass $T_{CRT} \approx 0{\cdot}7$.

The same explanation of course holds for rays projected onto the CRT screen from the light emitting pen. The effective maximum cone semi-angle being less than the critical angle of 42° ensure that no double reflection etc are seen on the viewing screen.

Moreover it may be shown from the symmetry of the reflection system in Spherical Mirror Optics, that rays exiting at $\geqslant \varphi_1$ to the normal to the CRT glass faceplate from screen locations other than that at the centre of the CRT screen, do not intercept the correcting lens and hence are not focussed on the projection screen. This is of course only true for systems where the maximum semi-cone angle of acceptance by the mirror from the CRT screen centre is "φ_1". This is shown by the two rays on the left-hand side of Fig.91(c). Hence if any stray light rays from whatever source eventually are incident on the CRT screen they are either attenuated by the CRT glass faceplate of $T_S \approx 0{\cdot}6$, or if they are reflected, their angle of incidence to the glass faceplate being $\geqslant 42^{\circ}$, they are not focussed on the rear projection screen as for all intents and purpose, this is the same case as CRT screen rays exiting at $\geqslant 42^{\circ}$.

It is thus seen that stray reflections and stray light are of little consequence in a Schmidt Optics System.

Similarly unless the central region of the mirror (of dimensions approximately equal to the CRT screen dimensions), is blacked out, or drilled out for Vidicon tube positioning, multiple reflections between mirror and CRT Phosphor are possible. For near-normal exiting rays, with the central mirror portion being present, the mirror reflected rays would be incident on the CRT screen again, causing secondary images to result; the reflection of the CRT screen is not by specular reflection but by reflection/diffusion from the CRT phosphor.

For projected light rays onto the CRT screen from the conjugate image screen due to the light emitting pen, the rays will follow the same paths as the CRT emitted rays incident on the viewing screens (except for reversion of direction). That portion of this luminous flux not directly intercepted by the spherical mirror and imaged onto the CRT scren, effectively generates stray light rays or may generate stray light rays.
Their effect is the same as the above described stray light rays and thus may be neglected.

6.6. THE LIGHT EMITTING PEN AND LIGHT SOURCE

6.6.1 The Required Light-Pen User Signals

In section 4.3.6 the requirements for the two major classes of user input signals were given. These are listed on Table 2 . Briefly these were:

(i) Graphics Information Input Signals
When illumination due to these signals is projected onto the CRT and thence a fraction of this is intercepted by the Vidicon, the resultant output current is to be no different than the output current due to the CRT emitted display information. The "objective criterion" however is that this output current signal is to be capable of being detected by the "i_{L1}" Level Detector.

(ii) Pointing Function and Erase Input Signals
The light pen illumination is incident on

existing luminous display locations and the resultant Vidicon output signal is to be capable of being detected by the "i_{L2}" Level Detector while the latter is enabled "on". Depending on whatever function is to be done at that location (via enabling the appropriate function buttons), the indicated display locations may be required to remain displayed, or be erased implying that at the next frame scan the signal output current at that location be less than "i_{L1}".
Further it was indicated (section 4.3.6) that the "Erase " signal was the most difficult one to implement. A reduction in light pen luminance for the "erase" signal may be required particularly for a Class II Photoconductor, otherwise, the Vidicon phototarget may become damaged. otherwise, if the light pen source has the same intensity and persistance as the "W" CRT phosphor, the above requirements are satisfied.

6.6.2 <u>User Actions During Light Pen Operators</u>

6.6.2.1 <u>Angle of Incidence of Pen with Respect to Screen.</u>

As already indicated in section 6.5.1, the angle at which the light pen is held greatly affects the quantity of luminous flux reaching the CRT screen and hence the Vidicon photoconductor target. Ideally with a RCA screen with a Fresnel lens, the light pen should be held perpendicular to the screen surface, with a slight bias of some several degrees off this normal, pointed towards the centre of the screen. Pen grip is thus of importance with a directional screen.

6.6.2.2. Hand Writing Speed.

Secondly the speed with which the pen is moved may affect the signal output amplitude.

For the CRT generated illumination incident on the Vidicon, current signals are generated only once per frame time interval and read out once per frame i.e. every 40ms. On the other hand, when the user is pointing to some location for erasure say, that location may be illuminated for the interval that the light pen is stationary at that location, which may be one or more seconds, quite feasibly. This is a very short time for the user but is equivalent to 25 Vidicon-CRT recycle times. Since the "i_{L2}" level detector controls some logic and may tie up the CPU I/O interface depending on the particular function being performed, then for as long as the pen is incident on the same location, I/O interrupts for that location will occur.

A great advantage will result if the light pen luminance is blanked out after the first scan i.e. after it has performed its required function. The signal to enable this to be done may be derived from the output of the "i_{L2}" detector. A light source is thus required which switches off or blanks off on command in less than 40 ms. For this reason constant illumination light sources are unsuitable for the light pen.

A conterbalancing advantage occurs, compensating for the uneven writing speed of the user. Results of user actions are directly and immediately visible to the user. An indicated location for erasure may remain displayed, while the adjacent location has been erased say. This is seen by the user and as he originates these commands and actions, he determines whether the displayed result is correct or not. If not, then he may immediately take corrective action without tying up the CPU, because wrong display information (i.e. incorrectly located or not erased) does not tie up or involve the CPU I/O interface.

Any errors occuring due to other causes, say by excessive noise (see section 5.7) may be corrected by this way.

6.6.3 Requirements of the Light Pen

In addition to being able to generate the two classes of signals described briefly in section 6.6.1, the following requirements are needed :

(i) the availability of at least two luminance levels, one amplitude for graphics information input, the other, lower level for "pointing" and "erase" signals.

(ii) The pen must be held very nearly perpendicular to the screen surface, particularly when a directional screen with a Fresnal lens is used.

(iii) Spectral and Persistance characteristics of "W" phosphor are desirable for the light source.

(iv) The light source of the light pen to be capable of being blanked off under signal command at any instant with negligible time delay.

(v) The output illumination of the light pen "$E_L(t)$" from expression 6.18(a) is given as

$$E_L(t) = \frac{B_{L-CRT}(t)}{0 \cdot 25} \cdot \left(\frac{0 \cdot 045}{d}\right)^2 \quad \ldots\ldots \quad 6.18(b)$$

where "d" is the diameter of the exit pupil of the pen and it is assumed then this is focussed by a converging lens to a spot of diameter 0·045" x 0·045". The lens may be assured to have a Transmission Coefficiant of 0·75.

"$B_{L-CRT}(t)$" is the resultant CRT screen luminance which must be able to satisfy the Vidicon required illumination. This, as was indicated in Fig.68 is of the order of > 100-120 ft-L average luminance of "W" type phosphor. With $B_{PEAK} = 63\ B_{AV}$, the $B_{L-CRT}(t)_{PEAK}$ is of the order of 7000ft-L (peak) and is the value used in the calculations following.

For a light-pen illumination having a different persistance or luminance-time relationship, the above figures will differ. However, they will need to be of the same approximate order of magnitude.

Evaluating 6.18(b) for a W-phosphor illumination with the above values, results in a required "$E_L(t)_{PEAK}$" of

$$E_L(t)_{PEAK} = 2{\cdot}8.10^4.\left(\frac{0{\cdot}045}{d}\right)^2 \text{...ft-L.} \quad .6.18(c)$$

With the useful light pen exit pupil "d" of the order of 3-4x(0·045)", this indicates a peak light pen exit pupil luminance requirement of

$$E_L(t)_{PEAK} = 3.10^3 \text{....ft-L} \quad .6.18(d)$$

Such luminances are quite readily feasible with available light sources such as flash-lamps or even constant illumination lamps. More so, this luminance is even more readily available from the CRT, where peak luminances of $1{\cdot}5.10^5$ ft-L are available (259).

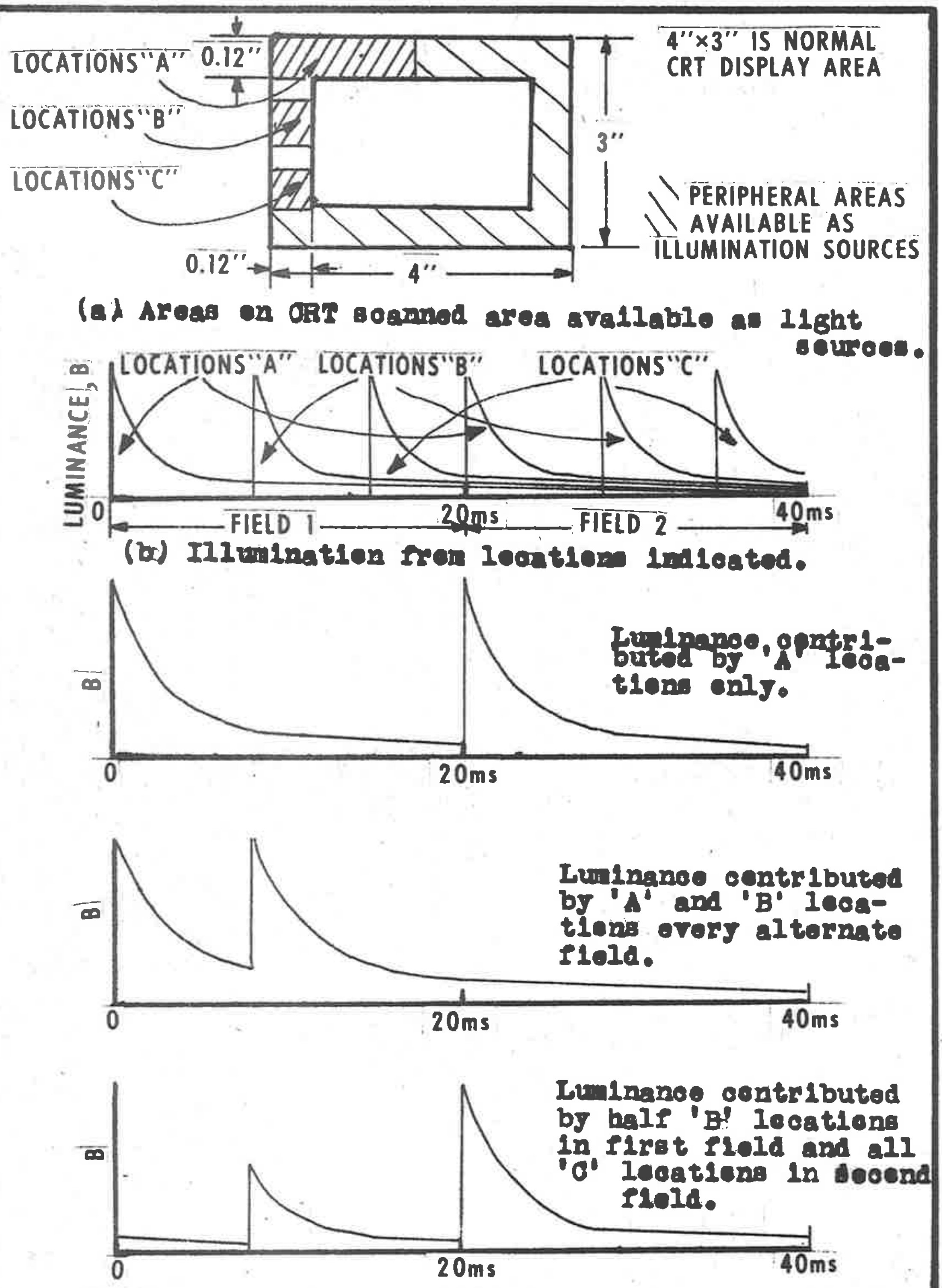
6.6.4 Commercially Available Illuminating Sources

Before examining the proposed CRT-derived light pen illuminator, the other, more obvious illuminating sources will be briefly examined, under their ability to meet the requirements enumerated in the previous section.

The most common laboratory illuminators, particularly for optic fibre illuminators, are based on a projection lamp of some 4" length which has a parabolic reflector within the bulb, reflecting in a nearly parallel beam the luminous flux from the incandescent filament (279). This beam in turn is focussed by a converging lens (external to the bulb) onto the fibre optic terminals. The reflector has a "dichroic" reflecting film, that is a wavelength selective reflector; it reflects visible light but transmits infra-red, generated by the filament, away from the optical fibres. A cooling fan is required. Bulbs have a short life of some 100-200 hours and cost in the vicinity of $5-10 (280). Of 150 watt rating, their current is some $\frac{1}{2}$ - 1 Amp average. The steady illumination on some area 0·3" x 0·3" is some 20-50.10^3ft-C and can be varied by varying the supply voltage.

Providing a luminance-time characteristic of similar form to W-phosphor persistance by switching 150-watts 25 times/sec. provide certain problems (particularly as time-constants are required to be negligible i.e. less than 1-2ms!), and lowers lamp life greatly. Relay-operated mechanical shutters (derived from commercial cameras) could be used instead; shutter opening and closing times of the order of 2-3ms are quite common (281). The resultant required illumination is a sequence of narrow pulses of some 10ms width spaced every 40ms.

Of the other possible light sources (279)



(a) Areas on CRT scanned area available as light sources.

(b) Illumination from locations indicated.

(c) Typical resultant luminances due to contributions shown in (a).

Figure 92. CRT-derived Programmable Light Source.

flashlamps are completely unsuitable as they have extremely short life (less than 10^4 flashes, equivalent to a life of a few minutes in our system).

Flash Discharge Tubes such as are used in stroboscopes could potentially be used but require high operating voltages (several KV) and are expensive.

6.6.5 Advantages of Using CRT Luminance as a Light Source

Some advantages are obvious. The persistance spectrum and potentially high available luminance of the order of $1{\cdot}5.10^5$ft-L are what is exactly required from our viewpoint.

However, the following additional advantages are also present:

(i) The Vidicon has an unusable peripheral area adjacent to its scanned area boundaries of some 10-15% of its total scanned area (section 5.5.5). As the CRT and the Vidicon are required to have a 1:1 display area spatial relationship, about 10-15% of the CRT display area is also unusable for display purposes. This area can be used as the light source for the light pen!

(ii) The CRT light source is a "cold-light" source. In incandescent light sources, some 80% of the wattage is converted to unwanted thermal energy (hence the required "dichroic" reflector mentioned above). This, when optic fibres are used to channel the luminous flux to the light pen, requires forced-air cooling and consequent increase in cost size and noise.

(3) The major advantage however is the potentially fast switching speed and control of the light pen illumination. The light pen illumination may be due to several individual luminous locations on the CRT screen (the available area for this is the periphery of the display area). Each of these locations has a defined sequence of switching on (due to the raster scan) and providing its contribution to the resultant total illumination; the collection of this illuminating flux is done by optic fibres. The enabling of each of these contributing sources can be controlled selectively by controlling the number of enabled locations at any one region, determines the resultant peak illumination. By controlling, within a frame time, which of the contributing groups of locations will be enabled, alters the combined persistance curve of the illumination (see Fig.92).

Because all of these contributing sources are capable of being switched on or off, either selectively or in toto , at speeds inherently compatable with the CRT and Vidicon timing system, an extremely flexible and versatile programmable light source results.

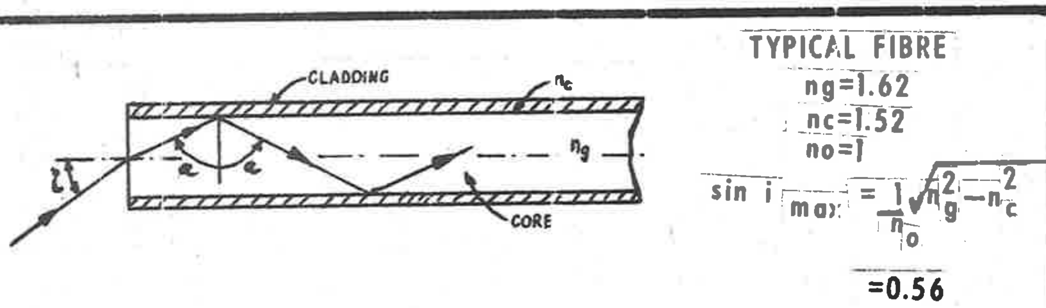
(4) The final advantage is cost. All the required components to construct the light source and pen are inherently present.

6.6.6 Fibre Optics

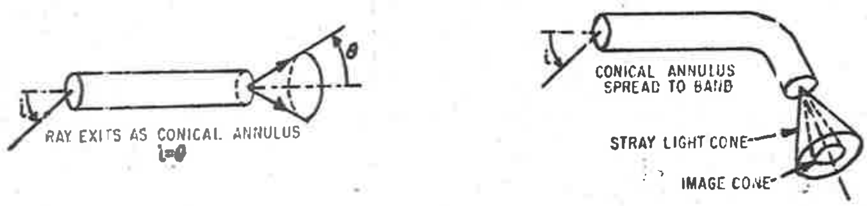
6.6.6.1 Introduction

The means of collecting the luminous flux from the CRT light source and transmitting it to the "exit pupil" (the output aperture) of the light emitting pen is through "optical fibres". Optical fibres are thin fibres (approximately 0·001" → 0·02" in diameter), most commonly of glass or plastic, which can "channel" or guide luminous flux, incident on one end of the fibre, along their length with very samll attenuation; the transmitted luminous flux is emitted from the other end of the fibre. The major advantage is that the transmitted light follows the curve of the transmitting optic fibre; the curvature can be up to about 10 times the radius of an individual fibre radius (see Fig 93). Cost is very cheap, about 65c(US) per foot of bundle containing 64 individual fibres (280) . The theory of operation and capabilities of optic fibres have been adequately described elsewhere (282-285) and are of no great concern here. Of prime interest here are the terminal properties of the optic fibres; optical fibres, will thus be treated as "black boxes", with interest centered on the amount of luminous flux accepted by the fibre, the fraction transmitted, the maximum angles of exit and entry of light rays, and the transmission spectrum. The efficiency and optimization of light flux efficiency depend on these.

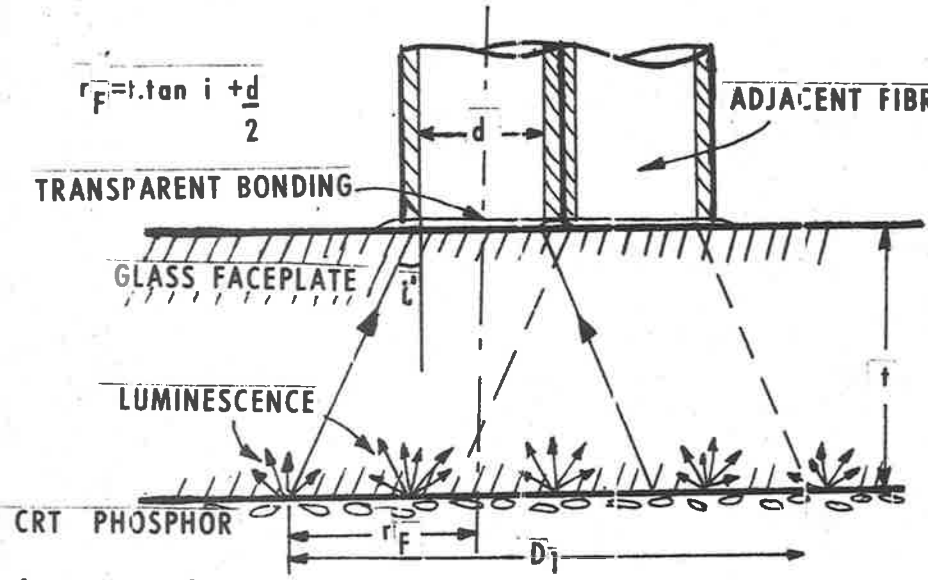
For fibres of diameter "d" appreciably greater than the wavelength of the transmitted light (i.e. d > 5-10 microns), light can be considered to propagate though the fibre by a series of reflections from wall to wall (see Fig.93(a)). Hence, only the rays which are incident on the entry pupil at an angle equal to or less, such that total internal reflections can occur, are propagated. To reduce light leakage, "cladding" of each fibre by material of lower index of refraction is used; as the thickness of cladding is only several microns, the total cross sectional area of the fibre is effectively the same as that cross section area through which light is propatated.



(a) Propagation of light ray along optical fibre.



(b) Entry and exit light ray angles.



(c) 'Cone' of light acceptance of optic fibre bonded to CRT glass faceplate. 'r_F' is the radius of 'cone'.

Figure 93. Fibre Optics.

6.6.6.2 Incident Illumination on Optic Fibre Entry Pupil

It is a trivial exercise to show (using Snell's law of refraction) that the condition for total internal reflection is

$$\sin i \leqslant \frac{1}{\eta_o}\sqrt{\eta_g^2 - \eta_c^2} \quad \ldots\ldots\ 6.19$$

where "i" is the angle of incidence to the fibre axis
"η_o" is the refractive index of the medium where the incident luminous flux is present.
"η_g" is the refractive index of core material
"η_c" is the refractive index of the cladding material.

For a fibre in air (η_o=1),"i" is between 30°and 60° both for plastic and glass fibres. Manufacturers usually supply this data.

Sin "i_{max}" defining the cone of light acceptance, is thus the measure of luminous flux gathering efficiency. For a Lambert illuminating source of "$B_S(t)$" ft-L, it is shown in (Appendix 8.3.1) that the illumination at the centre of the fibre, "$E_{OF}(t)$", is

$$E_{OF}(t) = B_S(t)\ \sin^2{}_{max}(i) \quad \ldots\ldots\ 6.20$$

When an optic fibre is cemented to the CRT glass faceplate, the distance of the fibre from the CRT phosphor (the Lambert illuminating source) is equal to "t", the faceplate thickness. It is assumed the cement is optically transulent, of negligible thickness, and of refractive index similar to glass (about 1·5-1·6); the adhesives used to cement compound lenses suggest themselves. From Fig. 93(c) the resultant field of illumination which contributes to the illumination on the optic fibre has a radius "r_F," where

$$r_F = t.\tan i + \frac{d}{2}$$

Now "t" for projection CRT's is of the order of 0·1"-0·15"; taking t = 0·13, η_o = 1·54 (glass faceplate) and $\sqrt{\eta_o^2 - \eta_c^2} \approx 0{\cdot}55$ (a typical value), results in

$$"i" \approx 21^{o}$$

and the radius "r_F" of the contributing field of illumination being $(0{\cdot}05 + \frac{d}{2})$". For a fibre thickness d = 0·01", the total diameter of the field of illumination is 0·11".
As the angle subtended by the fibre at the illuminating source is less than 1°, the "$\mathrm{Cos}^4\varphi$" variation over the fibre is negligible.
From expression 6.19, the average illumination for i = 21° across the optic fibre cross section "$E_{O.F}(t)_{IN}$" is

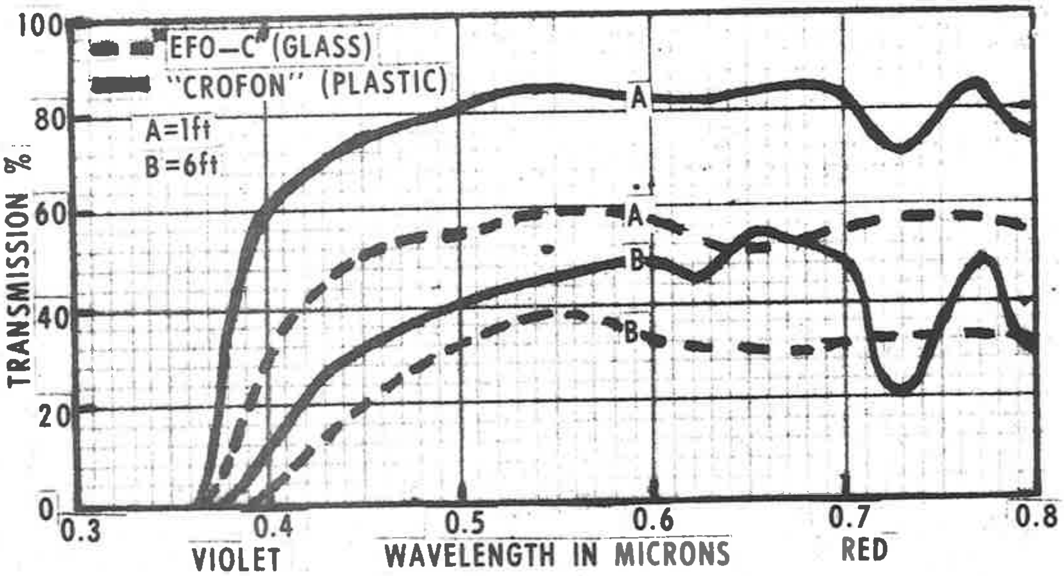
$$E_{OF}(t)_{IN} = 0{\cdot}13\ B_S(t) \ldots \text{ft-C.} \quad \ldots\ .6.20(a)$$

This is contributed by that field of illumination of 0·11" diameter.

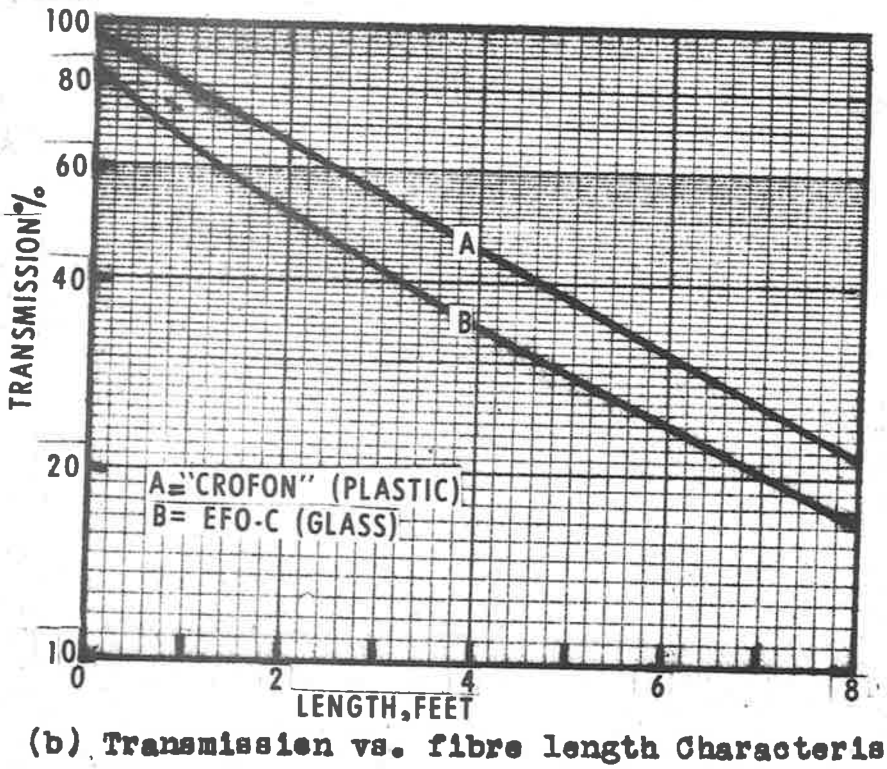
When a bundle of fibres with a total effective diameter "D" is used rather than a single fibre, then because the illuminating source is a Lambert radiator, the effective diameter of the illuminating source necessary to provide a constant illumination for the optic fibres is $2(t.\tan i + \frac{D}{2}) \approx (0{\cdot}1 + D)$".

6.6.6.3 Transmission of Luminous flux in Optic Fibres

The transmitted incident illumination is now subject to attenuation when travelling through the fibre lengths. From Fig. 94(b), showing the "transmission vs length" of fibres, it is seen that the plastic "CROFON" fibres are superior to the glass fibres. For a 6' length (the length required) about 30% of "white" light is transmitted.



(a) Transmission of two typical fibres as a function of wavelength and length of fibre.
(EFO-C - Electro FiberOptics Corp.)



(b) Transmission vs. fibre length Characteristics.

Figure 94. Fibre Optics Parameters (based on [284,285])

The fibres also show preferred transmission for various wavelengths; this is shown in Fig. 94(a). Greater attenuation occurs at low wavelength (blue) than at the others.

Again for visible wavelength, the plastic fibre is superior to the glass fibre.

Consequently "CROFON" plastic fibres are selected for use.

The frequency selectivity in transmission has been allowed for in the "transmission vs length" curves as these are the average transmission for "white light".

Thus the illumination across the exit pupil of the optic fibres of 6' length, "$E_{OF}(t)_{OUT}$", is

$$E_{OF}(t)_{OUT} = 0{\cdot}3.0{\cdot}13.B_S(t)..\text{ft-C}. \quad . \; 6.20$$
$$= 0{\cdot}042.B_S(t)...\text{ft-C}. \quad . \; . \; .6.20(a)$$

As the peak luminance "$B_S(t)_{PEAK}$" of the CRT phosphor can be $1{\cdot}5.10^5$ft-L, the illumination at the light pen exit pupil can be

$$E_{OF}(t)_{OUT\ max} \leq 6300\text{ft-C} \quad . \; . \; . \; . \; . \; . \; .6.20(b)$$

<u>6.6.6.4 Output Luminance at Exit Pupil of Optics Fibres</u>

The luminous flux at the exit pupil disperses in a cone of light (see Fig.93(b)), whose semi-angle is given by an identical expression to 6.19 (due to the Principle of Reversability of light rays in Optics). However, the output medium being now air, with a refractive index $\eta_o = 1$ and as $\sqrt{\eta_g^2 - \eta_c^2}$ was taken as 0·55, the exit semi-cone angle "i_o" is given from

$$\sin i_o = \sqrt{\eta_g^2 - \eta_c^2} = 0{\cdot}55. \quad . \; . \; . \; . \; . \; .6.19(a)$$

resulting in "i_o" = 33°.

This angular dispersion means an effective illuminated "spot" at distance "S" from the exit pupil of diameter "D_o", where

$$D_o = 2S.\tan i_o + D$$

where "D" is the fibre bundle diameter.
Consequently a short focal length converging lens is used in the light pen to intercept this emitted exit pupil luminous flux and focus it to the required spot of diameter 0·045" (see Fig.97(b)).

6.6.7 The CRT Illuminating Source

6.6.7.1 Introduction

Expression 6.20(a) gives the maximum output illumination at the exit pupil of the fibre optics bundle, for a given CRT Luminance.
In section 6.6.3, the expression 6.18(c) was derived linking the required output luminance for the light pen with the resultant Vidicon illumination of about 400ft-C peak, when the light pen luminance is projected into CRT-Vidicon system. This was

$$E_L(t)_{max} = 2\cdot 8.10^4 \left(\frac{0\cdot 045}{d}\right)^2 \text{ ft-C} \qquad 6.18(c)$$

where "d" is the diameter of the exit pupil of the pen and thus the diameter of light fibre bundle, "0·045" is the resultant spot on the screen (a focussing lens being used).

Equating these two expressions 6.18(c) and 6.20(a), results in

$$d = 0\cdot 045\sqrt{\frac{2\cdot 8.10^4}{0\cdot 042.B_S(t)}} \text{ inches} \quad .\ .\ .\ .\ .\ .\ .6.21$$

Thus a tradeoff between the active diameter of the fibre bundle "d" (and hence the number of fibres required) and the illuminating screen luminance "$B_S(t)$", exists.

For a maximum peak CRT luminance "$B_S(t)$" of $1{\cdot}5.10^5$ ft-L, the active fibre bundle diameter results in

$$d = 0{\cdot}095". \quad \ldots\ldots\ldots\ldots \quad 6.21(a)$$

As each "CROFON" fibre has a diameter of 0·010"(286), about 90 "CROFON" fibres are thus required.

6.6.7.2 Method of Affixing Fibres to CRT Screen.

CROFON fibres (as glass fibres also), are supplied loose or in bundles of 32 or 64 fibres in PVC jackets. The ends of the fibres need be optically polished and capped for normal light guiding application. It is thus assumed that both ends of each optic fibre is polished prior to attaching to the CRT glass faceplate.

6.6.7.3 Finite Scanning Speed and Generation of CRT Luminance.

Several complications arise because of the finite scanning speed of the beam which generates this luminance of the CRT illumination source. Above it was assumed that all points of the illuminating area on the CRT screen have identical persistance at any given time and identical luminances.

The top strip on the CRT screen available for illuminating is 0·12" wide (corresponding to 3% of the scanned area dimension at each side-see section 5.5.5). For a 3" high CRT raster area corresponding to a field time interval of 20ms (2 field intervals = 1 frame time interval in 2:1 interlaced scanning), 0·12" corresponds (allowing for 9% fly back) to

$$\frac{0\cdot 12}{3} \times 18\cdot 3 \text{ ms} = 0\cdot 735 \text{ ms} \quad . \quad . \quad . \quad . \quad . \quad 6.21$$

From Fig.64(a), the persistance curve for "W" phosphor, the luminance 0·735ms after the start of excitation, is only some $0\cdot 14 B_{PEAK}(t)$

Clearly then for the illuminating area which takes 0·735ms to generate, the effective overall average luminance is somewhere between "B_{PEAK}" and "$0\cdot 14\ B_{PEAK}$". This must be the luminance used in to calculate the output light pen illuminance.

In Appendix **A.9.3** it is shown that the decay for "W" phosphor in the interval between 10us to 1ms is given by approximately,

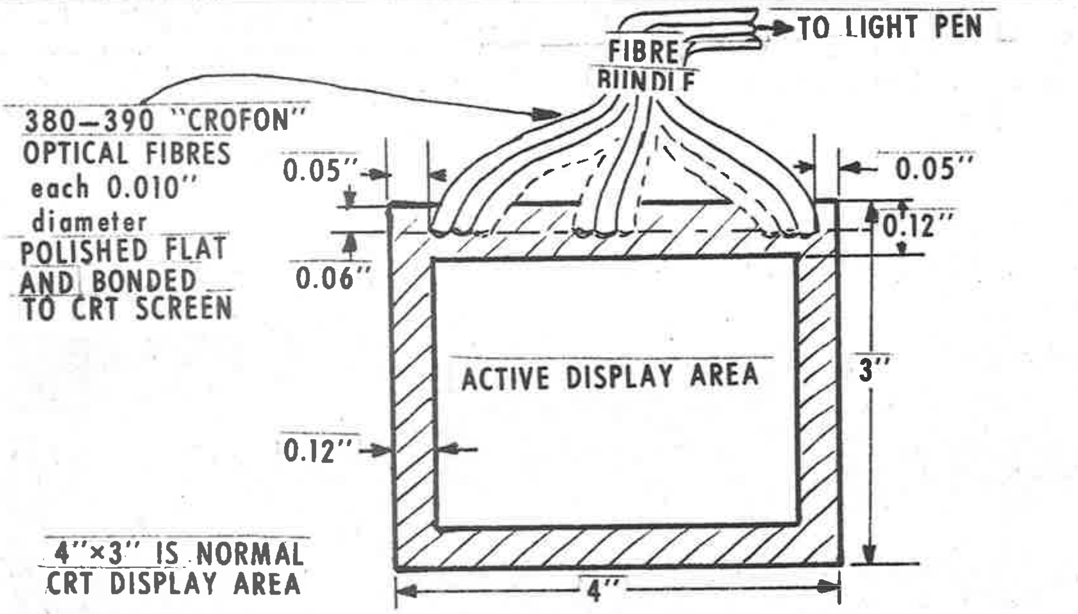
$$B(t) = B_{PEAK} \cdot \left(\frac{1}{9\ 5.10^4 t}\right)^{0\cdot 47}$$

Using this relationship and the fact that a known number of illuminating locations occurs within the time interval 0·735ms.,the effective average luminance within that interval occuring at t = 0·735ms after the start of the frame interval is shown, in Appendix **A.9.3** to be equal to

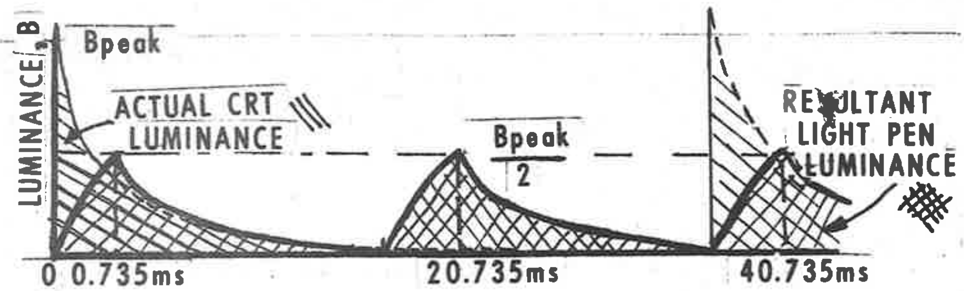
$$B_{PEAK\ AV} = 0\cdot 23\ B_{PEAK} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 6.22$$

Consequently if 90 fibres were required for a constant peak luminance B_{PEAK}, then $\frac{90}{0\cdot 23}$ = 390 fibres, for the above reduced luminances are required.

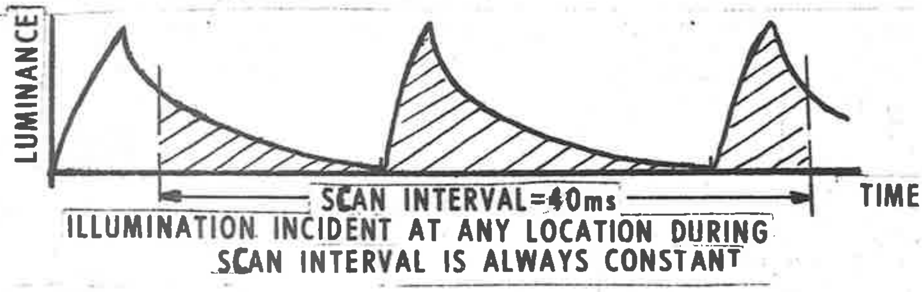
Allowing a area of width 0·05" at each end of the illuminating strip (see section 6.6.62) leaves a



(a) Layout of CRT Illumination Source for the Light Pen on a 5" Projection CRT.



(b) Resultant luminance at the CRT due to projection and reflection at CRT screen due to the above 380-390 fibre light pen, compared with the normally emitted CRT luminance.



(c) Illustrating the constancy of luminous flux uppl supplied to any CRT location.

Figure 95. The CRT Illuminating Source for the Pen.

strip width of (4 - 0·1)" = 3·9" where fibres can be located and bonded to collect the luminance. This, purely by coincidence, exactly accomodates 390 fibres bonded side by side in a line, as each CROFON fibre is of 0·01" diameter. The width available for the illuminating strip is 0·12", but as explained in section 6.6.6.2 the necessary diameter (or strip width) of the illuminating source for a single fibre is 0·11" (see Fig.95(a))

When bundled into a circular bundle, at the other end, 390 fibres each of 0·01" diameter have a a diameter of some 0·16" - 0·17". This needs be focussed down by the light pen tip lens to some d' = 0·045" i.e. a reduction magnification of some 3·5.

The second difference between the resultant light pen illumination and the CRT luminance is the fact that the raster is interlaced 2:1. That is, although each particular location is accessed every 40ms, adjacent line locations are accessed relative to each other, every 20ms. Thus alternate lines, rather than consecutive lines are "adjacent". In the illuminating CRT area only half of the lines are excited successively and then 20ms later, the other alternate lines are excited. Consequently the resultant luminance reaching the pen exit pupil consists of peak luminance "$\frac{B_s(t)_{PEAK}}{2}$" every 20ms and not peak luminance "$B_s(t)_{PEAK}$" every 40ms. This is shown in Fig.95(b) Except for amplitude and repetition rate being doubled, the persistance is nearly that of the CRT luminance.

The third difference, although not very serious, is the fact that the light pen luminance has its peak always fixed in time - one peak at the start of the frame time and the other 20ms later. The instant of scanning however for any given location may occur anywhere within those 40ms. However the time between scanning for any given point is still 40ms. Thus even though the two origins may not coincide, two complete cycles of light pen illumination are incident at any given location when the light pen is held stationary. The total light flux incident on any location is thus constant.

6.6.7. Resultant Luminance Signals from CRT Illuminanation.

Consider the following two types of signal at some given location due to a light pen containing some 380 - 390 CROFON fibres. A peak of "$\frac{B_{PEAK}}{2}$" occurs every 20ms and the persistance is as for the W-phosphor; hence the curves of Fig.68 are valid in determining the net potential buildup on the Vidicon photoconductor.

From Fig.68 for Photoconductor Class II, it is seen that for "$\frac{B(t)_{PEAK}}{2}$"(equivalent to a incident photoconductor for "B_{PEAK}" resulting in 400 ft-candles) a net photoconductor potential rise of about 5·3V occurs. 20ms later another peak occurs giving another 5·3V potential rise. Thus with 40ms, 10·6V potential rise has occured as compared with about + 8·5V for a peak of $B_{PEAK}(t)$ luminance every 40ms (see Fig.68). Consequently after the first complete scan time interval, a signal current is generated greater than for a CRT generated luminance for display refresh.

Similarly when pointing the light pen at an existing location, the two luminances sum. If the location is somewhere in the centre of the display, the summed luminances and summed luminous fluxes may be adequate to generate a scan output current sufficient to switch the "i_{L2}" Level Detector before the second half-frame light pen signal is generated. The output signal from the "i_{L2}" Level Detector then switches off the CRT illuminating elements, which stays off until the next display location is being pointed to, when the illuminating locations are enabled on again. This switching off of the illumination and its necessity to do so is left till the following section 6.6.8.

Normally however the full frame-time interval with the contributions each 20ms apart, must be superimposed on an existing luminous location to effectively result in an illumination equal to the resultant Vidicon illumination as given in expression 4.25(a).

Thus $$E(t) = 2\ E(t)_{CRT} \quad \ldots\ldots\ldots 4.25(a)$$

which easily switch the "i_{L2}" level detector on, when it is enabled on.

6.6.7.5 Summary

The resultant light pen luminances, even though not identical to CRT emitted luminance from a given location, adequately generate the two classes of user-initiated signals. The requirements for the CRT illuminating source are:

(1) CRT luminance at illuminating area to be set to a maximum (about 2500ft-L_{AL}), setting the video signal at those locations to the maximum level.

(2) a strip at the top of the CRT display area 0·12" wide and the whole width (4") of the scanned area, is the light pen illuminating area.

(3) a row of 380-390, 0·010" diameter CROFON plastic fibres, 6ft in length to be used.

(4) both ends of each fibre are optically polished. One set of ends is to be made into a circular bundle of some 0·16" - 0·17" diameter, bonded together and polished flat - this is the exit pupil of the fibre bundle.

(5) The other ends are to be bonded via some adhesive such as Canada Balsam etc in a line, adjacent to each other, 0·055" from the top of the CRT raster area i.e. mid-way along the available illumination strip.

(6) The fibre bundle to be encased in a PVC sheath.

6.7 THE LIGHT PEN

6.7.1. Introduction - Light Pen Requirements.

The function of the light pen is to provide the means for the user to directly input graphic information or to select, by pointing, certain display features for further CPU processing, or for "localized processing" such as erasure.

The light pen emits luminous flux, (channelled from the CRT illuminating source area via the optic fibres) which is incident on the viewing screen and thence via the Schmidt Optics to be reflected off the CRT phosphor onto the Vidicon photoconductor target; from there the information is either channelled into the CPU I/O interface, or is circulated for display refresh purposes.

As the light pen is in direct use by the operator, certain features are required of the pen for simple, effective operation:

(1) The pen must be capable of being guided to the desired screen location by the user holding it; it thus must have ease of handling. A slightly thicker than normal "20c" ball point pen barrel is required; one end, the "writing tip" for the luminous flux exit pupil, while at the other end the optic fibre bundle, supplying the luminous flux, is inserted.

(2) The light pen must have ease of operation. A function keyboard (see section 2.4.4.1) is necessary to work with the light pen (e.g. "SCALE feature B" by such and such a factor by pushing function buttons "SCALE" while, by the light pen, feature "B" is selected directly off the screen). However, on the light pen, a simple control switch, the "mode" switch is to be located which is used to indicate whether "class I signals" (graphic information input) or "class II signals" ("pointed to" features requiring processing or erasure) are required. As "class I" signals require only to be detected by the "i_{L1}" level detector, which is always enabled on, no switch is required for this. The "ON" switch position indicates that the following user-pen actions specify locations for processing or erasure. As these locations are detected by the "i_{L2}" level detector, the switch is thus merely to enable the "i_{L2}" Detector on. In the "OFF" position, the "i_{L2}" Detector is inhibited.

This is the only user operated switch on the pen, to differentiate the mode of user signals to be carried out. Several extra optic fibres may channel light from a lamp (say $1\frac{1}{2}$ watts) to illuminate an "i_{L2}" Level Detector "ON" indicator, made of say a red filter glass, indicating the "ON" status of this Level Detector. The user switch thus also enables or inhibits this small indicator lamp.

(3) The luminous flux generated from the pen, a fraction of which is eventually incident on the Vidicon, is a very critical factor. The useful light flux emitted and radiated by the light pen depends on the direction of the pen to the normal of the viewing screen and on the distance of this screen from the pen tip; the pen tip thus requires careful (and even "critical") pen-alignment and tip positioning. This aligning is done "automatically" by two pressure sensitive contacts located near the pen exit pupil. When the contacts are "in contact", the CRT illuminating source is enabled on; otherwise when there is no pen tip pressure or uneven pressure, the CRT luminance is inhibited.

The two contacts are together only if the pen is touching the screen and slightly pressing against it at a normal, or near normal screen incidence: this is because the contacts are placed symmetrically about the pen axis.

Simultaneously when the pen is in this position, the light output at the exit pupil of the pen is at the correct image or focussed plane, with the exit beam being now parallel and of the correct diameter of 0·045" and of correct intensity.

Thus unless the pen is correctly positioned, no output light is generated as the CRT light emitting source is inhibited. The user adjusts the pen contadt until a signal is registered. This "ON" condition may be seen by the user by several extra optic fibres illuminating a green "ON indicator" near the pen tip, which themselves are tapped off the CRT illuminating source.

At any other time, while the pen is in the "ready" position or resting on the console, or approaches the screen,then as no light is emitted, no stray signals or reflections etc due to it, are generated.

(4) Another feature associated with the light pen is the following:

Assume a display feature is to be pointed to, say for erasing. It is then required that as soon as the "i_{L2}" Level Detector has deteoted this signal, the CRT illuminating source area is to be blanked off. Otherwise a cycle of graphic input at that location and its erasure, would continue during the time the pen was located at that spot for the following reason: The "i_{L2}" Level Detector as soon as it detects the signal for erasure, outputs an "Inhibit" signal which blanks the video output signal at that location. As the "i_{L1}" Level detector through which all Video Signals pass, has a slight delay of some 0·1us or less introduced with respect to the "i_{L2}" Level Detector, this inhibit signal is merely applied to the output of the "i_{L1}" level detector output (see Fig.71) i.e. the video pulse, corresponding to the required location to be erased, outputted from the "i_{L2}" level Detector, "blanks itself out" by inhibiting the same video pulse when it is output from the "i_{L1}" Level Detector.

No signal at that location is input into the CRT and thus that point in the first CRT-Vidicon cycle is erased.
However the light pen is still located at that position, emitting adequate luminous flux to, at least, be detected by the "i_{L1}" Level Detector which is always enabled, even though the "i_{L2}" Level Detector is enabled. This is effectively the same condition as though new graphic information is being input at that location. Thus at the next (the 2nd) Vidicon-CRT cycle a spot reappears on the CRT which then is detected by the Vidicon and then will be erased again, as the light pen is still in the "erase" mode.
This "erasure - writing in - erasure" cycle will exist for as long as the pen is at that location, and since each erasure-write-in cycle takes 2 frame times (80ms), while at the very best the user time reaction is appreciably greater than his fastest reaction time (about 200ms), at least several such unwanted cycles will be present and the location may not be erased!
Similarly if the location was indicated for further processing, requiring the CPU, the CPU I/O Interface would be in a "receive" mode as long as the "function and erase" switch was enabled, and would receive point coordinates of that indicated location every alternate frame

time interval.

The above undesired situation may be eliminated by using perhaps a reduced illuminating source, controlled by enabling the "mode" switch.

However, it is simpler to use the "i_{L1}" output signal, indicating that the location has been successfully detected, to inhibit the illuminating source (See Fig. 96) The user may keep the pen at the location as long as he likes without causing unwanted "erase-write-in" cycles or tying up the CPU I-O Interface. The green "illuminating source "ON" light, being switched off, indicates to him erasure or location-acceptance for CPU processing has been achieved.

When the pen tip is lifted off to point to some other features, and brought down again to the required location, the illuminating source is enabled on again by the pressure sensitive switch.

Fig. 96 shows a block schematic of the light pen and of the associated subsystem. It is seen that the user has only the "mode-switch" to operate directly if graphic display features need be pointed to or erased.

(5) When "pointing" is required to features not displayed, then the pen subsystem takes 2 frame intervals to perform this function. With the "i_{L2}" Level Detector enabled, the first light pen signal, on a blank location, merely writes-in that point, which is detected by the "i_{L1}"

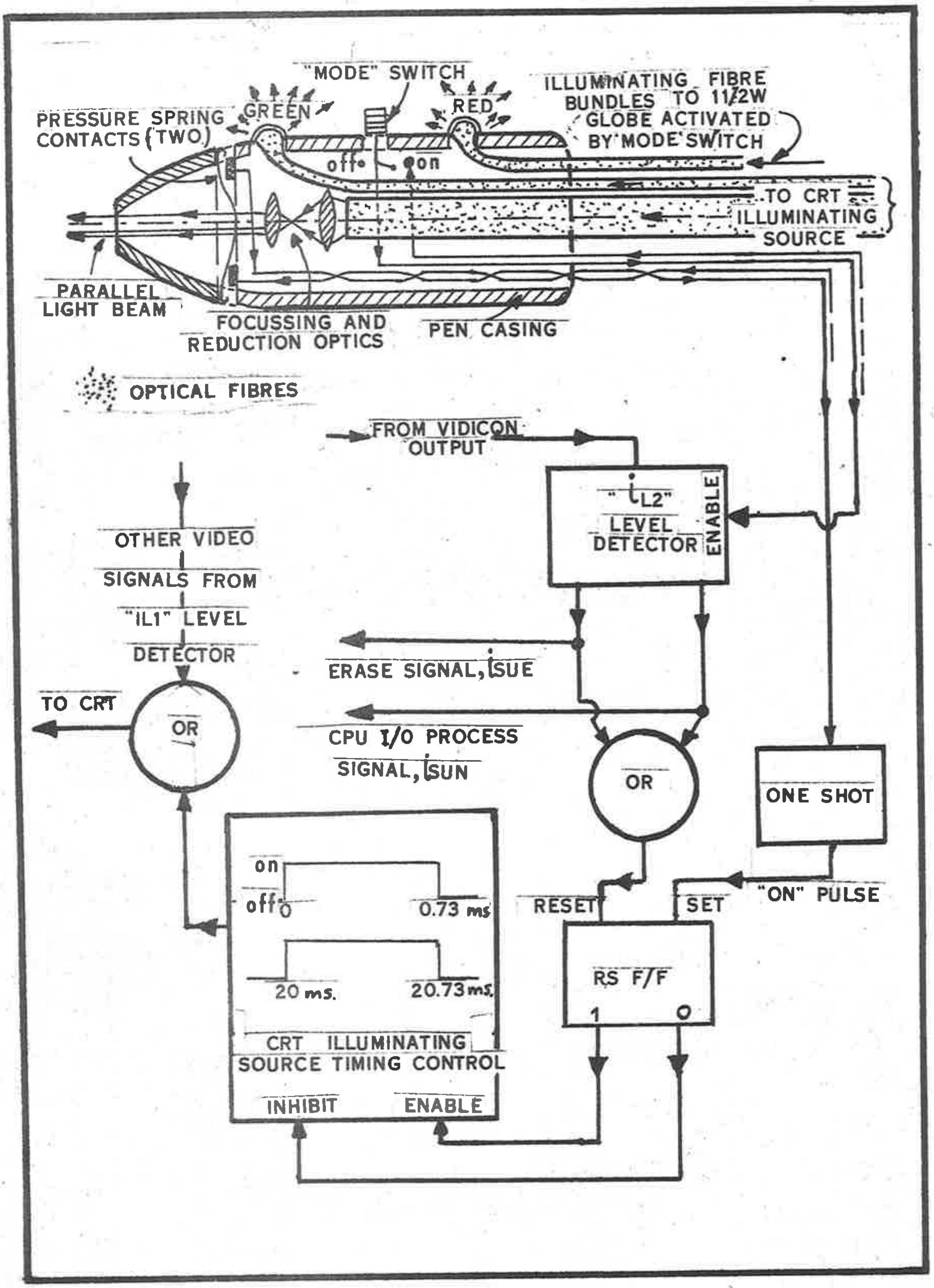


Figure 96. Schematic and Block Diagram of the Light Pen Subsystem.

Detector but is not adequate to be detected by the "i_{L2}" Detector. At the next frame interval the two luminances sum, due to the previous cycle "written in" point and the light-emitting pen, and thence are detected by the "i_{L2}" Detector and the required function is carried out.

.6.7.2 Construction of the Light Pen

Other than the spring loaded two-contact switch, and the user operated ON-OFF "mode-switch", the pen is completely passive.

The writing tip has a small aperture, from which the output luminous flux is emitted. The other end of the pen has the fibre bundle of some 0·2" diameter (which includes a protective outer cover) and the two sets of fibre bundles of some 10-20 fibres each, one bundle illuminating the "mode switch" light (Red) which indicates the "ON"-status of this switch, the other bundle illuminating the (Green) light indicating the "ON"-status of the illuminating source. This green light "ON", means that the pen is properly positioned for operation, and if the "mode switch" is enabled, then, when the green light switches off, it means that the function or erasure for the location indicated has been carried out. Table 3 lists the status of the pen, according to the lights seen by the user. The cable out of the pen, in addition to the fibre optic bundles, also carries the signal leads from the two switches.

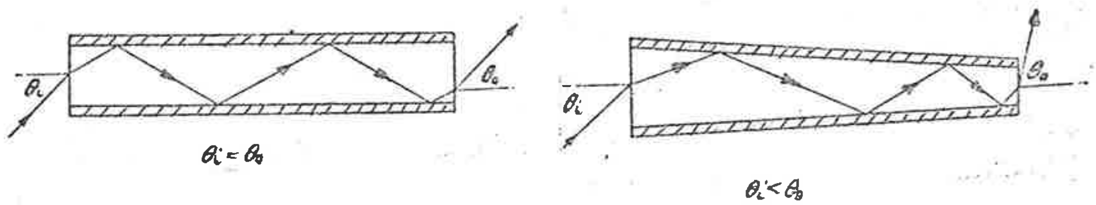
.6.7.3 The Light Pen Optics

The optical fibre bundle carrying the luminous flux from the CRT illuminating source to the exit pupil,

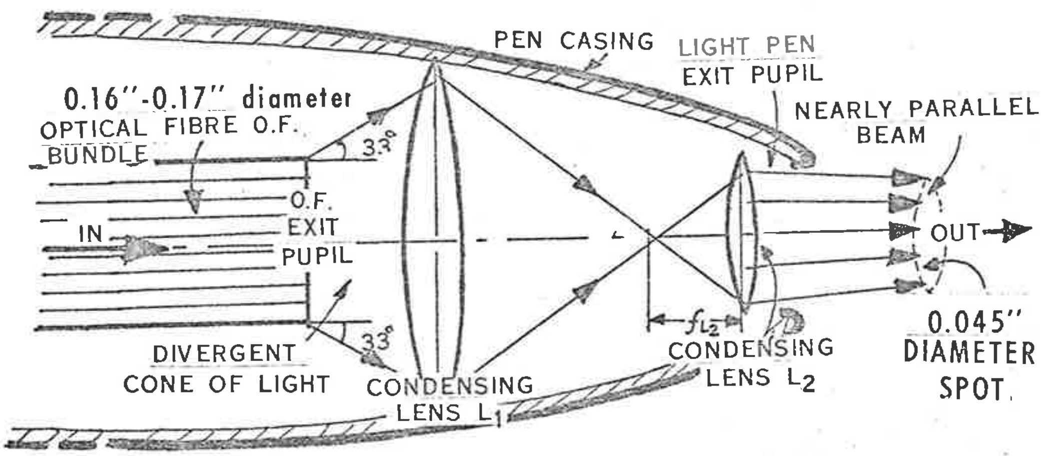
TABLE 3

LIGHT–PEN STATUS LIGHTS INDICATING LIGHT PEN MODE AND FUNCTIONS

RED Status Light	GREEN Status Light	Class of User Signals	Explanation
OFF	OFF	Graphics Input Data $i_{L1} < i_{sout} < i_{L2}$	Pen is inactive or incorrectly positioned on screen.
OFF	ON		Pen correctly positioned and writing-in user-graphic data.
ON	OFF	Pointing to Display Features for further Processing or Erasure $i_{sout} > i_{L2}$	1. Pen incorrectly positioned or 2. if the Green Status light has switched off, Pen subsystem has detected indicated location
ON	ON		Pen correctly positioned immediately prior to detection of indicated location.



(a) Illustrating the reduction in spot size and increase in luminance by using a fibre optic cone.



(b) Light Pen exit pupil 'reduction' optics.

Figure 97. Light Pen Exit Pupil 'Reduction' Optics.

is of some 0·16" diameter active area, and has its luminance emitted in a cone of semi-angle of 33^{o}. (see section 6.6.6.3). This luminous flux is required to be "funnelled" into an area of about 0·045" diameter, with the exit light rays essentially parallel to the light pen axis. This directivity of the light rays is required because the User-Screen Fresnel Lens will than refract these rays along the required direction for projection onto the Schmidt Reflective Optics (see section 6.4.4).

With fibre optics, image size reduction and hence corresponding luminance increase, is achieved very efficiently and economically by using tapered cones of similar construction and material as optical fibres (284), except that the sides rather than being parallel are tapered (see Fig. 97(a). All the light incident on the large cross-sectional area, is available at the reduced end. Thus image reduction occurs with the corresponding increase in luminance. The angle of exit of the rays also increase. However it is stated (284) that "with careful design and construction", cones of reduction of image size by 4-5 can be achieved with brightness increases of 16-25. A lens system must still be used to redirect the light rays direction.

However, because of the possible difficulty in obtaining the required cone dimensions and possible high cost(?) the following two lens system is suggested (Fig. 97(b)). Two convergent lenses are used, in a configuration somewhat analogous to a telescope system where the entry incident rays on the entry lens are parallel and the exit rays are convergent. In our requirement, the entry incident rays are divergent and the exit rays are to be essentially parallel. The primary objective lens "L_1" of very short focal length and large aperture (low F-number) intercepts the rays which are emitted from the fibre optic bundle exit pupil in a semi-cone angle of 33^o. These are thus brought to a real image plane which is at the focus (focal object plane) of the second converging lens "L_2". The image plane of this is at, or near, infinity, and thus the exit rays are essentially parallel or nearly parallel. This is the required condition.

The whole pen is housed in some ball point or pen-type plastic casing.
It features simplicity, low cost, near "automatic" operation,and performs all the required user-graphic display interaction functions.

6.8. RECAPITULATION

6.8.1 Recapitulation of Optics Subsystem and User Input Subsystems.

(1) To enable the user to view the CRT display simultaneously while the Vidicon intercepts a fraction of the CRT emitted luminance, and to enable the user to input graphics information and interact with the display by selecting display features for further processing or erasure, an optics subsystem is required. Further, a real image of the CRT display must be available on a screen to enable the above two functions to be performed.

(2) The RCA Schmidt TV Projection Optical System is the system chosen. It has several advantages over other systems:

(i) A very efficient light utilization.

(ii) No interference with the CRT luminance projected on the Vidicon photoconductor target.

(iii) It enables direct user-input information superposition on the CRT screen with no misalignment and hence no registration problems. Simultaneously it allows the CRT screen, which is a Lambert radiator/reflector, to accept this user-generated input information for insertion in the CRT-Vidicon loop.

(iv) Stray reflections and hence the possibility of unwanted signals is negligible.

(v) Such TV projection systems are commercially available at very reasonable cost.

(3) The user-viewing Screen must be capable of bi-directional acceptance and transmission of incident luminous flux. This is compatable with TV Projection Units using rear-projection. The screens available provide light "gain" and the Fresnel Lens provided with the screen optimize both user-viewing and light-pen efficiency when the light pen is held normal to the screen surface.

(5) For the light pen illuminating source, the CRT "dead areas" around the scanned area periphery provide an excellent, high luminance programmable, system-timing-compatable light source. Some 380-390 "CROFON" 0·010" diameter plastic

optical fibres, of a total of 0·16-0·17" diameter are necessary to supply adequate luminous flux to the user light pen from the CRT illuminating light sources. A 6' length optical fibre bundle is required.

(5) The light pen has several desirable features:

(i) screen pressure contact when the light pen is correctly aligned (normal to the screen) enables the light source on and allows pen operation.

(ii) a user "mode switch" enabling the "i_{L2}" Level Detector, to indicate display feature selection for CPU processing or erasure.

(iii) a Feed Back loop between the "i_{L2}" level Detector and the CRT illuminating source which allows for the inhibition of the light source when the "i_{L2}" Detector has detected the appropriate location signal. This eliminates any undesired successive "readin-erase" "oscillations" and does not tie up the CPU I-O Interface unnecessarily, which would otherwise occur.

(iv) "Status lights" to indicate light pen status.

6.8.2 Recapitulation of Chapters 4-5-6

Chapter 6 concludes the feasability study of VIDIOGRAPHIC form the viewpoint of the ability of adequate luminous energy being generated within the short frame-time intervals of 40ms, to enable the system to perform:

(i) display refresh of a whole CRT display within a frame time interval, taking note of the long response times of the photo-currents and "discharge lag" effects in Vidicon tubes.

(ii) and enable new graphic information to be input, either via the CPU I/O interface, which is a relatively trivial matter, or more importantly by the user, using a light emitting pen.

(iii) enable the viewer to observe the CRT display.

These three major requirements have been shown to be quite feasible at no great expense or complex circuitry. Indeed the whole aim of the feasability study is the construction of a very economical, versatile, yet simple-to-use interactive graphics system. It has been shown that VIDIOGRAPHIC certainly does these things.

<u>Chapter 4</u> dealt mainly with the primary source of light energy or flux within the system, available from the CRT, the amount of this flux incident on the photo-conductive target of the Vidicon, and finally the response and ideal signals available at the Vidicon output due to the CRT originating illumination. It was indicated that the "W" phosphor persistance was eminently suitable for this application.

<u>Chapter 5</u> dealt with the real (as distinct from the ideal), signal outputs from the Vidicon due to the electron scanning beam neutralizing the charge buildup

due to photocurrents. A systematic examination of the deviations from ideal conditions occuring in the Vidicon tube were made and the expected magnitude of the deviations were calculated. It was shown that because a Current Level Detector was used at the output to determine whether a valid signal was present or not, the above signal defects due to these deviations could be ignored. The required Vidicon illumination conditions were thus capable of being calculated.

Chapter 6 dealt with the User-VIDEOGRAPHIC interaction - the Display-Viewing sub-system and the Graphics-information Input subsystem. The light quantities required to enable this were calculated and shown to be quite feasible and easily achieved with a TV-Projection Unit and Fibre Optics. The light pen, a very versatile device, requires minimum user activation.

It has thus been shown that VIDICGRAPHIC is feasible from the viewpoint of initiating, maintaining, viewing and interacting with some generated graphic display.

In the following three chapters, the other major requirement, that of CRT and Vidicon display linearity and the maintenance of a steady or static display is discussed.

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CHAPTER 7
DISPLAY DISTORTION : EFFECTS IN "VIDIOGRAPHIC", MEASUREMENT AND DISTORTION INFORMATION STORAGE

7.1 Introduction

7.1.1 Scope of Problem

The feasability of VIDIOGRAPHIC depends on two main requirements being met:

(i) the generation of a detectable signal and the maintenance of this signal in the CRT-Vidicon loop for display refreshing within the short frame intervals of 40ms. This depends on adequate light flux being generated at each required location. The requirement was found to be completely feasible in Chapters 4 - 6.

(ii) the maintenance of a steady display once the display is generated.
It is of no use to have a display which gradually shifts off the viewing area or which expands off the screen or completely disappears after a few frames.
It is the maintenance of a steady display, and the requirements to achieve this that is the concern of this and the following two chapters.

7.1.2 Display Distortion Effects

Geometrical or Display Distortion is present in all optical and electro-optical devices to a lesser or greater degree. It is the presence of such geometrical distortion that causes, in our case, resultant non-steady display, unless some corrective action is taken.

Assume say that only the CRT has some distortion present. Each display location in a TV raster scan is associated with the time interval between the beginning of a frame-time interval (corresponding to the upper left-hand corner of the display area) and the occurence of the video pulse indicating that particular display location. Ideally no distortion implies that the same constant factor between the time interval and the location of the resultant locations, applies for all locations on the display. Distortion implies that some deviation from the ideal or nominal position results when that location appears on the display. This deviation, in what is termed a "good-linearity" display, is of the order of 1% of the display height, say. Thus for a CRT-Vidicon loop, at each successive frame (i.e. every 40ms or 25 times per second), any location is displaced by 1% of the display height from its nominal position; this displaced location is detected by the Vidicon and recirculated back to the CRT, becoming its new nominal position. Again it is displaced by 1% of the display height from its nominal (i.e. previous) location. After several frames, which is still a fraction of a second, appreciable display movement would have occured, with the consequent result that the user would see a transient display and nothing else; all attempts at writing-in of display data, for example, would result in that written-in data disappearing from his view before he has finished writing it in!

Assume that each of the subsystems introducing distortion, that is the CRT, the Vidicon and the Vidicon lens (see below) contribute a 0·01% distortion component in the same direction (such "linear" opto - electronic devices are very rarely met with, and then only in Research Labs).

Each frame time then, a location is displaced by up to 0·03% of the display height. For the display to be displaced by a half of the frame height (i.e. to "half disappear" from view) takes

$$\frac{50}{0\cdot 03} \text{ frames}$$

or

$$\frac{50}{0\cdot 03} \times \frac{1}{25} = 67 \text{ seconds}$$

Clearly even the "best" of available equipment will be totally unsuitable for our purposes of maintaining a steady display.

Even CRTs , Vidicons, etc which at some given instant may be distortion-free, will either with temperature, supply-voltage variations or ageing etc, have distortion introduced, thus precluding steady displays.

Thus wholly "distortion-free" CRT and Vidicons are required with a 1:1 geometrical position relationship between the CRT display and the Vidicon scanned area.

7.1.3 "Permissable" Distortion

The conclusion is that corrections need be carried out on the display locations to relocate them to their nominal locations. The time intervals between each correction need be such, that within this time interval, the drift due to distortion at each location, is to be such, that when repositioned, the display "jitter" on relocation does not cause annoyance to the user.

This 'relocation jitter' which can be tolerated, is of the same order as the tolerable display jitter

mentioned in section 2.2.2.6; this is about 1-2 element sizes, or in a 625 line system, about $\frac{1\cdot 5}{600} \simeq 0\cdot 2\%$ display of height.
Thus there is a tradeoff between

(a) the amount of distortion in the system
(b) the time intervals of correction of the resultant cumulative distortion.

The shortest interval between correction is one frame or 40ms for any given location , and consequently, if this interval is chosen, the largest distortion can be tolerated before correction is required. As high distortion is expected to occur in the cheaper commercially available equipment, and the aim of this thesis is a low-cost economic IGC, the correction interval will be set at a frame time interval of 40ms.

7.1.4 Causes of Distortion

Three separate distortions are recognized in VIDIOGRAPHIC. They are -

(a) distortion in the CRT
(b) distortion due to the Vidicon lens system
(c) distortion in the Vidicon

The Schmidt Optics system makes no direct contribution to the distortion, however distorted the resultant display on the display screen may appear to be. So long as the user, when inputting graphics input information or pointing to features, locates the desired points in correct relation to existing locations, these user-generated locations, when projected back by the Schmidt Optics onto the CRT for reflection again and projection onto the Vidicon photoconductor target, all suffer the same distortions as the locations on the viewing screen, and are thus located in the correct position when incident on the CRT screen.

An indirect contribution to distortion is that, as a "good linear" display is required on the viewing screen, and because the finite size of the object -CRT-screen on the focal plane of the spherical mirror induces some "pincushion distortion, then for a resultant linear display, the actual CRT display is deliberately "barrel"-distorted to compensate for this. Hence as far as the Vidicon is concerned, the CRT display has barrel distortion on the top of its usual distortion.

The types of distortion present, in theory are predictable, and analytically describable. In practice, however, due to manufacturing tolerances, component misalignment, stray fields etc, distortions are non-analytically describable and the distortion at one location does not allow prediction as to the distortion at a neighbouring location. This complicates the problem of distortion correction even more.

7.1.5 Feed-Forward Distortion Correction

Since distortions are deviations from ideal conditions which are known, the correction can be achieved by either of two methods

(i) "Feed/Back"
(ii) "Feed/Forward"

A fundamental problem exists with Feed/Back. In F/B, a portion of the resultant signal is fed back, and generates a difference signal with the oncoming signal, which is then used to modify the oncoming signal to be required condition.Due to delays etc, the correction information thus generated cannot be used on the original signal but on signals some time later. However in our system there is no direct correlation between the distortion at adjacent locations ,and thus an "error signal" between two successive locations would have no meaning, and correction would not result.

This leaves only Feed/Forward correction. "Feed Forward" (FF) implies apriori knowledge of the required corrections at any given location,and hence the storage of these required corrections is needed. Since the distortions at each point are considered unpredictable, correction information must be stored for each location.

Thus a fixed storage capable of being read out at video rates is required. The whole point of the economical advantages of VIDIOGRAPHIC would be lost if the distortion-correction fixed store would be of the same principle and cost as the display refresh store of current interactive display units.
A major problem thus is to obtain a very simple means of storing the correction information and reading it-out at video rates.

The second major problem (actually the first as far as implementing VIDIOGRAPHIC goes) is to obtain this correction information, both for the CRT and the Vidicon (the Vidicon lens and Vidicon tube may be treated as one unit).

This involves the measurement of the display distortion to at least twice the maximum distortion permitted per frame time interval (i.e. to at least 0·1%).

Present day methods of obtaining display distortion are clumsy, expensive and not blessed with accuracy. Computer Display CRT's are recognized to have some degree of distortion and the order of 1% distortion is considered to be of "high linearity". Consequently, present day distortion measurements are not considered to warrant greater precision than about 0·5% distortion.

A simple accurate means of obtaining display distortion was found based on Moire patterns (77). Thus the problem of display distortion, so crucial to the feasability of VIDIOGRAPHIC, rests on two problems:

(i) the measurement of the distortion of the CRT and Vidicon subsystem.

(ii) the correction of the distortion based on this distortion information.

7.2. DISPLAY DISTORTION and EFFECTS

7.2.1 Introduction

Display distortions are introduced in the CRT, in the Vidicon and by the Vidicon lens. Briefly they are:

(i) in the CRT, distortion is introduced by the non-linearities in the scanning waveform, the screen curvature, the deliberate "barrel distortions" to compensate for the "pin-cushion" distortion introduced by the Schmidt Optics, and tube element misalignments and electro-optical aberations. (These are further discussed in Chapter 9).

(ii) in the Vidicon, distortions are due to non-linearities in the scanning waveform, flatness of the Vidicon photoconductive target, tube element misalignments and electro-optical aberrations.

(iii) in the Camera lens, by the usual presence of distortion and other optical aberrations.

The minimization of the above present distortions can be achieved if the major causes of these distortions is analysed and,particularly,if they can be described by analytic expressions in terms of the currents driving the H- and V- deflection coils. Similar analytic expressions but of opposite signs which, when added to the deflecting scanning current waveforms, effectively reduce the distortion to negligible values. The derivation of such analytic distortion expressions is left till Chapter 9.
However the unpredictable distortion due to component misalignment, stray fields etc still may be present even if the predictable distortions are compensated for. It is thus assumed that these small remanent distortions, along with the lens distortions,are still present.

7.2.2 "Display location Transfer" Curves of VIDIOGRAPHIC

The total resultant distortion at any display location and its effect at subsequent frame time intervals can be obtained by three transfer curves linking:

(i) the time position of an input video pulse "x_{CRT-T}" to the CRT with the resultant CRT location "x_{CRT-P}".
This is called the "CRT Time/Position Transfer Curve".

(ii) the CRT screen position " x_{CRT-P}" with the resultant position on the Vidicon photoconductor target as imaged by the Vidicon lens, "x_{V-P}". This is called the "Lens Transfer Curve".

(iii) The Vidicon target location, "x_{V-P}", with the resultant video time pulse output from the Vidicon "x_{V-T}". This is called the "Vidicon Position/Time Transfer Curve".

(iv) Since the Vidicon time video pulse output is fed directly to the CRT input, except for an identical delay time for all video pulses introduced by the "i_{L1}" Level Detector, the transfer curve linking the Vidicon video pulse output with the CRT video pulse input is considered to be distortion free i.e. a line of unity slope. This is called the "Electric Loop Transfer curve".

These transfer curves are drawn in Fig.98.

A complete loop, anti-clockwise in this Fig.98 is equivalent to a circulation of a particular location signal around the CRT-Vidicon loop and hence shows any resultant displacement of a given location, if deviations from non-linearity (i.e. distortion) is present. The final "steady state" position may be found by taking enough loops, until two successive loops are coincident or else until the location runs off the transfer curves.

Two such sets of transfer curves, one for the horizontal coordinates and the other set for the vertical coordinates, and thus for each set of scanning waveforms, are required for both the Vidicon and the CRT.

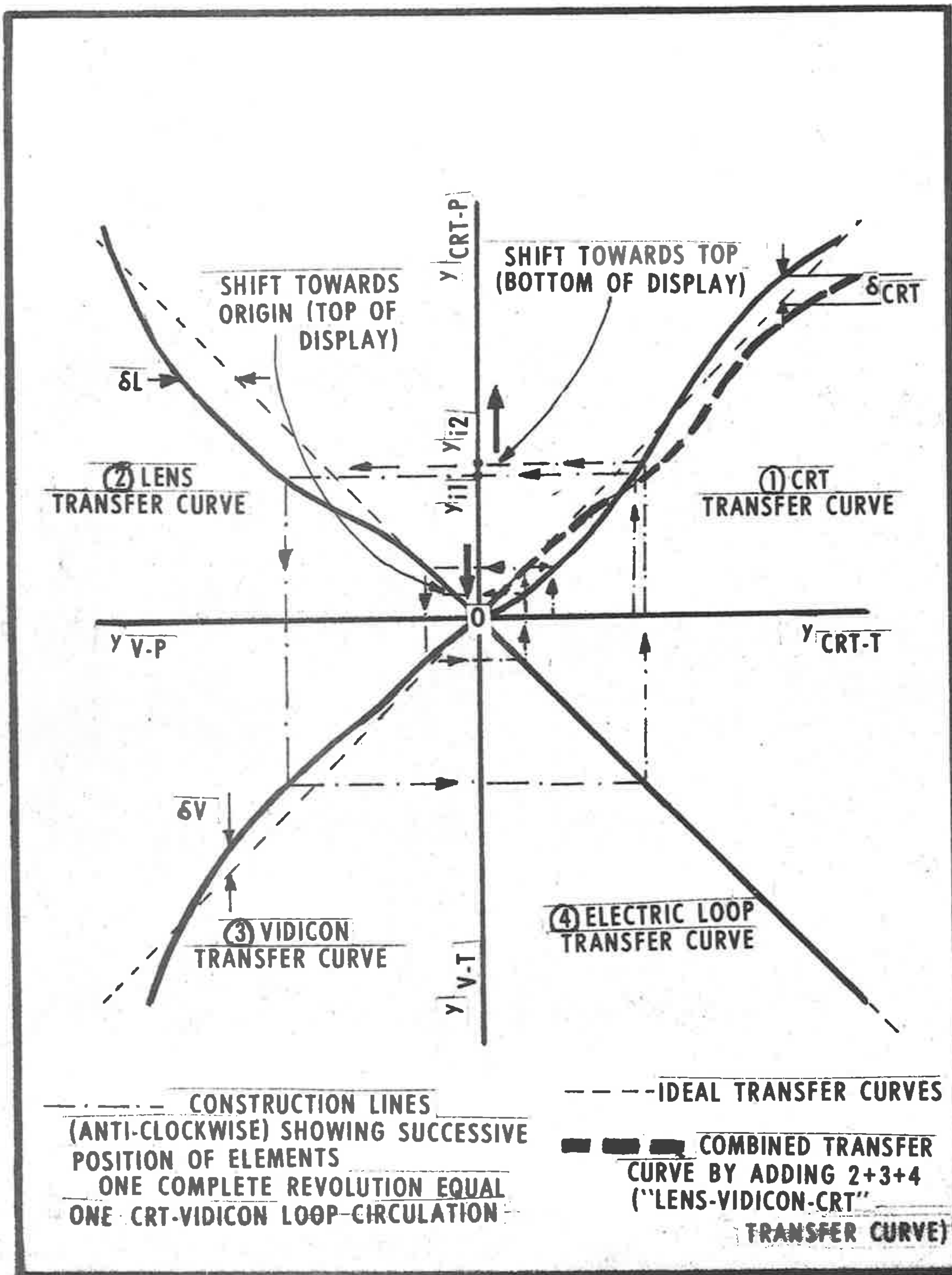


Figure 96. Individual Subsystem and Total System Transfer Curves from which Individual Display Locations Stability may be Determined.

For the example shown, display locations in the upper half of the display (if the T-curves refer to the vertical coordinates) shift upwards while points in lower half, are shifted downward. Thus a display, as represented by the position transfer curves of Fig.98 would gradually "split" into two parts, unless corrective action is taken.

7.2.3 Modified "Display Location Transfer" Curves

The actual effects for various conditions of subsystem non-linearities can be seen more clearly if the separate curves are combined together and located within the same quadrant. It is seen from Fig. 98 that the various transfer curves are related as follows:

(i) for the CRT Time-Position Transfer Curve

$$y_{CRT-P} = y_{CRT-T} + \delta y_{CRT} \quad \ldots\ldots\ldots 7.1$$

(ii) for the Lens Transfer Curve

$$y_{V-P} = y_{CRT-P} + \delta y_L \quad \ldots\ldots\ldots 7.2$$

(iii) for the Vidicon Position-Time Transfer Curve

$$y_{V-T} = y_{V-P} + \delta y_V \quad \ldots\ldots\ldots 7.3$$

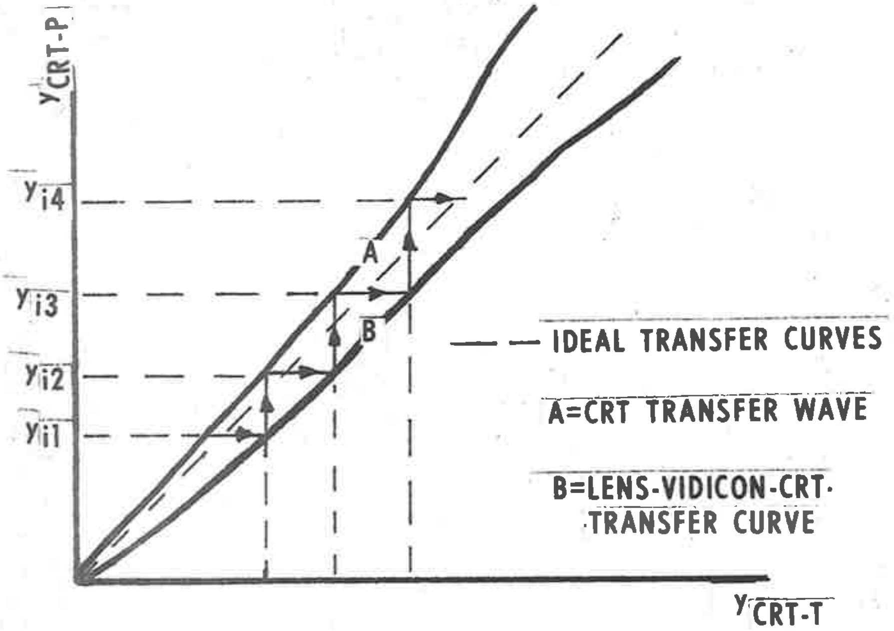
(iv) for the Electric Loop Transfer Curve

$$y_{CRT-T} = y_{V-T} \quad \ldots\ldots\ldots 7.4$$

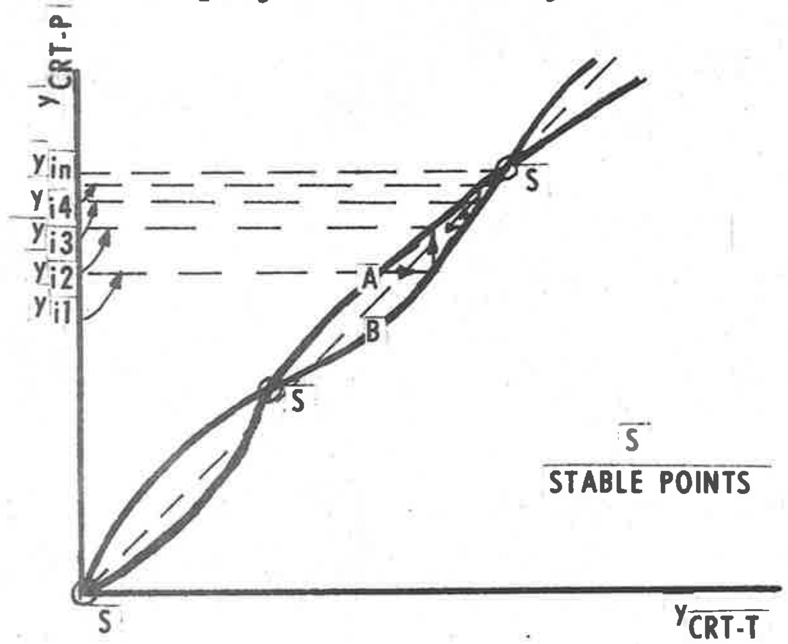
where "δy_{CRT}", "δy_L", δy_V" are the distortions caused by the CRT, lens and Vidicon subsystems respectively.

Clearly after one cycle operating on the above expressions,

$$\left. y_{CRT-P} \right]_{i+1} = \left. y_{CRT-P} \right]_i + \delta y_{CRT} + \delta y_L + \delta y_V \quad \ldots . 7.5$$



(a) Divergent Transfer Curves - all display locations eventually are shifted to the bottom of the display and eventually disappear.



(b) 'Crossing' Transfer Curves- showing 'stable' points where the the curves are coincident.

Figure 99. Examples of Nonlinear Total System Transfer Curves (Vertical y-Coordinate).

where the subscripts "i + 1" and "i" indicate successive frame times. Clearly the term "$\delta y_{CRT} + \delta y_L + \delta y_V$" refer to the total system distortion after one complete Vidicon - CRT cycle.

If expressions 7.2, 7.3, 7.4 are combined to give

$$y_{CRT-T}\Big]_{i+1} = y_{CRT-P}\Big]_{i} + \delta y_L + \delta y_V \quad . \; . \; . \; .7.6$$

and plotted with expression 7.1 in the same first quadrant, the combined "Lens-Vidicon-CRT" transfer curve, "B" results (see Figs.98 and 99).

The successive location of a given point, say "y_i", merely follows the "staircase" between the two curves, and thus at a glance the expected effect of system distortions on the graphic display can be predicted. Several such possibilities are shown in Fig.99. Fig.99(a) shows a graphic display moving to the bottom of the display area within four or five frame time intervals. Thus in the "steady state", there will be no display visible.

Figure 99(b), shows the two transfer curves "crossing" at several locations. These are called "stable points" and correspond to locations where graphic data "accumulates"; this may be either data written in at these locations, or else data shifted from other locations.

It is clear that if each display location had its own "stable point" associated with it, the data locations, once inserted into the CRT-Vidicon, would remain at their original locations

Each location having its own "stable point", of course is equivalent to saying that the two transfer curves are coincident at all times, and this of course is an almost unattainable condition.

The only other alternative is to generate these stable points. The number of stable points generated is equal to the number of "steady-state" display locations per horizontal or vertical coordinate; the total number of display locations is equal to the product of the horizontal and vertical stable points.
The generation of stable points is achieved by altering the "Electric Loop Transfer curve (see Fig.98), by selectively delaying or advancing the time position of these locations. The resultant transfer curve instead of being linear as normally, now becomes non-linear and discontinous. When this transfer curve is combined into the "Lens-Vidicon-CRT" Transfer Curve, the latter "straddles" or crosses the CRT Transfer Curve a number of times, equal to the required number of locations. This is further discussed in section 7.4.

The information required to provide this time-advance or time-retardation information for correction must first be obtained. This is obtained from measuring the remanent distortion of each subsystem, namely that of the CRT and that of the Lens-Vidicon system.

7.3. MEASUREMENT of DISPLAY DISTORTION

7.3.1 Display Distortion Measurement Requirements

In a two dimensional display, each location has two coordinates, the "(x,y)" or horizontal and vertical coordinates, which are generated by two scanning current waveforms, generating orthogonal time-varying deflection fields. Further, two sets of system transfer curves are used, one for the horizontal, the other for the vertical coordinate, and each of these coordinates requires separate correction. Consequently two distortion measurements, one for the horizontal, the other for the vertical coordinate, need be obtained for each of the CRT and the lens-Vidicon subsystems.

7.3.2 Current Methods of Display Distortion Measurement

Present day methods of measuring distortion leave much to be desired. Whatever methods exist are based on standards associated with commercial TV receivers (288). The Society of Information Display has been, for several years, preparing standards with little published results; a Workshop (289) is currently being organized to thrash out these problems and set standards.

Available methods are orientated towards commercial TV receivers. Since up to 10-15% distortions (see the definition of distortion in section 2.2.2.5) are quite common in TV receivers, particularly the vertical distortion in the upper half of the display, while 3-5% are considered to be "very good" linearity, the necessity for highly accurate distortion measurement is not considered to be of demanding importance.

In normal usage, if the distortion or "linearity" is stated "to fall within 2%" or "better than 2%", it means that any given display location is expected to fall within a circle of radius of "0.02H," centered at the nominal location, where "H" is the display height. Indeed, the accepted way of measuring distortion of a TV-type display or CRT is by the RETMA "Ball" chart (see the example, for a "precision" display, shown in (290)). This is a standard pattern, provided on a slide, which is projected by a slide projector onto the screen of the display device under measurement. This projected regular pattern consists of a number of circles, of radii 0·01H and 0·02H, where "H" is the display height. When projected from a certain distance onto the CRT, and centered appropriaely, then an electronic pulse generator generates a series of dots on the CRT, ideally to be located at the centres of these circles. For a distortion-free CRT, the CRT generated spots coincide with the centres of the projected circles. Otherwise, under distortion, they fall within or outside of the circles. Depending on their positions, if they fall within the 0·01H circle, the distortion is, at that location, "better than 1%". If they fall within the annulus bounded by the 0·01H and 0·02H circles, the distortion is "better than 2%", and so on. Linearity controls on the CRT are then adjusted to relocate the CRT spots to within these circles.

The disadvantages are clear:

(i) accuracy expected can be no better than say 0·25%, if the result is photographed and carefully measured.

(ii) there is no separation between the horizontal and vertical distortion components.

(iii) possible sources of errors exists in the pulse generator.

(iv) bulky, and difficult to set up.

(v) expensive test equipment.

Other methods include the comparison of vertical and horizontal linear patterns ("cross-hatch" patterns) generated on the CRT screen, with an ideally identical spaced cross-hatch pattern on a transparency superimposed on the CRT screen. Any deviations "δs", between two corresponding lines on the patterns, that is, between the CRT generated line and the "transparency line", indicates distortion and can be calculated as

$$\text{Distortion,} \quad D\% = \frac{\delta s}{H}$$

With a cross-hatch pattern the two horizontal and vertical components may be separated out. However, the other disadvantages, enumerated for the RETMA chart method still apply to this method. The accuracy is of the same order, i.e. 0·25% or thereabouts for this method.

For Vidicon (or any other TV) cameras, no physical transparency is needed for the method using either a cross-hatch pattern or a RETMA "ball" chart. A "hard copy" of the RETMA chart or standard pattern is placed in front of the camera and scanned by it; the camera video output is combined with the corresponding standard pulse generator which was used to generate the CRT pattern previously. The result is displayed on a CRT - the distortion of the CRT does not influence the resultant display as the comparison (video pulse combination) was done prior to the CRT (288). The accuracy of the results is again of the same order as before.

As the accuracy required in distortion measurement was seen to be of at least 0·1% in both the horizontal and the vertical coordinates, other, more accurate methods need be devised to implement the corrections to enable VIDIOGRAPHIC to be realized.

7.3.3. Distortion Measurements using Moire Patterns

The method devised to deduce the horizontal and

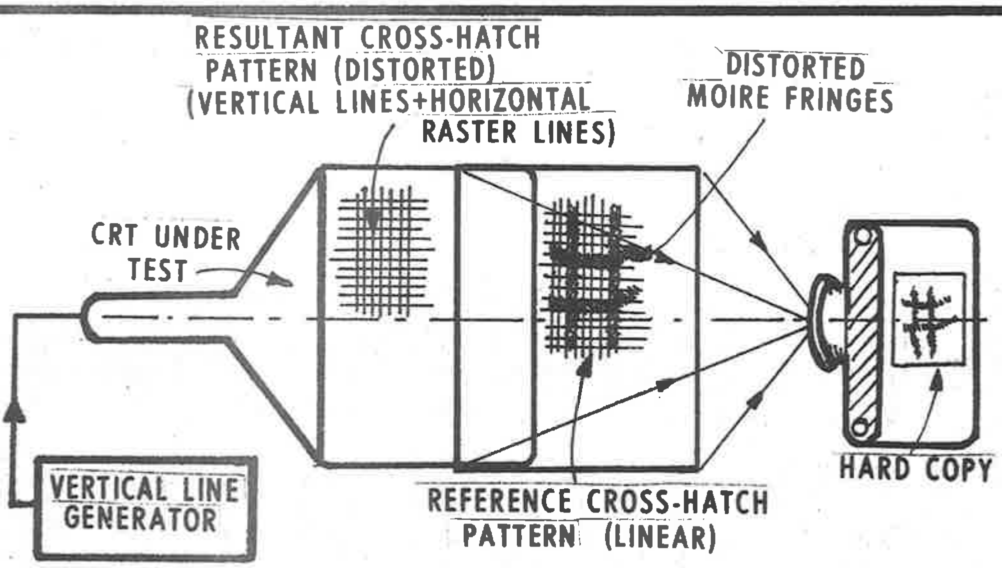
vertical CRT and Vidicon distortions is based on "Moire patterns", or "Moire fringes". (291,292,77)
The method meets the requirements of

(i) ease of measurement
(ii) low cost
(iii) high accuracy - potentially to better than 0·01%.

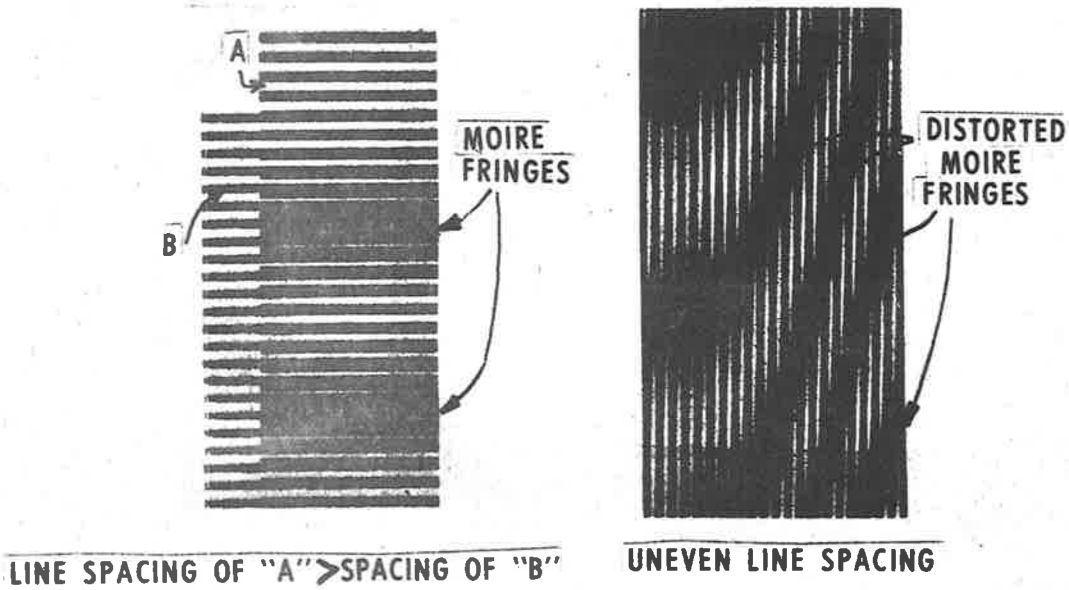
Rather than redescribe the method, theory and results in detail here, a reprint of the paper where this is all described,along with results is attached in Appendix 11.5 together with some more results of direct relevence. Only a very brief outline of the method is given here.

Briefly, Moire fringes occur when two nearly identical patterns of lines are superimposed. If the patterns are identical in all respects, and aligned and superimposed, then the resultant is the same as if only one pattern was viewed. If the two patterns differ, or are misaligned, certain lines overlap and intersect; these overlaps or intersections are seen as darker regions in the resultant pattern and are the "Moire fringes". Two components are thus necessary for the production of Moire fringes. In our method one of the patterns is generated on the CRT (or scanned by the Vidicon), while the other is a "reference transparency", superimposed in front of the CRT under test. If the two patterns are identical, then no Moire fringes result; hence no distortion is produced by the CRT or the Vidicon. Otherwise if Moire fringes occur, then distortion is present.

What makes this method especially attractive for TV-mode displays is the inherent raster line structure of the raster scanning process. This provides the horizontal line pattern component for the CRT generated pattern.



(a) Setup for measuring distortion.



(b) Examples of Moire Fringes. The lines 'A' may represent the horizontal raster lines, while the set 'B' may be the reference pattern.

Figure 100. Display Distortion Measurement by Moire Fringes.

The other pattern component is a vertical "bar" or "line" generator, the result of which is a set of "fine" vertical lines on the CRT. The two combined, form a very "fine" cross-hatch pattern.
An ideal cross-hatch pattern on a transparency is located as near to the CRT screen surface as possible, to eliminate parallax effects. The resultant Moire fringes as seen by observing the CRT screen through this cross-hatch transparency are photographed ("hard copy") and from these photographs the distortion at any point on the CRT is obtained (see Fig.100).
The distortions are obtained from the Moire fringe spacings at the point where distortions is being evaluated. Both the horizontal and vertical distortions are obtained separately from the one hard copy photograph, satisfying the requirement of ease of measurement.

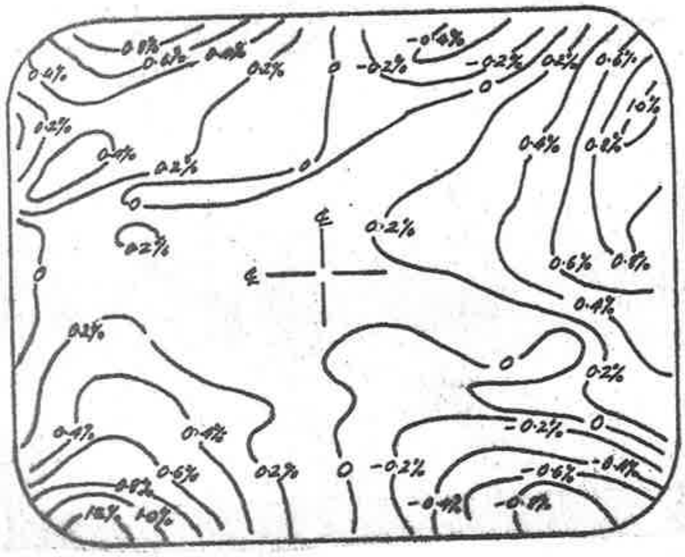
The standard patterns are commercially available patterns on transparencies, very similar to printers' or photographers' "screens" ("screens" are used to break up half-tones images into "dot" structures prior to printing) (293).

An alternate method of finding the horizontal or vertical distortion separately is also given. Both methods have their particular advantages.

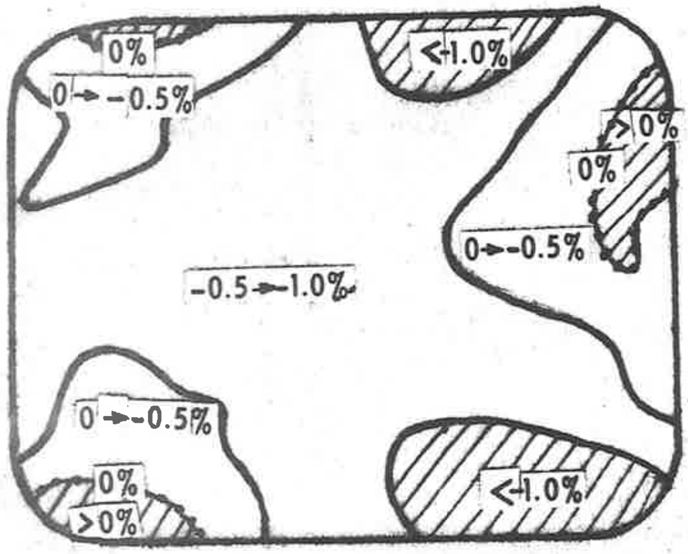
Similar methods are used to obtain the distortions of the Vidicon-lens combination. (see Appendix 11).

7.3.4 CRT and Vidicon Distortion Contour Maps

From such distortion measurements a set of distortion "cross-section" or "profiles" (see Fig.12 in the reprint in Appendix 11) can be drawn across the display area, for each of the horizontal or vertical



(a) Example of 'Distortion contour map' of actual CRT under test - Horizontal distortion.



(b) ~~Above example divided into distortion~~ regions prior to display correction. The distortion 'origin' has been shifted by -0.8% .

Figure 101. Display Distortion Contour Maps.

distortions of the Vidicon or the CRT. Joining the distortion measurement of each sign and magnitude, a "distortion contour map" of the display area can be drawn. Fig.101(a) shows such a distortion contour map for the horizontal distortion for the PYE 14" TV monitor which was available; the contours are in 0·2% distortion increments.

The signs arise because of the unidirection of the scanning or horizontal raster line generation,as each H-line is always generated from the left-hand side of the raster of the area to the right. Similarly the vertical direction of scanning is from top to bottom of the raster. Ideally each horizontal or vertical coordinate is associated with the time interval from the beginning of the horizontal or vertical scan to the instant that point is displayed. Distortion occurs if the instant at which the particular display location under consideration does not correspond to the ideal time interval from the start of the scanning time interval. That "instant" of display location generation can occur before or after its "ideal" instant of generation.

The convention adopted for the signs of the distortion is:

(i) a positive sign on the distortion contour maps means that the display location is generated an instant later, than the instant for "no-distortion". Such a display location signal would need be advanced in time to be located at the correct location.

(ii) a negative sign means that the display location is generated an instant before the instant for "no-distortion". Within such regions signal generation requires a slight time delay to be located at the correct location.

The necessary information for display correction can now be extracted from these distortion contour maps. Regions in which the distortion lies between 0 and -0·5% say, are delineated; this means that display locations within that region need be advanced by an interval from 0secs. to "$0 \cdot 005T_H$" seconds where "T_H" is the time taken to generate the active (or "visible") section of the horizontal line, and in a 625-line system is of the order of 54us. Similarly regions of distortion from 0·5 → 1·0%, -0·5 → -1·0% etc are delineated. The resultant modified distortion map is shown in Fig.101 (a); in this Figure, the "distortion origin" has been shifted by - 0·8% (by adding -0·8% to all contours) to make the distortion negative over most of the display region so that corrections can be implemented by delays, rather than by "time advancing" of the display location pulses.

Four such distortion maps are necessary :

(i) the horizontal and vertical distortion map of the CRT display.

(ii) the horizontal and vertical distortion map of the Vidicon.

7.4 THEORY OF DISTORTION CORRECTION IN "VIDIOGRAPHIC"

7.4.1 Requirements of Display Distortion Corrections

The purpose of system distortion correction is to ensure that display locations are located at identical locations during successive CRT-Vidicon cycles. This, it was indicated above, is identical to the requirement of a certain number of "stable" points or "cross overs" of the two separate CRT and CRT-Vidicon-lens transfer curves, when these are located in the "first quadrant" as in Figs.98 and 99.

An "infinite" number of stable points of course means direct coincidence of the two transfer curves over their whole length (or during the complete scanning time interval), and this is almost impossible to achieve. The requirement is thus reduced to generating as many stable points in the Horizontal or Vertical system transfer curves as there are required display locations per H- or V- coordinate.
If "N_H" is the maximum number of horizontal display location and "N_V" is the maximum number of vertical display locations, then the resulting display available in VIDIOGRAPHIC is positioned on a "point grid" of $N_H \times N_V$ locations. This is exactly the same as in the currently available displays with say a 512 x 512, or 1024 x 1024 addressable locations grid.

<u>The function of the distortion correction circuits is to provide "N_H" stable points in the H-coordinate system transfer curve, and "N_V stable points in the V-coordinate system transfer curve</u>.

For the 625-line TV system, complete ideal transfer curve coincidence implies that $N_V \approx 600$ and $N_H \approx 750$ (Video-bandwidth $\approx 7 \cdot 5$Mhz); since this cannot be achieved in practice, "N_H" and "N_V" are greatly reduced below the above maximum values, resulting in a display grid of some 200 x 200, say. Such a relatively coarse display grid is quite adequate for a working interactive display for which VIDIOGRAPHIC was envisaged for (see chapter 1 - section 1.3.43).

The number of required stable points "N_H" and "N_V" in the horizontal and vertical system transfer curves is thus 200 per H or V- coordinate.

From Fig.99(b) it is seen that stable points can occur even with highly non-linear CRT and CRT - Vidicon-lens transfer curves.
The thought immediately comes to mind that the problem of correction would be partially or wholly solved, if both curves, although by themselves showing considerable distortion, can have this distortion tolerated so long as they are of the same magnitude but of opposite sign to each other. In the "first quadrant" then, these two curves would be near-coincident, partially solving the need for distortion correction.

This arguement is valid if the system was required only to maintain a stable display and refresh it, that is, all of the signals circulating in the CRT-Vidicon-loop would be acted upon by both CRT- and CRT-Vidicon-lens Transfer Curves. However when graphic data is extracted from the electric loop and diverted into the CPU I/O interface, the location coordinates corresponding to the graphic data do not correspond to the locations coordinates as seen on the CRT display, due to the Lens-Vidicon distortion. When these graphic display coordinates are proccessed and reinserted into the system, then due to the differential distortion over the display area, they may appear, when viewed from the CRT screen on the user Viewer screen, to be in the "wrong" display locations. Thus the CRT and lens-Vidicon distortions present may generate, after CPU processing,display errors and display misalignments.

Similarly unless the CRT transfer curve is itself linear, then the CRT display as projected onto the user viewer screen is distorted, and any new user-graphic data input will become "distorted" in the CRT-Vidicon system i.e. a straight line input with the light pen and a "straight edge" will appear curved by the same degree as the CRT distortion is, but in the opposite direction, when redisplayed one CRT-Vidicon Cycle later, causing misalignments and loss of user confidence.

For the same reason, newly inserted graphic data from the CPU I/O interface will appear distorted when displayed in the CRT display; graphics data representing a straight line say, will be distorted by an amount equivalent to the lens-Vidicon distortion, gain giving rise to display defects and loss of user-confidence.

For these reasons the CRT and CRT-Vidicon-Lens transfer curves must themselves be linear.

Since the display is located on a point grid of N_H x N_V locations, any remanent distortions which can be tolerated (as ideal linearity cannot be realized), must be less than half the spacing between the H- or V-locations, so that a location displaced due to this remanent distortion, is still allocated and associated with its nominal location.

Clearly the coarser the display grid, and thus the larger the interlocation spacing, the greater can the remanent distortion be tolerated. Thus a tradeoff, between the display capacity (given by N_H x N_V locations) and the tolerated remanent distortion of the CRT or the lens-Vidicon combination, can be made.

Hence, from this additional viewpoint of correct registration of input graphic data with existing display data, the CRT and Lens-Vidicon Transfer Curves need be made individually linear, such that the remanent distortion "δ_R" within the display area is

$$\left.\begin{array}{l} \delta_R{}^H < \dfrac{1}{2N_H}\ \% \\ \text{and} \quad \delta_R{}^V < \dfrac{1}{2N_V}\ \% \end{array}\right\} \quad \ldots\ldots\ldots 7.7$$

The total requirement for system linearity required of the distortion corrections circuits is as follows:

(i) the number of stable points within the area containing the display is:

(a) N_H = 200 stable points for the H-coordinate system transfer curve.

(b) N_V = 200 stable points for the V-coordinate system transfer curve.

(ii) the CRT must itself have a linear CRT transfer curves, such that any remanent distortion within the display region is

$$\begin{array}{l} \text{CRT} \ldots \delta_R{}^H < \dfrac{1}{2N_H}\ \% \\ \text{CRT} \ldots \delta_R{}^V < \dfrac{1}{2N_V}\ \% \end{array} \quad \ldots\ldots\ldots 7.7(a)$$

(iii) the Vidicon-lens combination must be made linear in the same way as the CRT. Any remanent distortion within the Vidicon display region on its scanned area is such that

$$\begin{array}{l} \text{Vidicon-lens} \ldots \delta_R{}^H < \dfrac{1}{2N_H}\ \% \\ \text{Vidicon-lens} \ldots \delta_R{}^V < \dfrac{1}{2N_V}\ \% \end{array} \quad \ldots 7.7(b)$$

7.4.2 Methods of Distortion Correction

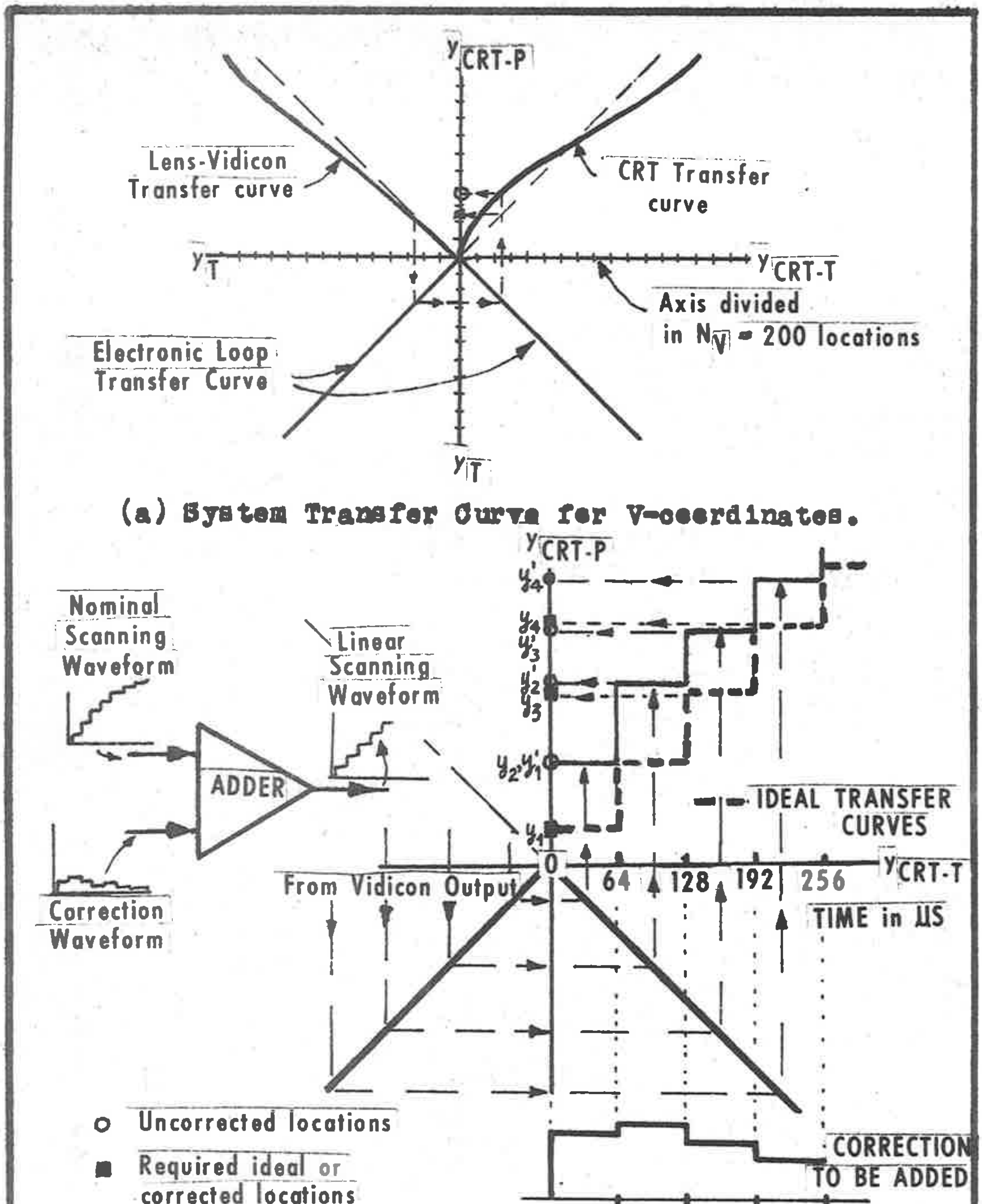
Since these individual requirements are inter-related for either the H- or V- coordinate, then for both the CRT and the CRT-Vidicon-lens Transfer Curves, these requirements can be shown on the total system transfer curves as in Fig.102(a). The CRT-Vidicon-Lens Transfer curve is merely the "sum" of "curve 2" and "curve 3" of Fig.98. These transfer curves are effectively the current scanning waveforms giving the time/current relationship, driving the electron beam-deflection coils in the CRT and the Vidicon.

To re-align the actual distorted transfer curves with the ideal linear transfer curve to obtain the required number of stable points, two approaches can be taken:

(i) the actual slope of the scanning or transfer curves can be piecewise altered at each location or in certain regions to align the curve with the ideal transfer curve, and leaving the time transfer curve unaltered. This is called the "Scanning Waveform Correction Method", (Fig.102).

(ii) the time-transfer curve is piecewise altered, effectively delaying or advancing each time pulse, indicating a display location, while the scanning waveform or the transfer curve is left unaltered. This is called the "Time Delay Correction Method" (Fig.103).
The result is the same for both cases - the location is displayed at a location as if an ideal transfer curve were operating.

Both methods have their advantages and disadvantages and both methods need be implemented, the



(a) System Transfer Curve for V-coordinates.

(b) Illustrating correction (for the CRT) and implementation. The V-coordinate transfer curve is a staircase for both the CRT and the Vidicon.

Figure 102. 'Scanning Waveform Correction' by Analog Derived Correcting Waveforms.

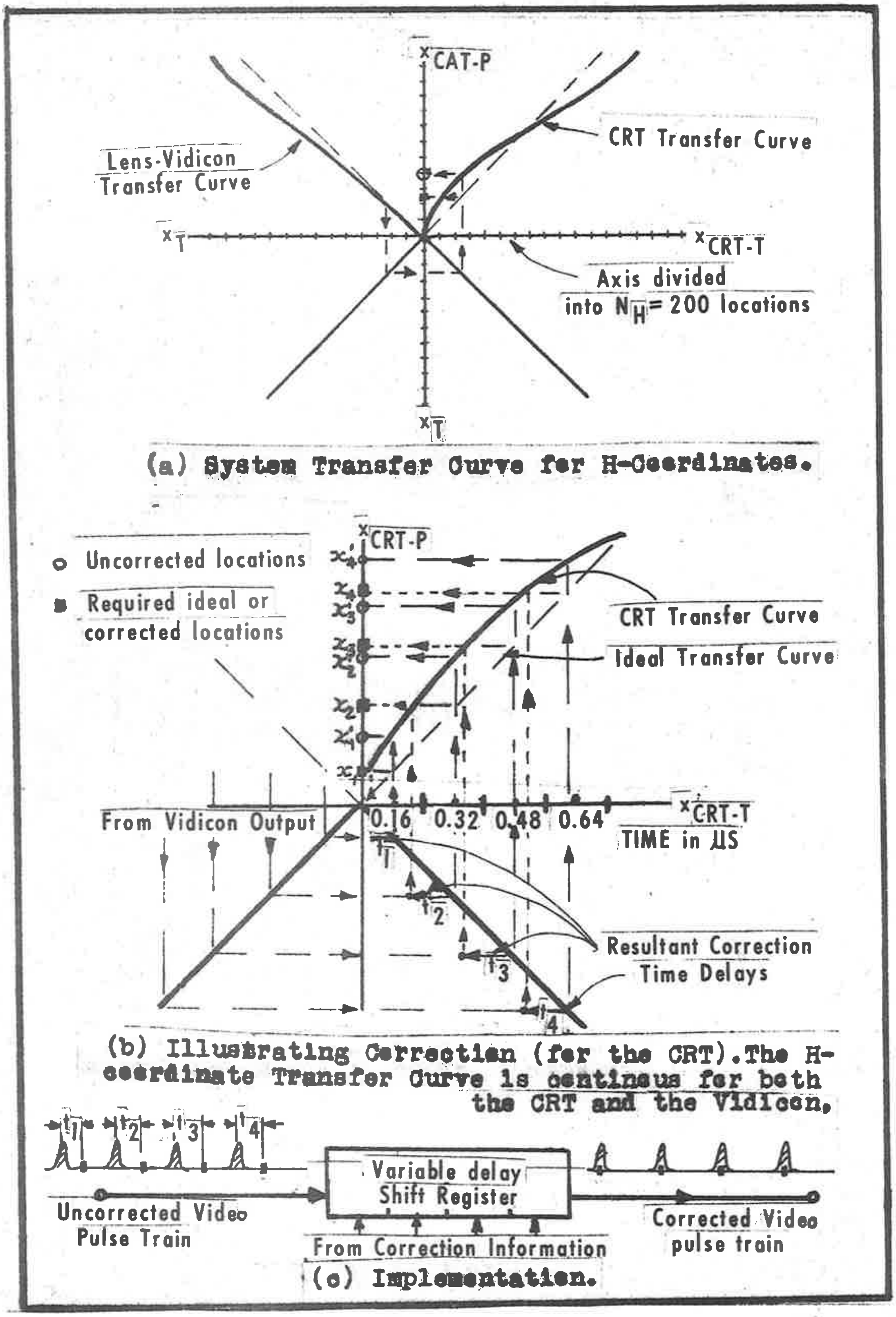


Figure 103. 'Time Delay Correction' by Variable Time Delay Shift Register.

main reason being the different rates at which the horizontal and vertical location coordinates are generated during the linear raster scanning process, and the differing amount of information associated with a change of a horizontal or vertical coordinate.

A horizontal line in the display requires some 54us to be display generated (64us for line interval and 10us for flyback time). For $N_H = 200$, this implies an interval of some 0·3µs for each location (actually 0·16us, see section 7.5.4). Attempting to correct the scanning waveform implies that the correction need be implemented in about $\frac{1}{4}$ or so of this location interval i.e. in some 0·08us. As the inductance of the scanning coil fed by this current scanning waveform is typically of the order of 1mH in both the CRT and the Vidicon, and deflection currents changes of the order of 0·5mA are are associated with each charge in location, certain problems arise when such currents are switched at those speeds of 0·08µs. "Scanning Waveform Correction" is thus out of the question for this reason, for correcting the horizontal subsystem transfer curves.
On the other hand delaying single location-indicating pulses, by a delay of the order of 0·3us pose no problems.

Thus for the horizontal distortion correction the "Time Delay Correction Method" must be used for both the CRT and the Vidicon.

For the vertical coordinate, it must be remembered that a correction of a vertical coordinate means the same correction applied to all horizontal locations associated with that V-coordinate. Attempting to provide variable delays (as in the "time delay" correction method) equally well for up to 200 horizontal locations requires variable delay lines, programmable shift-registers etc, which certainly increases cost.

However, since a Vertical location coordinate changes nominally every 64us (a H-line period) and a inductance of the order of 50mH is associated with the V-deflection coil, the need of switching variable currents of the order of 0·5mA or less poses little problems. In actual fact, a staircase scanning waveform is used, where the number of steps is equal to "N_V". (10µs or thereabouts is available during which the variable step height (due to correction) is generated; this is the horizontal line "fly-back" time).

<u>Hence for the Vertical coordinate correction, the "Scanning Waveform Correction Method" must be used for both the CRT and the Vidicon.</u>

7.4.3 Vidicon and CRT Distortion Correction

7.4.3.1 CRT Distortion Correction

The requirement for the CRT with a linear transfer curve is simply a linear video time-pulse input resulting in a linear point grid display. The time pulse input is either from the CPU I/O interface, or the Vidicon output, of equi-spaced time pulses sychronized by a crystal controlled clock; each clock pulse represents a potential display location. The location of each horizontal line (and hence the vertical coordinate) is determined by some integral number of clock pulses. This clock thus sets the basic timing of the system.

With no correction applied, the resultant CRT display, with the above linear pulse input, is a distorted display given by two distortion maps of the type shown in Fig.101.

The horizontal distortion map provides the selective delay information at each horizontal line location to give the constant separation CRT horizontal locations. Because only time delay of display information is possible and not "time advance", the "origin" of the distortion has been shifted to make the distortion unidirectional over the display area; this has been shown in Fig.101(b). Over most of the area, the distortion is from 0 to 1% implying that at the beginning of each horizontal line (the left-hand side of the display area) the display locations need be delayed by a time interval equal to "$0{\cdot}01T_H$," where $T_H = 54\mu s$, the period of the display portion of the horizontal line interval. At the right-hand side of the display, the distortion being nearly 0%, the time delay required is almost negligible.

Similarly from the vertical distortion map, the information generating the step height of the staircase scanning waveform is derived (see section 7.5.7).

It simplifies the distortion correction requirements if no vertical pincushion or barrel distortion is present, i.e. it is required that any pincushion or barrel distortion is removed prior to this, even, if necessary, at the cost of introducing extra non-linear spacing between the H- lines. The removal of such distortion is quite feasible as barrel or pincushion distortion is analytically predictable at any display location, and hence can be compensated by waveforms of similar analytic description (see sections 9.4). Hence it is assumed that the horizontal display lines are at least parallel to each other over their length, even though their spacing is non-linear.

The resultant CRT display will after the necessary "Time Delay Corrections", for the horizontal coordinates of the location, and "Scanning Waveform Correction", for the vertical coordinates, be linear at all display points.

7.4.3.2 Vidicon Distortion Correction

For the Vidicon, the requirements are nearly identical to those of the CRT. The input is a geometrically linear point-grid imaged onto the photoconductive target. The scanning mechanism, controlled by the scanning waveform, or the "Vidicon Transfer curve", will generate a pulse train, whose pulse time position corresponds to the horizontal coordinate positions of the point grid. With no distortion corrections, the resultant time pulse train, when fed into an ideal distortion-free CRT will appear distorted, with the resultant distortion maps for the H- and V- direction giving the lens-Vidicon distortions.

Again the horizontal distortion map has an origin chosen to make the time delay correction unidirectional.
For the vertical correction, similarly as for the CRT correction requirements, pincushion or barrel distortion need be eliminated, if need be at the cost of increasing the non-linear spacing between the horizontal lines (see section 9.5).

One major difference exists between the CRT and the Vidicon distortion correction. In the CRT, the input time pulse positions and the resultant display locations occur in predictable locations. The vertical staircase scanning waveform contains as many stairs as there are "N_V" coordinates i.e. horizontal display lines. On the Vidicon photoconductor target, display locations can be incident in-between two adjacent horizontal display lines, when graphic data is input manually with the light pen. To be detected by the electron scanning beam, the complete Vidicon display area need be scanned. Thus unlike in the CRT, the electron beam needs to access all the scanned area, and not just the scan lines containing the display.

Thus, analogous to the small horizontal time intervals equal to some $t \approx 0 \cdot 3\ \mu s$, associated with each horizontal display location, there is a vertical "strip" area associated with each display line; for 600 active display lines, and $N_V = 200$, three horizontal raster lines are associated with each display line. Whatever the output detected by the "i_{L1}" or "i_{L2}" Level Detectors in any of these three raster lines, it is associated with the appropriate vertical display coordinate. The vertical scanning waveform has its "stair-height" controlled by the vertical distortion map information.

The resultant Vidicon output will after the necessary "Time Delay Corrections" for the horizontal coordinates and the "Scanning Waveform Corrections" for the vertical coordinates, consist of a constant time interval pulse train, each pulse corresponding to the linear point grid display imaged at its input photoconductive target.

7.5. STORAGE AND FORM OF DISTORTION CORRECTION INFORMATION

7.5.1 Distortion Correction Information Requirements

The storage capacity required for distortion information can be easily calculated.

For commercially available projection CRTs and Vidicon cameras, with pincushion or barrel distortion removed or minimized by appropriate correction waveshapes (see section 9.3,9.4) the remanent distortion prior to correction is of the order of 0·2 - 0·5% of display height (For the CRT H-distortion map shown in Fig.101(a), no pincushions distortion correction was implemented, except for external correction magnets).

For the maximum display capacity in a 625-line TV-system, $N_H \approx 750$ and $N_V \approx 600$, implying that the permissable distortion after correction which can be tolerated is, according to expression 7.7,

$$\delta H \leqslant \frac{1}{2N_H} \leqslant \frac{1}{2.750} = 0{\cdot}067\%$$

$$\delta V \leqslant \frac{1}{2N_V} \leqslant \frac{1}{2.600} = 0{\cdot}083\%$$

"δH" and "δV" can be considered to be the smallest units of distortion correction, implying that they can be used as "distortion correction increments". Thus to correct up to 0·5% remanent distortion prior to correction, requires up to some $n = \frac{0{\cdot}5}{0{\cdot}067} = 7.5$ "distortion units". Thus up to 3 bits of distortion information for each H- and V- coordinate per display element need be supplied. Thus as thereare $N_H.N_V$ display locations, up to

$$N_H N_V . \left(\ln_2 \left(\frac{D_{VCRT}}{\delta V}\right) + \ln_2 \left(\frac{D_{HCRT}}{\delta H}\right) \right) \text{ bits}$$

are required to store display connection information for the CRT, where D_{VCRT}, D_{HCRT} are the display distortions prior to correction. Substituting for "δV" and "δH" from above, and having a similar expression for the Vidicon, the maximum total number of display distortion correction information required is

$$N_H N_V \Big(\ln_2(2N_V . D_{V-CRT}) + \ln_2(2N_V . D_{V-VID}) + \ln_2(2N_H D_{H-CRT}) + \ln_2(2N_H D_{H-VID}) \Big) \text{ bits} \quad \ldots .7.8$$

For the maximum number of display location $N_H N_V \approx 4\cdot 5.10^5$, and for a remanent distortion $D_V, D_H \approx 0\cdot 5\%$,

$\ln(2Nr.D_{V-CRT}) \approx 3$; thus a total number of $4.5.10^5 \times 12 = 5\cdot 5.10^6$ bits is required. These are to be read-out in 12 separate channels (3 bits in parallel for each of the H and V corrections for the CRT and the Vidicon), 25 times per second (the frame rate), implying 12 separate channels with a access and read-out rate at some 10M-bits/sec each.

In practice the above requirements can be relaxed somewhat, as between adjacent locations, display distortion do not vary from 0 to 0·5%, but vary gradually; and, as the locations and hence the distortion correction information are accessed in an order predetermined by the scanning process, information of 1 bit per display location is adequate, determining whether the distortion need be changed by one distortion correction unit or not, and one bit for several locations determining the sign of this increment. Thus only approximately $N_H . N_V$ bits of correction information are required for each H and V-coordinate for the CRT or the Vidicon.

The actual information for display distortion correction "DDG bits" for the above values lies thus between the values:

$$4.4\cdot5.10^5 < D.D.G < 12.\ 4\cdot5.10^5 \text{ bits} \quad \ldots.\ 7.9$$

which still requires a large capacity store capable of being read out at video rates of about 10M-bits per second.

Alternatively for any arbitrary N_H, N_V less than the above maximum value,

$$N_H N_V \begin{Bmatrix} (\ln_2(2N_V.D_{V-CRT}) + \ln_2(2N_V.D_{V-VID}) \\ +\ln_2(2N_H.D_{H-CRT}) + \ln_2(2N_V.D_{V-CRT}) \end{Bmatrix} < D.D.G < 4N_H N_V \quad \ldots\ldots\ 7.10$$

7.5.2 Standard Methods of Distortion Information Storage

To implement the above storage capacity and read-out rate requirements with magnetic core storage is out of the question because :

(i) the required read-out rates of 10M-bit second cannot as yet be achieved with current cores.

(ii) the whole exercise of VIDIOGRAPHIC would be pointless, if magnetic core storage for distortion correction information far exceeds the core storage required, if magnetic core stores were used for display refresh.

Another possible, alternate method of storage is video-tape storage, in which case at least 4 stored frames and a maximum of 12 (for the above values of distortion) frames would need to be scanned simultaneously and in synchronism. Synchronizing problems at the beginning of each run, and during the run, tape wear and hardware cost again would preclude this method.

Other forms of fixed (or "read-only") with fast read-out times exclude themselves because of cost.

Thus some other form of storage is required, simultaneously necessitating some tradeoffs between the amount of distortion information storage required and the nett number of display locations available on the resultant display.

Another objection arises, as to whether the locations by location display distortion can be obtained exactly. Even though the Moire fringes method of measuring distortion can give an accuracy of up to and better than 0·01%, the exact boundary between one amount of distortion present and another is difficult to pinpoin precisely. The display distortion itself is derived from the centre to centre spacing of the resultant Moire fringes; however it is a characteristic of Moire fringes, that as greater accuracy is required and the smaller the distortions being measured, the width of the Moire fringes increases, making it difficult to precisely locate the centre of a fringe, particularly when the fringe is non-linear (see Figure 100(b), for example). Thus to be able to precisely locate locations where distortion measurement accuracy is better than 0·067% ($\delta H = \frac{1}{2N_H}$), is rather hopeful. One can only say that within such and such a region, distortion is better or worse than a certain value, accurate to 0·06% say, but without specifying individual locations too accurately.

This, and the above storage requirements for the maximum number of display locations, make it necessary for the number of display locations to be reduced below the ideal maximum capacity of $N_H \approx 750$ and $N_V \approx 600$ to the

200 x 200 locations grid display, say.

7.5.3 Display Distortion Storage by Graphical Means

It has been established that as exact display distortion for each individual location cannot be obtained exactly and because of the difficulties and cost in storing and reading-out such distortion information even if it were available, reduction in the number of display location is necessary. The resultant reduction in storage information, as can be seen from expression 7.8, is greater than a simple linear proportional reduction in the number of display locations.

It is the logical policy when reducing the number of display location, to eliminate them from the areas where the display distortion is the greatest. As the distortion increases away from the central axis of the display area (see section 9.3-9.5), these peripheral areas of the display area thus can be the first to be eliminated from display purposes.
<u>However, these peripheral areas can be used to store the distortion information in graphical form (and thus in analogue form) which may be read-out at the required video rates (imaged onto the Vidicon photoconductive target and read-out by the Vidicon scanning electron beam</u>).

It will be seen that this graphical form of distortion information is nothing more than a highly "compressed" form of the display distortion maps as shown in Fig.101. The lines forming these distortion maps define intervals, corresponding to certain intervals on the actual display area, within which certain corrections need be carried out, such as defining the interval within which each incoming video pulse, representing a horizontal display location, need be retarded by a certain time delay say, of length corresponding to the interval between two display locations; or else defining a time interval proportional to the step height of the vertical staircase scanning waveshape. The information defined by the intervals between the lines is thus in analogue form and the correction will thus be primarily by analog circuits; non-linearities are thus easily accomodated for.

The two side peripheral areas, on either side of the central display area, can be used to store this information correction, the right hand peripheral area storing the CRT distortion information, while the left-hand peripheral area storing the Vidicon distortion information.

The two remaining peripheral areas, top and bottom of the central display area are used partially for the light pen illumination source (a thin strip at the top of some 3-4% of display height), with the corresponding section on the Vidicon scanned area blocked off, while the remainder of the two top and bottom areas can be divided up into an electronic "light button" keyboard (see section 1.3.3.2) and "cue" function light keys, used in conjunction with a light pen. Fig.105 shows the division of the display area into functional areas.

7.5.4 Requirements of Graphical Information Storage

Assume that N_V = 200 and N_H = 200 (reduced from the ideal maximum values of N_V = 600, N_H = 750). Let the "N_V" locations occupy the central $\frac{2}{3}$ of the display height, while "N_H" occupies the central 60% of the display width. On the RCA 18" x 24" display screen, the active display area corresponding to N_V x N_H becomes 12" x 14.4".

In $\frac{2}{3}$ of a display height containing 600 active display lines, there are 400 lines, and thus for $N_V = 200$ there are 2 active raster lines, one in each interlaced field associated with each display line "N_V"!
For a "54µs" long active display line, and if in 60% line length there are $N_H = 200$ locations, then a time interval of

$$\frac{0{\cdot}6 \times 54}{200} \approx 0{\cdot}16\mu s.$$

is associated with each horizontal location. A "usual" display location, on the other hand, has a time interval of some 0·08 - 0·1µs associated with it.

If over the total display area the remanent distortion prior to correction is 0·3 - 0·5% of the display height (the values are taken for the sake of arguement), then approximately, over that central "active" display area, it is some 0·2 - 0·3% of the display height. If "L_V" and "L_H" are the actual "active" display area dimensions, then in terms of display height "H",

$$\left.\begin{aligned} L_V &= \tfrac{2}{3} H &&= 0{\cdot}67H \\ \text{and} \quad L_H &= \tfrac{4}{3} \times 0{\cdot}6H &&= 0{\cdot}8H \end{aligned}\right\} \quad \ldots\ldots 7.11$$

implying the distortion in terms of active display dimensions "L_V" and "L_H" rather than full display height "H" are

$$\left.\begin{aligned} D_V &= \frac{0{\cdot}003H}{0{\cdot}67H} \leqslant 0{\cdot}45\% \\ D_H &= \frac{0{\cdot}003H}{0{\cdot}8H} \leqslant 0{\cdot}36\% \end{aligned}\right\} \quad \ldots\ldots 7.12$$

From expression 7.7, the allowable remanent distortions are respectively

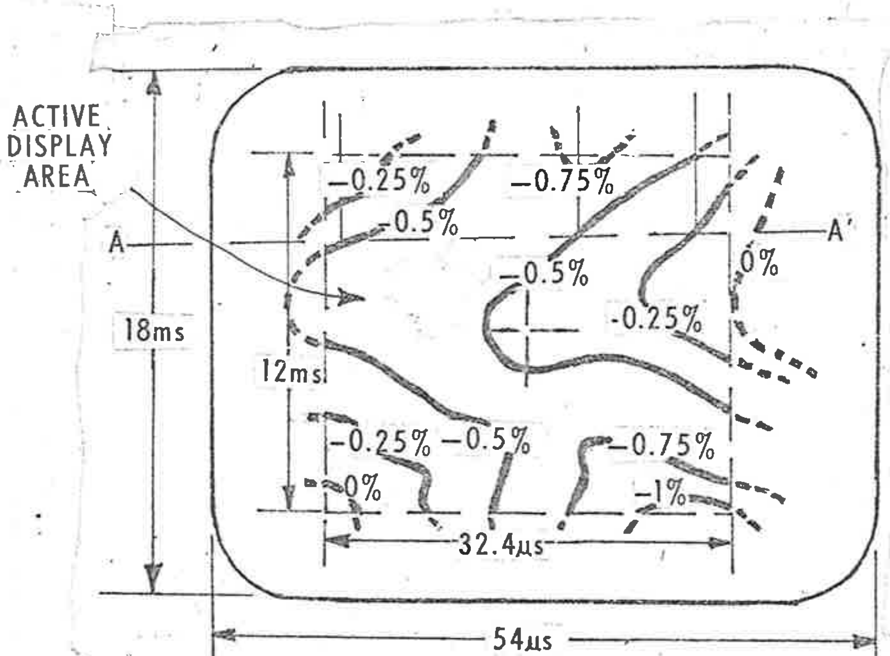
$$\left.\begin{aligned} \delta V &= \frac{1}{2.N_V} = \frac{1}{2.200} = 0{\cdot}25\% \\ \text{and} \quad \delta H &= \frac{1}{2.N_H} = \frac{1}{2.200} = 0{\cdot}25\% \end{aligned}\right\} \quad \ldots. 7.13$$

Thus the correction circuitry from the stored display distortion correction information must be capable of correcting a maximum V-Coordinate distortion of some 0·45% to better than 0·25%, and a maximum H-coordinate distortion of some 0·36% to better than 0·25%. The minimum "distortion correction increment" can be taken thus as 0·25%, implying that for both H- and V- distortion correction, a correction by at most, 2 such units is necessary. This is of course for the values chosen of 0·3-0·5% distortion correction, used only to illustrate this.

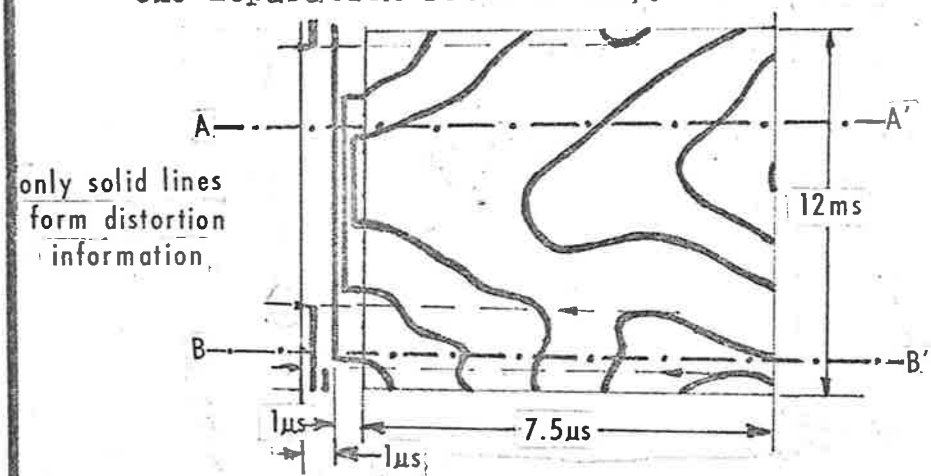
7.5.5 Horizontal Correction Graphical Storage

The CRT and the Vidicon Horizontal Distortion Map as obtained from Moire Fringes measurement requires the "distortion origin" changed so that at either the left-hand or right-hand edge of the active display area (depending on the actual distortion), the necessary distortion correction is zero, while at all the other display locations, correction can be implemented by a variable time delay. The distortion, obtained as a percent distortion of full display height "H," is rescaled to express it as percent distortion of the new active display area dimensions "L_V", "L_H", as per expression 7.12. New distortion contours in "δH" units are redrawn. This is shown in Fig.104(a) corresponding to the contours shown in Fig.101(a).

Ideally for the case where a H-distortion prior to correction is given by 0·36% (expression 7.12), two correction regions are only necessary from 0 to 0·25% and from 0·25% to 0·36%. As the active display area corresponds to 54 x 0·6 = 32·4μs, then 0·25% of 32·4μs corresponds to a delay of 0·081us.



(a) The distortion contours in the central det-ted area have the distortion contour at the R.H.-edge set to 0%.(corresponding to the 0.5% contour in Figure 101(a). The distortion contours are then rescaled as explained in section 7.5.4 such that the separation between contours here is equal to the separation between 0.2% contours in Figure 101.



(b) The graphical form of distortion information. The same map as above but compressed for display by 4:1.L.H.edge lines are for correction control.

Figure 104. Derivation and Form of Stored Information in Graphical Form.

However because pincusion or barrel distortion, particularly in the vertical direction, must be removed at even the cost of introducing extra Horizontal distortion (say by means of external magnets (see section 9.4), the actual correction regions may, for a total distortion of up to 0·36%, vary from 0% to 0% correction at both edges of the active display area, and yet require correction delays of up to 0·081us in certain central regions of the active display area; thus three correction regions may be present in this case. The H-distortion of Fig.101 is redrawn in Fig.104 showing the rescaled distortion contours, and the method of drawing the corresponding distortion map which is to be used directly as the distortion information, and located in the peripheral areas reserved for this graphic distortion information.

Several features of these redrawn graphic distortion maps must be mentioned:

(i) One such map is located in the Right-hand peripheral area, which provides the horizontal distortion correction for the CRT, and another such map is located in the Left-hand peripheral area providing the distortion correction for the Vidicon.

(ii) the height of such a distortion correction map is identical to the height of the remaining active display area. The top and bottom edges of the map align with the top and bottom edges of the active display area also.

(iii) the greater the remanent distortion prior to correction, the greater is the number of distortion contours on each distortion correction map for a given minimum distortion correction unit "δH."

(iv) the full width of the distortion correction map represents the full width of the active display area. The contour spacing in the map directly corresponds to the areas on the display area where a certain correction is required.

(v) each distortion map contains all of the boundaries for each distortion correction region, even if these need be drawn-in or "closed" outside the area corresponding to the active display area. Thus at each scan line, the same number of lines, (although differently spaced) will be detected.

(vi) Each successive pair of video pulses, corresponding to each pair of these detected lines, can control Monostables which define the corresponding regions in the active display area, when the electron beam scans the active display area, where the required delays of up to 0·081µs are required to be implemented.

The following chapter describes the circuits more fully and how the display correction curves are used. Chapter 8 contains further details of H-distortion information interpretation.

7.5.6 Dimensions of Graphics Storage area.

20% or 10·8us of the active horizontal line length is available for storing the CRT distortion information and another 10·8us is available for the Vidicon distortion information.

About "9.5us" of this is required for storing a distortion map containing the 6 distortion contours, any successive pair specifying a region where correction of up to 0·25% need be carried out. "7·5us" of this is used for the actual display area correction data, the other "1us" for the distortion contours drawn outside the area boundaries to complete the contours, with the remaining "1 us" for up to 3 additional lines (see section 7.6).

On a 4" x 3" CRT display area, "7·5us" corresponds to $\frac{7 \cdot 5}{54} \cdot 4 = 0 \cdot 55"$.

Now each distortion contour can be located with a precision of, in the worst case, of ± 0·005" (particularly if photographic reduction is used). The percent positioning accuracy is thus

$$\frac{\pm\ 0 \cdot 005}{0 \cdot 55} \approx \pm\ 0 \cdot 9\%$$

which corresponds to a delineation of correction boundaries in the active display area of also ± 0·9% or about ± 1·8 locations. This makes little difference to the overall results.

The "thickness" of the lines, if made 0·01" correspond to approximately $\frac{54}{4 \times 100} = 0 \cdot 135$us, which is adequate as a nominal spot size is usually 0·005" (600 lines in 3")

7.5.7 Vertical Correction Graphical Storage

To correct for the vertical distortion, only one distortion "curve" is necessary for each of the CRT and Vidicon vertical scanning waveforms. It is assumed that pincushion or barrel distortion has been removed leaving all of the horizontal display lines parallel, but not necessarily equispaced. Thus if a distortion "profile" is taken through any vertical line across the display, this distortion or "distortion trace" is identical for all such vertical lines; call this distortion trace "fV. Any distortion correction applied to any horizontal display line shifts each location within that line by the same amount.

The resultant distortion correction line is a single line drawn in the vertical direction, closely adjacent to one of the R-H or L-H edges of the display, at a maximum distance equivalent to 1us from the display edge and thus from the horizontal blanking interval; for a 4" x 3" CRT display, 1us corresponds to about 0·075". As explained below, the distortion correction line, one each for the Vidicon and for the CRT, is derived from the above mentioned "distortion trace" and defines a time interval, between the adjacent edge of the display (and hence the H-blanking interval edge) and itself, which is then made proportional to the correction required to make the display linear in the vertical direction. As such a correction line is detected each H-line interval (due to the raster scan), the resultant correction is applied also to each H-line, or to all points with the same vertical coordinate.

Ideally for a staircase scanning waveform where the resulting screen position (either on the photo-conductive target or the CRT screen) is incremented by some "Δy", the distance between adjacent vertical lines, for a scanning current increment "ΔI", it is required that

$$\Delta y = K \, \Delta I \quad \ldots\ldots\ldots\ldots 7.14$$

and for any given "nth-line" from the start of the scan ("n counts from the top of the display),ideal linearity conditions require that

$$y = n\Delta y = Kn\Delta I \quad \ldots\ldots\ldots 7.14(a)$$

In practice due to distortion, the "nth" line vertical position is displaced by some "ΔY", resulting in

$$y' = y - \Delta Y \quad \ldots\ldots\ldots\ldots 7.15$$

$$= n\Delta y - \sum_{i}^{n} \delta y_i$$

$$= Kn\Delta I \quad \ldots\ldots\ldots\ldots\ldots 7.15(a)$$

"ΔY" is due to accumulated line displacements "δy" from their ideal locations. This cumulative displacement is apparent as the resultant distortion as a percent of total display height, obtained from Moire pattern distortion measurement; this is the distortion trace "fV".

As $$fV(n) = \frac{\Delta Y(n)}{Y}$$

where "Y" is the display height, "$fV(n)$" is the distortion at the "nth" horizontal line, and "$\Delta Y(n)$" is the accumulated distortion at the "nth" line.

What is required, is from expression 7.15, 7.15(a),

$$y = Kn\Delta I + \sum_{i}^{n} \delta y_i$$

$$= Kn\Delta I + K\sum_{i}^{n} \delta I \quad \ldots\ldots\ldots 7.16$$

where "δI" is the individual line correction current. As "n", the line number varies from 0 to 200, the summation can be replaced by the integral

i.e. $$\sum_{1}^{n} \delta I_i \Longleftrightarrow \int_{0}^{n} \delta I.dn \quad \ldots\ldots\ldots 7.17$$

As $$\Delta Y(n) = fV(n).Y = K\sum_{i}^{n} \delta I_i = K\int_{0}^{n} \delta I.dn$$

then $$K\delta I = Y.f'V(n) \quad \ldots\ldots\ldots 7.8$$

where "$f'V(n)$" is the derivative of the distortion trace w.r to "n" and can be obtained graphically from "$fV(n)$". Hence the distortion correction current required to be added to each nominal current increment "ΔI" is determined by the slope of the vertical distortion trace.

Although the remanent distortion is usually non-analytically describable, a reasonable assumption (see section 9.4), is a distortion "$fV(n)$" with a parabolic distribution; thus

$$fV(n) = ay^2(n) \quad \ldots \ldots \ldots \ldots \quad 7.19$$

For a remanent distortion of about 0·45%, occuring at the extreme display edges where $y(n) = 100\Delta y$ and

$$a = 0{\cdot}45.10^{-2} \,.\, 10^{-4}.(\Delta y)^{-2}$$

thus

$$f'V(n) = 2a.y(n).\Delta y \quad \ldots \ldots \ldots \ldots \quad 7.20$$

as the differentiation is only with respect to "n" and not to "$n\Delta y$"; and hence

$$K\delta I = 2a\,y(n)Y.\Delta y \quad \ldots \ldots \ldots \ldots \quad 7.21$$

and substituting $y(n) = 100\,\Delta y$ and $Y = 200\,\Delta y$, $a = 0{\cdot}45.10^{-6}(\Delta y)^{-2}$.

results in

$$K\delta I = 1{\cdot}8.10^{-2}\Delta y$$
$$= 1{\cdot}8.10^{-2}\,K\Delta I \quad \ldots \ldots \ldots \quad 7.21(a)$$

i.e.

$$\delta I = 1{\cdot}8.10^{-2}\Delta I \quad \ldots \ldots \ldots \ldots \quad 7.22$$

implying that the maximum correction required is equal to 1·8% of the current increment generating a step in the current scanning staircase waveform.

Thus the variable interval or separation between the vertical correction information line and the end of the horizontal blanking pulse may be made proportional to this required "δI."

If this maximum line separation is made equivalent to 1us, and if the line can be located to ± 0·005", then as 1μs corresponds to $\frac{4}{54}$ inches on a 4" x 3" CRT, and 1μs is to accomodate up to say 2% correction (1·8% actually), the correction accuracy per vertical coordinate is

$$\pm 0{\cdot}005 \div \frac{4}{54} \times 2\% = \pm 0{\cdot}14\%.$$

For this distortion to become apparent, the complete distortion correction curve must be mislocated with the above error, as the resulting total horizontal line displacement is due to the cumulative line mislocations. Any errors in locating the distortion curve, would in practice be distributed about its ideal location, reducing any total horizontal line displacement. Even in the worst case, of the distortion line being displaced, the above resulting error is still acceptable within the limits as given by expression 7.13.

A similar set of distortion correction lines is provided in the R-H peripheral area for the CRT correction with the vertical correction line now specifying an interval between its occurence and the beginning of the horizontal blanking pulse. The information in any scanning line is used to correct the CRT in the following scanning line.

A typical video signal for one H-line, circulating between the Vidicon and the CRT in the "electric loop," with an explanation of the significance of the Video pulses is shown in Fig.105.

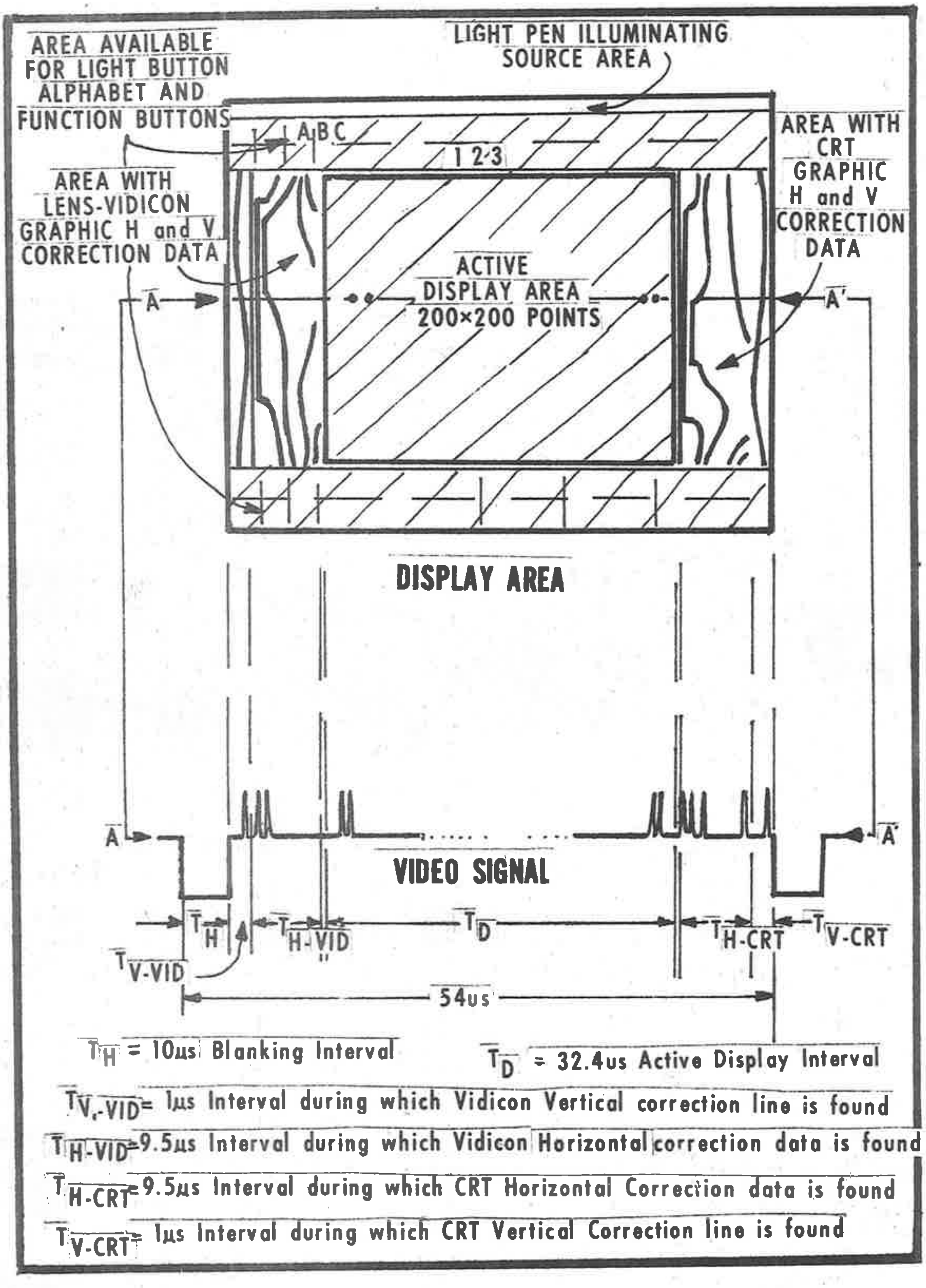


Figure 105. Functional Layout of Scanned Area of VIDIOGRAPHIC with Resulting Video Signals.

7.5.7 Physical Implementation of Graphic Storage.

This graphic correction information may be drawn large scale, and photographically reduced with the resultant photo-negative being the correct form i.e. transparent correction lines on a black opaque background. The two sections, one for the CRT, one for the Vidicon are then affixed on the appropriate CRT display screen location, shown in Fig.105. The CRT luminance can be enabled on beneath these areas so that more than adequate luminance is available to indicate this correction information for detection and imaging onto the Vidicon photoconductive target. At each horizontal scanning line, a "cut" of this correction information is detected and output from the Vidicon, and channelled to the appropriate correction circuitry (see Fig.105).

Since the areas of the Vidicon where this information is imaged on is itself not corrected (other than to the remanent distortion prior to correction), it may be thought that extra unwanted distortions are re-introduced into the system. These inserted distortions are in fact negligible. Even allowing for the fact that the full 0·5% remanent distortion appears across the distortion correction storage area, of some ~7·5μs width, giving an effective distortion there of $0{\cdot}5\% \times \frac{54}{7{\cdot}5} \approx 3{\cdot}8\%$, the fact that the full correction information only has a full correction effect of some 0·5%, means that a 3·8% distortion in this information has a (3·8% of 0·5%) overall distortion effect i.e. a resultant 0·02% added distortion may be introduced, which is totally negligible.

7.5.8 Graphic Storage for Larger Capacity Displays

For displays requiring a larger display point grid "$N_H \times N_V$" of say 400 x 400, which would :

(1) eliminate area available for graphic information storage,

yet (2) require more information storage area,

a second Vidicon camera (cost $300) is required, whose sole function is to scan in synchronism with the master system timing (the quartz-controlled clock), a fixed display, back-lit, containing all the necessary system correction information in graphic form as above.

In this case from 80-100% of the CRT display (and hence of the Vidicon in the CRT-Vidicon loop) may need to be utilized to get the required display locations, while up to 100% of another display area may be utilized for correction information storage.

7.6. SUMMARY

(1) To maintain a steady display which does not move off the viewing screen, a 1:1 geometrical positional relation between the CRT and Vidicon scanned areas need be maintained. Deviations from such 1:1 relationships are due to CRT Vidicon or Camera lens distortion.

(2) This requirement is almost impossible to achieve in practice, as CRT and Vidicon distortions are always present. However if:

(i) the active display area is divided into a grid of finite display subareas; whithin each such area a display location is assumed to be located. The area of each subarea is to be such that if a display location is shifted due to CRT or Vidicon distortion, after one CRT-Vidicon cycle, the location, although displaced, still falls within its own subarea.

and

(ii) if corrective action is taken to relocate these display locations back to their nominal location after each CRT-Vidicon cycle.

a steady display results.

(3) Relocations of display locations at each frame interval implies that the information specifying the correction need be known, and be made available at each frame time to activate the necessary correction circuitry.

(4) Prior to the specification of correction information, the distortion of the CRT and Vidicon need be determined very precisely - to better then 0·1%. This has been achieved by the Moire Fringe method of distortion determination.

(5) The CRT and Vidicon need be made as distortion free as possible, with the then remanent distortion to be measured and hence corrected. This means that:

(i) linear scanning current waveforms need be used.

(ii) pincushion and barrel distortion need be removed by feeding in analytically defined waveforms into the scanning circuits.

(iii) moderately "high "quality CRT and Vidicon tubes need be used with no gross mis-alignment of the major tube components with respect to the CRT and Vidicon tube axis.

(6) The remanent distortion measured (up to 1% distortion may remain) can be expressed in the form of "distortion maps" with distortion contours defining the regions where certain distortions occur. These maps, by suitably changing signs and scales, can be converted to a correction distortion map with correction contours drawn in.

(7) The distortion correction map directly generates the required correction information for the correction circuits.

(8) For the vertical distortion correction information, a vertical coordinate distortion trace results,defining a horizontal interval between it and some straight vertical line at any vertical coordinate. This horizontal interval defines a time interval within each horizontal scanning line,which directly specifies the vertical correction.

(9) For the horizontal distortion, a distortion correction map nearly identical to the original distortion map is required, with the difference being that the correction map is scaled down by a factor of approximately 4:1. Certain other coding and control lines are drawn adjacent to this distortion correction graphic storage information to help decode it and gate it to the appropriate correction circuits.

(10) The graphic distortion information, both the

"vertical distortion trace" and the "H-distortion correction map" are stored, to be available for the correction circuits, by scribing them on black film in the correct size (a reduction of about 4:1 in the horizontal direction and full scale in the vertical direction) and affixing these scribed films in areas on either side of the centrally located active display area.

(11) The active display area, containing the actual interactive display area of 200 x 200 addressable locations, is located horizontally in the central 60% of the maximum scanned area, and in the vertical direction, located in the central $\frac{2}{3}$ of the height of the scanned area.
The distortion correction graphics information for the Vidicon is located in the Left-Hand remaining 20% of the H-scanned area, while the distortion correction information for the CRT is stored in the Right Hand remaining 20% of the H-scanned area.

(12) During the raster scan of the display area, the set of scribed lines within any given horizontal scanning line, imaged onto the Vidicon photo-target, are detected at the Vidicon output as video pulses, processed by the correction circuits and the necessary correction information generated.

(13) The remaining upper and lower parts of the display can be used for "light button" keyboard and function keyboards. The thin strip at the top of the CRT display area is required as the illuminating source for the light pen.

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CHAPTER 8

DISPLAY DISTORTION : CORRECTION IN "VIDEOGRAPHIC"

8.1. VERTICAL SCANNING WAVEFORM GENERATION STORAGE AND CORRECTION.

8.1.1. Requirements

The vertical scanning waveform-generating circuits provide a driving current waveform for the vertical deflection coils of the Vidicon and the CRT, such that the Vidicon scanning beam and CRT display-generating beam are positioned to generate the vertical display coordinates of the required linearity.

These circuits and the V-deflection coils are required to perform three functions:

(i) ensuring that pincushion or barrel distortion is absent.

(ii) deflecting the electron beam to nominal display locations by a linear staircase scanning wave - form.

(iii) accurately deflecting the beam to the required display locations, from information derived from the "Vertical distortion correction line" information.

Each of the two interlaced fields in a TV frame interval can contain up to about 300 active display lines with a period of 64µS associated with each line; 10µs of this period is the "horizontal blanked interval", allowing for electron beam flyback to the L-H edge of the display. This 10µs period can be used to generate the nominally linear scanning staircase waveform, with the correction being generated within the interval defined by the lagging edge of the horizontal blanked interval and the "Vertical distortion correction line".

For both the CRT and the Vidicon the requirements are very similar, except for the following differences:

(i) For the CRT, the display need be generated only at the required locations, that is, at 200 vertical coordinates, spaced within the central $\frac{2}{3}$ of the display height. Hence no field interlacing is required, with the two fields being superimposed directly. A staircase current waveform is used for the V-sweep, of 300 steps, with the central 200 steps defining the active display area.

In the Vidicon, as the whole of the scanned area needs be scanned, the fields are interlaced by starting the first H-line of every alternate field at half the vertical staircase step height, with the subsequent H-lines at normal step height. The two fields are thus fully interlaced, with the two adjacent lines of the Vidicon output (in alternate fields) associated with, and displayed at, a single CRT display line.

(ii) The Vertical coordinate correction in the Vidicon is generated after the nominal height staircase step, as the "Vidicon Vertical Distortion Correction Line" is adjacent to the L-H display edge (the start of the H- blanked interval).

The correction for the CRT is generated prior to the nominal stepheight, as the "CRT Vertical

Distortion Correction Line" is adjacent to the R-H edge of the display (the end of the H-blanked interval).

(iii) The magnitude of the currents to drive the deflection coils are different in the Vidicon and the CRT. For the Vidicon, the current amplitude to provide the total display height deflection is some 20-30mA, while for the CRT the current amplitude is some 500mA. Thus for the Vidicon circuits, outputs from I-C operational amplifiers can be directly used to drive the deflection coils, while for the CRT, several stages of power amplifiers are required. In commercial CRTs, the input V-coil scanning waveform is often a voltage waveform and not a current waveform, as the impedance of the V-coils is mainly resistive and not inductive at the relatively low V- scanning frequencies of 50-60Hz. It is shown in Appendix A.6.2 that a voltage staircase waveform driving typical vertical deflection coils (evaluated for the 14" PYE TV monitor) does not satisfy the requirements of an equivalent current staircase waveform, as the transient effects due to the small coil inductance present, manifest themselves as display distortion, too large to be economically corrected by the circuits described below. Current amplifiers are thus required.

The requirements for the Vertical Scanning Waveform Generation and Correction Circuits are specifically as follows:

(i) the scanning staircase waveform has a repetition duration of 20ms, with each staircase step of 64µs duration. The timing control signals are derived from the system clock.

(ii) The number of steps, allowing for vertical retrace time of about 2ms etc, is about 300; the central 200 steps generate the active display area. For the CRT, successive staircase waveforms are identical, while for the Vidicon the first step in alternate staircase waveforms is half the height of the other steps in the staircases. This allows for full 2:1 interlacing in the Vidicon.

(iii) the step height is generated within the 10µs "horizontal retrace" time, otherwise called the "Horizontal Blanking Interval".

(iv) the correct "Vertical Correction Line" must be detected within the video signal from among all of the other correction lines. The interval between its occurence (or detection) and the "horizontal blanking" signal lagging edge (or leading edge, for the CRT), determines the correction to be added to the nominal step height.

(v) provision for pincushion or barrel distortion must be provided. The actual signals or waveforms for this is provided elsewhere and explained in section 9.4.

(vi) a summing circuit to combine all of the above signals, consisting of the nominal scanning staircase, the distortion correction, and pincushion distortion elimination, to form the resultant scanning waveform to generate a linear display.

(vii) suitable amplifiers and current drivers to provide adequate power drive for the scanning coils.

(viii) the V-correction line and associated correction interval have been given in section 7.5.7.

The timing control signals are all derived from the system clock, and are assumed to be available on separate signal lines.

8.1.2 Implementation

8.1.2.1 Vidicon Implementation

A block diagram with the required control timing signals is shown in Fig.106 and 107.

Referring to these, the V-scanning system is as follows:

At the beginning of each 20ms field, the output feeding the deflection coils is assumed to be zero. The two timing pulses "T_{HS}" and "T_{HE}", which define the H-blanking interval, turn on an R-S Flip/Flop "2", whose "1" output is thus a sharply defined 10us pulse at a repetition interval of 64us. This 10us pulse is fed into a "Constant Output Level Circuit "2", giving a 10µs long output pulse of constant height, voltage supply-variation- and temperature-variation stabilized. This constant pulse, fed through Summer "1", where the V-distortion correction is combined, controls a fast-response Pulse Integrator. The repetitive pulse input generates a linear ramp of 10µs duration for each input pulse; the output remains constant at the ramp value after 10µs, for the following 54us (the display width) until the next

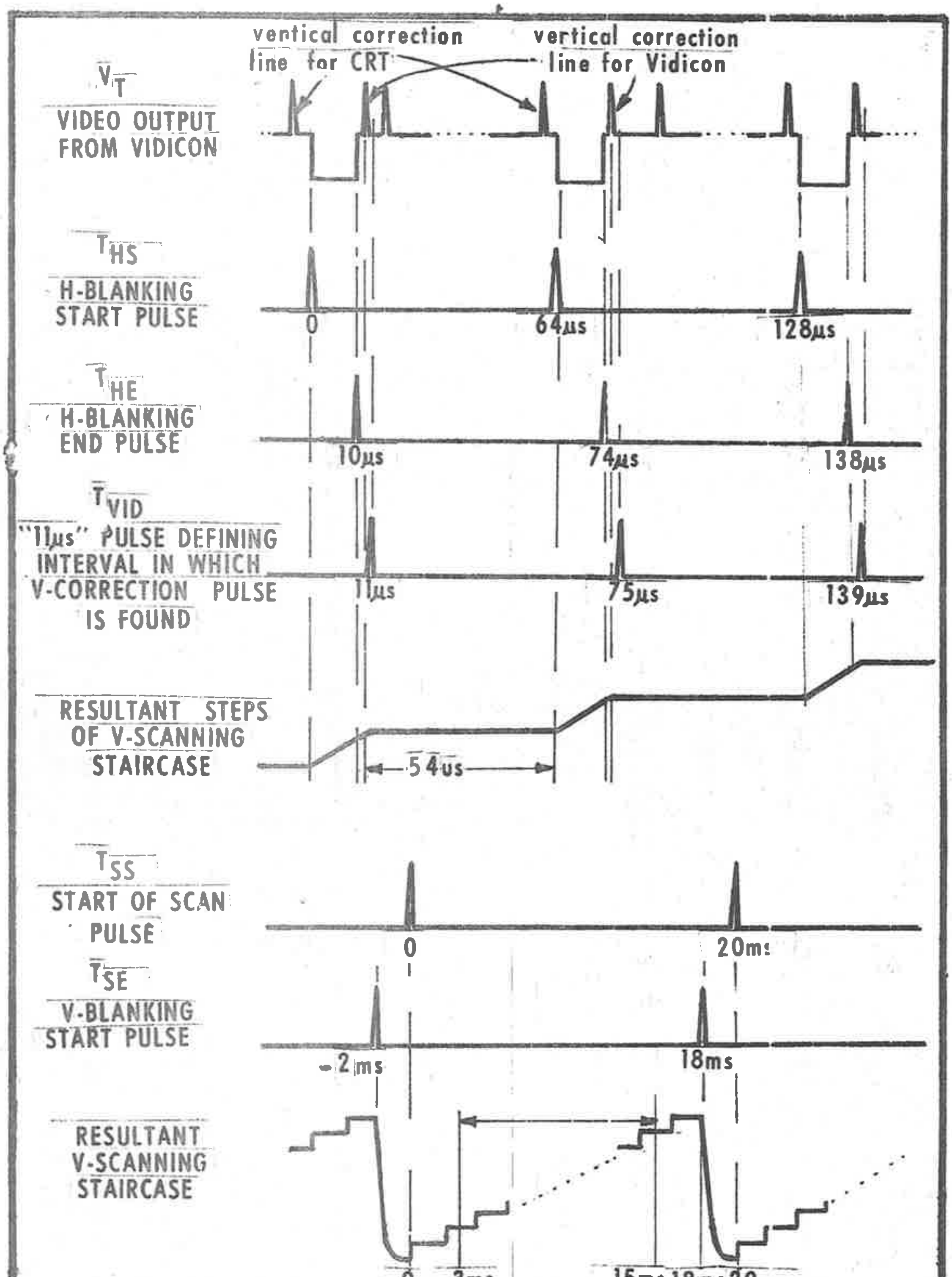


Figure 106. Timing Control Signals and Resultant Waveforms for Vertical Coordinate Generation.

pulse, when the following "step" is generated. The result is the nominal staircase as shown in Fig.106.

Similarly the pulse defining the lagging edge of the H-blanking interval and any pulse within an interval of 1µs from that lagging edge (the V-correction line pulse ,when fed into another R-S Flip/Flop "3", define a pulse of up to a maximum of 1µs long. This is fed into a Constant Output Level Circuit "1" and summed at Summer "1" with the 10us pulse, resulting in a pulse length of constant height, controlling the total step height of the output of the integrator, giving the required corrected step height. Since the 10µs pulse generates approximately 100% of the step height (the V-correction being only 1-2% at the most), while up to 1µs pulse width of the correction pulse corresponds to a maximum of 2% say, of the step height, the two input resistors at "Summer "1" would need to be scaled by 5:1 w.r to each other.

The output of the Pulse Integrator is fed into another Summer "2" which sums that and the analog pin-cushion distortion correction waveform derived elsewhere (see section 9.4).

The resultant is appropriately scaled at this summing junction; since the V-coil current required in Vidicons is of the order of 25-30mA, I-C Op-Amps can be used directly to drive the V- deflection coils.

The staircase is generated until the last (or "bottom") display line, whereupon the vertical blanking pulse singal "T_{SB}" (at about 18ms from the beginning of the V-scan) is generated to initiate the "vertical retrace".

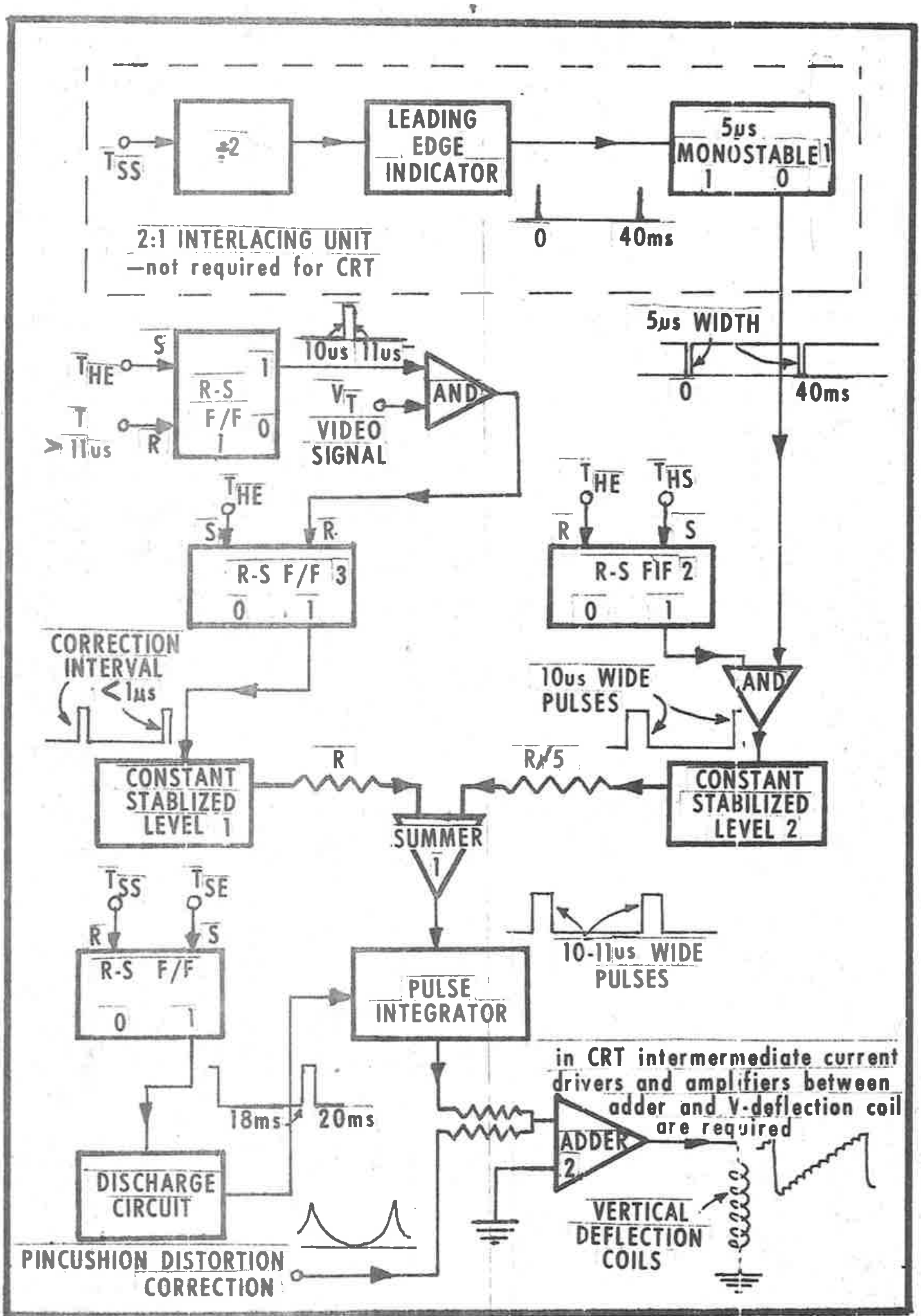


Figure 107. Functional Block Diagram of Vertical Scanning Waveform Generation and Correction Circuits.

The same V-blank pulse signal "T_{SE}" controls a FET-discharge circuit for the Integrator which resets the Integrator at zero output until the next field scanning waveform at t = 20ms is initiated again.

To provide alternate field interlacing, every alternate vertical field "start-scan" pulse "T_{SS}" is used to define a 5µs time interval (say via a Monostable "1") which when appropriately gated, ensures that the first staircase step-defining pulse in alternate fields is only 5µs and not 10µs long; the first step in the scanning current waveform is thus of half-height, resulting in the beam being deflected by half its normal interline deflection increment, ensuring 2:1 interlacing.

The above circuits are implemented in rather simple,yet effective circuits, and described,with results given in chapter 11. The current staircase linearity (not the display linearity) is better than 0·25% linear. This staircase non-linearity itself is part of the scanning system non-linearity,manifesting itself as display distortion. Thus when the"Vertical Distortion Map" is obtained using the Moire Fringe method, the above circuit should be used, with the V-correction input inhibited. The V-deflection block diagrem is shown in Fig.107.

8.1.2.2. CRT Implementation

The CRT scanning waveform generation circuitry is very similar to the above with the exception that:

(i) the 2:1 interlacing subcircuit is not required.

(ii) different timing pulses are used to determine the correction interval, because the" CRT V-correction pulse"occurs prior to the H-blanking interval (due to being adjacent to the L-H display edge). In the R-S Flip Flop corresponding to R-S F-F "3", the "Set" pulse is now the "V-correction line" pulse, while the "Reset" pulse is that defining the leading edge of the H-blanking interval "T_{HS}" (see Fig. 106).

(iii) the input to the deflection coils need be of the order of 500µA; thus I-C Op-Amps can no longer be used. For the TV monitor under test, the scanning staircase waveform need be amplified to some 70-80V before being inserted into the existing CRT circuitry; these linear amplifiers are also described in Chapter 11.

The above circuits can be implemented quite readily from readily available I-C Op- Amps, RTL or TTL logic, and readily available transistors, the total cost of each V-deflection system being less than $30(A).

8.2. HORIZONTAL SCANNING WAVEFORM GENERATION, STORAGE, AND CORRECTION - GENERAL COMMENTS

8.2.1 Introduction

8.2.1.1. General

The Horizontal Scanning Waveform Generating Circuits provide the driving current waveform for the horizontal deflection coils of the Vidicon and the CRT, such that the Vidicon scanning beam and CRT display-generating electron beam are positioned to generate the horizontal display coordinates of the required linearity, at the required display locations.

The mechanism of generating these H-coordinate display locations is quite different to the V- coordinate, as also is the method of providing the corrections to generate the linear display.

8.2.1.2. CRT- Horizontal Coordinate Generation

For any fixed vertical coordinate, the scanning beam is deflected in the horizontal direction at nominally a constant rate. Locations are displayed on the CRT screen by enabling on the electron beam at such time instants as to result in nominally linear horizontal location positions. Ideally for a linear H- scanning current waveform (or linear sawtooth), and a constant time interval pulse train modulating the electron beam, a linear display in the H-direction should result. Distortion in the CRT time-position transfer curve precludes this. The stored graphic information controls variable delay circuits which selectively delay the pulses in the pulse-train modulating the electron beam, such that a linear H-direction display occurs.

Thus in a CRT, a nominally linear horizontal scanning waveform deflects the electron beam, while a constant period or "synchronous" pulse train is the input to generate the display; the correction circuits reposition the pulses in the pulse train by selectively delaying them, resulting in an "asynchronous pulse train. The result is then a linear H-coordinate display.

For the following sections, the following notation is used:

(a) The "constant time interval" Video input pulses from the Vidicon or the CRT fed into the CRT, prior to correction, is called

"$V_{CRT}(n\,\Delta t)_{in}$"

with "$\Delta t \approx 0{\cdot}161us$,being the pulse period,
"n" being the pulse count corresponding to the "nth"Horizontal location.

(b) The variably delayed or repositioned pulses after correction,fed into the CRT electron beam modulation circuits generating the CRT screen locations is called

$$"V_{CRT}(n\Delta t + \delta t_n)"_{out} \text{ or just} "V_{CRT}(t)_{out}"$$

where "δt_n" is the required delay corresponding to the"nth horizontal"location.

8.2.1.3. Vidicon Horizontal-Coordinate Generation

In a Vidicon on the other hand, a somewhat different process occurs. The linear CRT display or the linear user-input information is imaged onto the Vidicon photoconductor target via the Vidicon Camera lens, resulting in a distorted image; for a typical camera lens and a correctly aligned Vidicon with respect to the lens, the lens distortion may be of the order of 0·25%,or less,of scanned area height. Over the scanned area corresponding to the active display area, the distortion may be 0·15%,or less.

At any fixed vertical coordinate, the scanning beam is deflected in the horizontal direction at nominally a constant rate. A video output pulse is generated at the coincidence of the scanning beam and a stored charge corresponding to an imaged CRT location. Ideally for a linear H-scanning current waveform and a constant linear CRT display, the output video pulse train should have constant time separation between pulses. Due to the combined distortion of the camera lens and the"Vidicon

Transfer Curve", the output video pulse train has non-constant interpulse-time-separation and thus appears "distorted". Morevoer,some expected video pulses may be "missing" from some lines or even from "adjacent" lines within a field due to remanent pincushion distortion, but with interlaced scanning,these "missing" video pulses will appear in the video signals in lines corresponding to adjacent lines to the line from which the Video pulses are missing, i.e. these pulses are displaced into the interlaced field. Thus distortion occurs in both coordinates, due to the lens distortion not having a preferred direction of distortion. To allow for this vertical distortion, effectively analogous to pincusion or barrel distortion in a CRT, 2:1 interlaced scanning is used with the output of 1 line per field, (and thus a "strip" of 2 line width) is associated with each display H-line of the CRT; whatever CRT location is imaged within that 2 line-wide strip,is redisplayed onto one CRT H-display line (see Fig.122(d)).

The remanent Vertical distortion or pincushion or barrel distortion is not quite as severe as expected. The Vidicon can have its own pincushion or barrel distortion corrected by similar waveforms derived analytically as for eliminating CRT barrel or pincushion distortion (see section 9.4. 3). Depending on whether the lens has barrel or pincushion distortion, the Vidicon waveshape can be under-or-over compensated to nullify the lens distortion, leaving a remanent pincusion distortion of less than 0·1% or thereabouts. This is very much less than a line width and thus a "distorted" location would still fall within the 2 line-wide strip associated with each location.

The graphic stored information controls Variable Delay Circuits which selectively delay the pulses in the video output train, repositioning them with respect to each other such that the interpulse time separation is constant.

In a Vidicon then, a nominally linear horizontal scanning waveform deflects the electron beam, with an image of a linear CRT display, somewhat distorted by the camera lens, being incident at the input, i.e. the photo-conductive target. The correction circuits reposition the output video pulses to result in a linear time pulse train.

For the following sections, particularly in section 3.4, the following notation is used:

(1) the distorted pulse train from the Vidicon target output, requiring correction, is called

"$V_{VID}(n\Delta t + \delta t_n)_{out}$" or just "$V_{VID}(t)_{out}$"

where "δt_n" is the time deviation of the "nth" horizontal location from its ideal undistorted location.

(2) the corrected or repositioned pulses after corrective delays have been implemented are called

"$V_{VID(n\Delta t)}$"

where "Δt" $\approx$ 0·161us, the corrected pulse period,
"n" is the pulse count corresponding to the "nth" horizontal location.

8.2.1.4 Differences between H- and V- correction

The two cases of CRT and Vidicon H- coordinate deflection and correction are different and thus warrant separate treatment. It is also radically different to the form of correction required and implemented for the vertical-coordinate generation and correction. The differences are:

(i) Vertical distortion correction depends on altering the scanning waveform and thus the position of the deflected beam, while Horizontal distortion correction depends on the selective time delay of the enabling pulses of the electron beam in the CRT or the output Video pulse in the Vidicon, no matter whether the scanning of the beam is linear or not (i.e. scanning velocity is constant or not). The difference in method is due to the difference in the speeds required to physically reposition electron beams - if the beam is to be shifted ("corrected) by one location within, say, $\frac{1}{5}$ of the time normally taken by the beam to travel from location to location, then about "12us" are available for the vertical coordinate and about "0·03us" for the Horizontal coordinate, a speed ratio of about 400:1!

(ii) each vertical coordinate may be individually corrected as the raster scanning process ensures that the "unusable" display area available for correction information storage is scanned at each vertical coordinate, enabling any vertical distortion correction stored to be accessed, and correction to be implemented for each line (i.e. for each vertical coordinate). For the horizontal coordinate however, continuous scanning occurs within each active display line and no unusable display area is available between successive display locations to store distortion correction information. The distortion information is stored prior to the display for all of the 200 Horizontal display locations per H-line. Consequently in the relatively limited area available for this correction information, the correction information is itself limited and thus resultant correction cannot be as precise as for the y-coordinate. Consequently the display capacity is set by the precision of H-distortion correction capable of being specified within the distortion correction space. The "ultimate" would be to have as many correction lines within that area as there are horizontal locations - in this case 200 correction lines would need to be stored! This of course is not possible (see section 7.5.5).

8.3. H-SCANNING WAVEFORM GENERATION AND CORRECTION FOR VIDICONS

8.3.1 Interpretation of Graphic H-Distortion Correction Information.

To simplify the description and avoid repetition, the H-distortion of the Vidicon prior to correction is assumed to be identical to CRT distortion shown in Fig.101 and having the form of the Distortion Correction Information as in Fig.104(a) (in fact, with pincushion distortion removed (and that in Fig.101 still has pincushion distortion), the distortion is much less and more symmetrical about the centre of the display; thus in actual practice, the number of distortion regions requiring correction increments of 0·25% would be less than that shown in Fig.104).

For two adjacent contours, say the −0·25% and −0·5% contour, it means that locations specified within that area need be delayed by a time interval varying from 0·25% to 0·5% of the time required to sweep across the active display area i.e. 0·25% to 0·5% of 32·4μs, the latter being the sweep time for the active area display. This, remembering that N_H=200 locations are located within that sweep-time, means a delay equivalent of between $\frac{1}{2}$ to 1 interlocation sweep time interval "Δt", with other distortions correction regions requiring delays measured in increments of one half of a interlocation sweep time interval i.e. "$\frac{\Delta t}{2}$" μs; "Δt" is equal to $\frac{32 \cdot 4}{200}$ = 0·162μs.

The other information obtained from the distortion correction map is that if "32·4us" is the electron beam-sweep time across the active display area, then say for the section AA' in Fig.104(a), the interval where the "$\frac{\Delta t}{2}$" to "Δt" delay need be implemented, lies between "T_{AS}" and (T_{AS} + 3·5)us and again between (T_{AS} + 20·2)us and (T_{AS} + 28)us, where "T_{AS}" corresponds to the time for the scanning waveform to reach the Left-Hand boundary of the active display area. The Correction Information Curves give exactly that same information, allowing for the fact that they are compressed by a factor of 32·4/7·5 = 4·32:1, as the display information lies in an H-time sweep interval of "7·5us."

Specifically then, for the line AA' of Fig.104(a):

(a) locations displayed in the region defined in the H-scanning time interval by "T_{AS}" to (T_{AS}+ 3·5)us need be delayed from between "$\frac{\Delta t}{2}$" to "Δt"us.

(b) display locations between $(T_{AS}+3\cdot5)$us to $(T_{AS}+20\cdot2)$us need be delayed from between "Δt" to "$\frac{3}{2}\Delta t$" us.

(c) display locations between $(T_{AS}+20\cdot2)$us to $(T_{AS}+28)$us need be delayed from between "Δt" to "$\frac{\Delta t}{2}$" us.

(d) the remaining display locations between $(T_{AS}+28)$us to $(T_{AS}+32\cdot4)$us need be delayed from "$\frac{\Delta t}{2}$" to "0us".

8.3.2. H-Distortion Correction by Variable Delays

The variable delay can be provided by feeding "$V_{VID}(t)_{out}$", the Vidicon output pulse train requiring correction, into a parallel set of Shift Registers, (one of which is enabled on at any instant), video pulse by video pulse, which are then shifted pulse by pulse by a clock pulse of "$\frac{\Delta t}{2}$ us" interval, and output from the Registers at "$\frac{\Delta t}{2}$us" clock pulse intervals. The input is thus the "distorted" or "anynchronous" video pulse train, while the output is the corrected, "synchronous" pulse train with the appropriate delay, "$V_{VID}(n\Delta t)$". The number of shifts per Shift Register is 1, 2, 3, 4, ...etc respectively, and the particular Shift Register giving the required delay is enabled on for a period equal to that specified by the Distortion Correction information, and implemented by control signals derived therefrom. A set of subcircuits which are activated by the Correction Information Lines implement the generation of these correction intervals, by linear Voltage-controlled Monostables, whose "1" output pulse width in the "quasistable" state, is made proportional to the time interval specified by any two consecutive correction information (or "distortion lines").

This is done by integrating a pulse whose duration is defined by the corresponding two consecutive distortion contour pulses, and the resulting Integrator voltage output being the required Monostable control voltage. The output Monostable pulse duration is the control signal to gate in to the appropriate shift register, the monostable "ON" trigger pulse corresponding exactly to one of the boundary correction lines, and its duration equal to the required time interval between two consecutive correction contour lines.
To ensure that the proper sequence of gating the shift registers is carried out, the "control lines" drawn just prior to the correction information lines are necessary within the H-scan time interval between t=11us and 12us. These provide the additional control for correct gating as explained in section 8.3.3.1 below.

Before explaining the H-deflection and correction system shown in Fig.108-112, the subcircuits required are listed below- they are:

(i) a linear Horizontal Scanning Current Waveform Generator. This is described in chapter11. For the Vidicon under test, an output scanning sawthooth current waveform of 120-130mA peak to peak is required. The relatively simple one designed has a linearity of better than 0·3%. Within the active display area its linearity is better than 0·2%.

(ii) a number of linear Voltage Controlled Monostables (VCMs) whose "1" output pulse length, the duration of the quasi-stable state, is directly proportional to the control voltage. These are temperature- and supply-voltage-variation stabilized and have linearity of the order of 0·3% over a pulse duration variation of 30:1. The circuit and performance are given in chapter 11.

The control voltage is taken from a simple Pulse Integrator (the pulse length being defined by the distortion correction lines) through high-input impedence analogue buffers. The linearity of the Integrator is of the order of 0·3% or better. The circuit and perfommance are given in chapter 11.

(iii) Thus a number of variable Pulse-length Integrators is required.

(iv) a set of "variable-length" Shift Registers, whose pulse inputs are shifted by H-clock pulses of twice the repetition rate of the nominal effective repetition rate of '$V_{VID}(n\Delta t + \delta t_n)'_{out}$ (i.e. pulse period of '$\frac{\Delta t}{2}$' $\approx 0{\cdot}081$us). The length and number of required Shift Registers, is 1, 2, 3 ....bits, the maximum length depending on the maximum distortion to be corrected, this being

$$\frac{(\text{maximum distortion present})\,\%}{0{\cdot}25\%}$$

For the case taken, as the distortion to be corrected, from Fig.104, is up to 1·25%, it implies that 5 Shift Registers are required, of length 1, 2, 3, 4, 5, bit positions respectively.

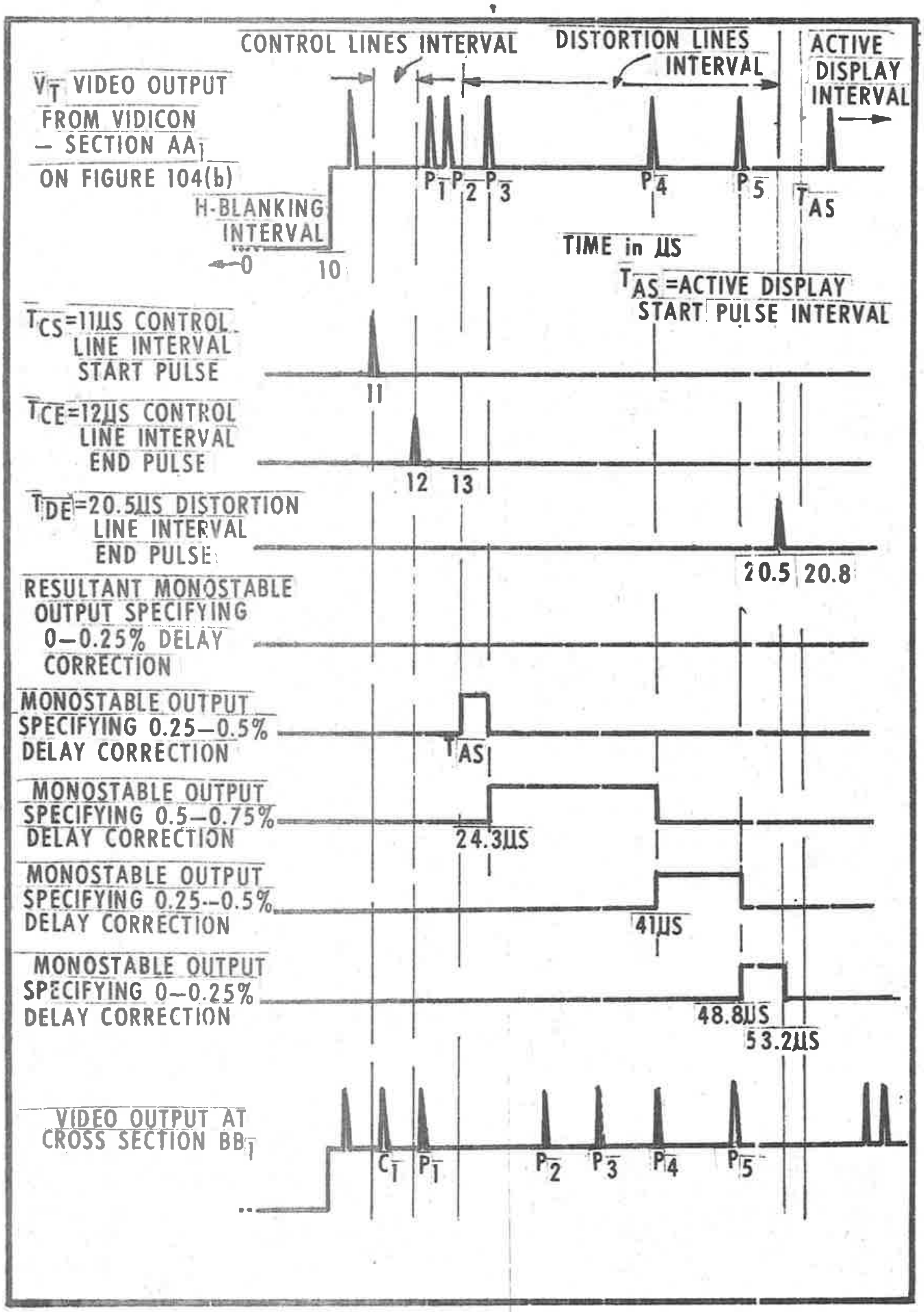


Figure 108. Timing Control Signals From H-Distortion Information For H-Coordinate Correction For Vidicon.

Each Shift Register is enabled on when "$V_{VID}(t)_{out}$" is gated in at the appropriate time with the output of a particular Monostable. The outputs of all the shift registers are OR-ed together, the output from this being the corrected linear video pulse output "$V_{VID}(n\Delta t)$" corresponding to the CRT display luminance positions imaged onto the photo-conductor target of the Vidicon.

(v) appropriate gating and selection logic, (RTL or TTL implemented), capable of about 20Mhz speeds is also required (as "Δt" corresponds to 0·162us, "$\frac{\Delta t}{2}$" corresponds to 0·081us). RTL or TTL logic capable of at least operating at $\geqslant$ 13Mhz is required).

8.3.3. H-Correction Implementation

The block diagram of the circuit is shown in Fig.109,110,112 with the required timing control signals shown in Fig.108 and 111.

The explanation of the circuit is in two parts:

(i) the subsystem which extracts and defines within the active display area, the regions where the required corrections are to be implemented, (this subsystem is also common for the CRT).

(ii) the subsystem consisting of the shift registers where the variable delay correction is implemented.

8.8.3.1 Generation of H-Correction Control Signals

Referring to Fig.109, the time origin of the system H-clock is taken at "T_{HS}", the start of the hori-

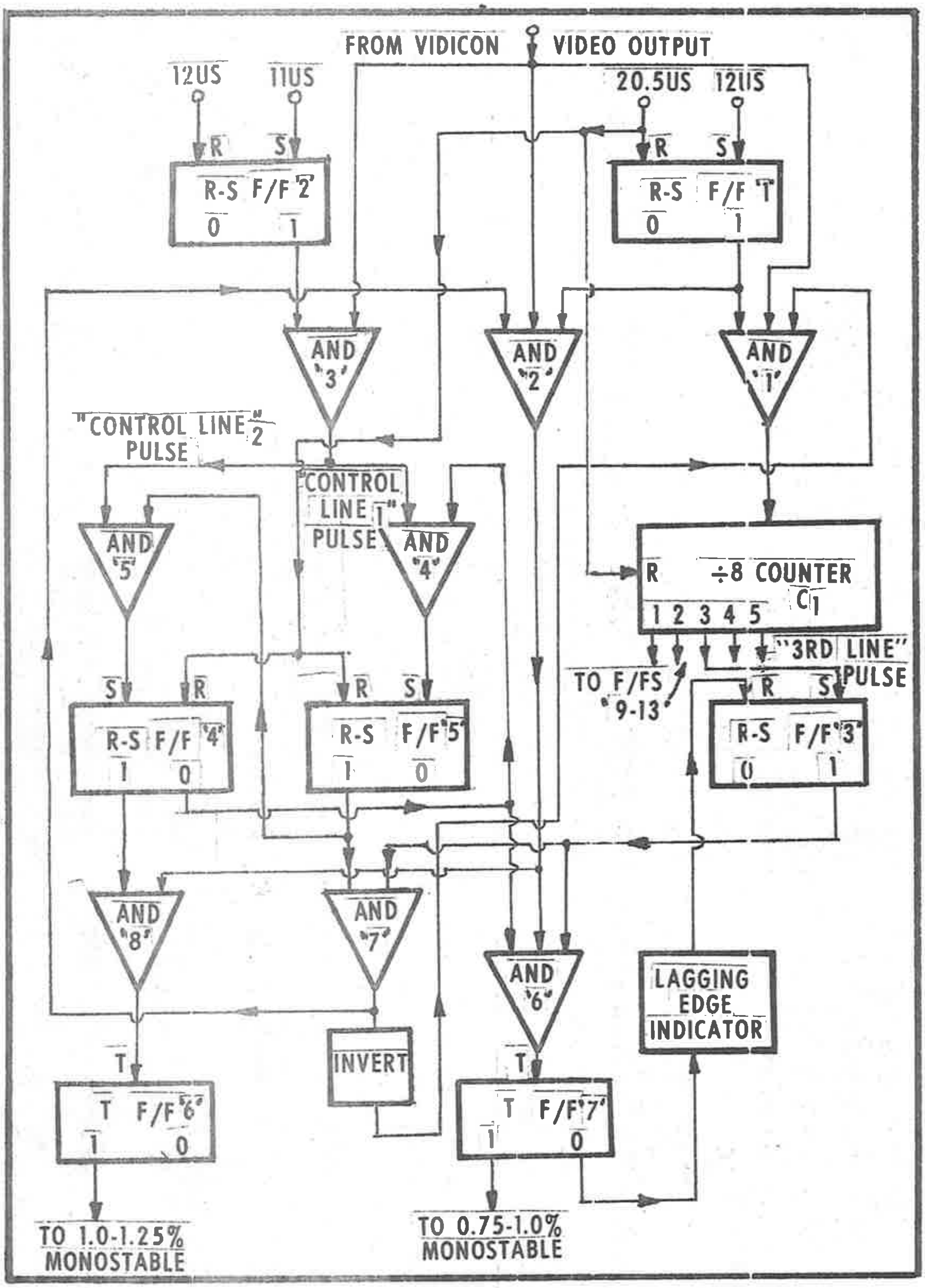


Figure 109. Block Diagram of Input Logic For Timing Control Signals for H-Coordinate Correction for Vidicon.

zontal blanking interval (see Fig.106). From the system H-clock, two pulses at "t=11μs" ("T_{CS}") and "t = 12μs" ("T_{CE}") are used to gate-in the "control" pulses "P_{ci}" present in the video signal during that interval, via the R-S Flip/Flop "2"; in the case shown in Fig.104, up to 2 pulses (corresponding to two lines) can be expected. These are used to control further logic. The function of these control signals is explained further below. For the line corresponding to AA' in Fig.104 no control line signals are present in this interval and hence this logic is not activeated. Clock pulses at "t=12μs" and "t=20·8 us" fed into the R-S Flip Flop "1" define a time interval within which the actual distortion information is expected.

Now it is the property of distortion contours that if a straight line (such as AA' in Fig.104) is drawn across an area containing them, then the intersection between the line and any two adjacent contours specify either the same distortion contour, or else they specify two contours differing by only one distortion contour unit. Consequently if any contoured area such as the distortion correction information area has all of the contours "closed", even by closing them outside the distortion area, such as by the vertical lines within the interval t = 12us to t = 13us), then any line drawn across the contours cuts them in a predetermined order. Specifically for the section AA':

(1) the 1-st line encountered (and first pulse within the H-correction time interval) defines the "0% Distortion Line."

(2) The 2nd line (2nd pulse) defines the "-0·25% Distortion Line".

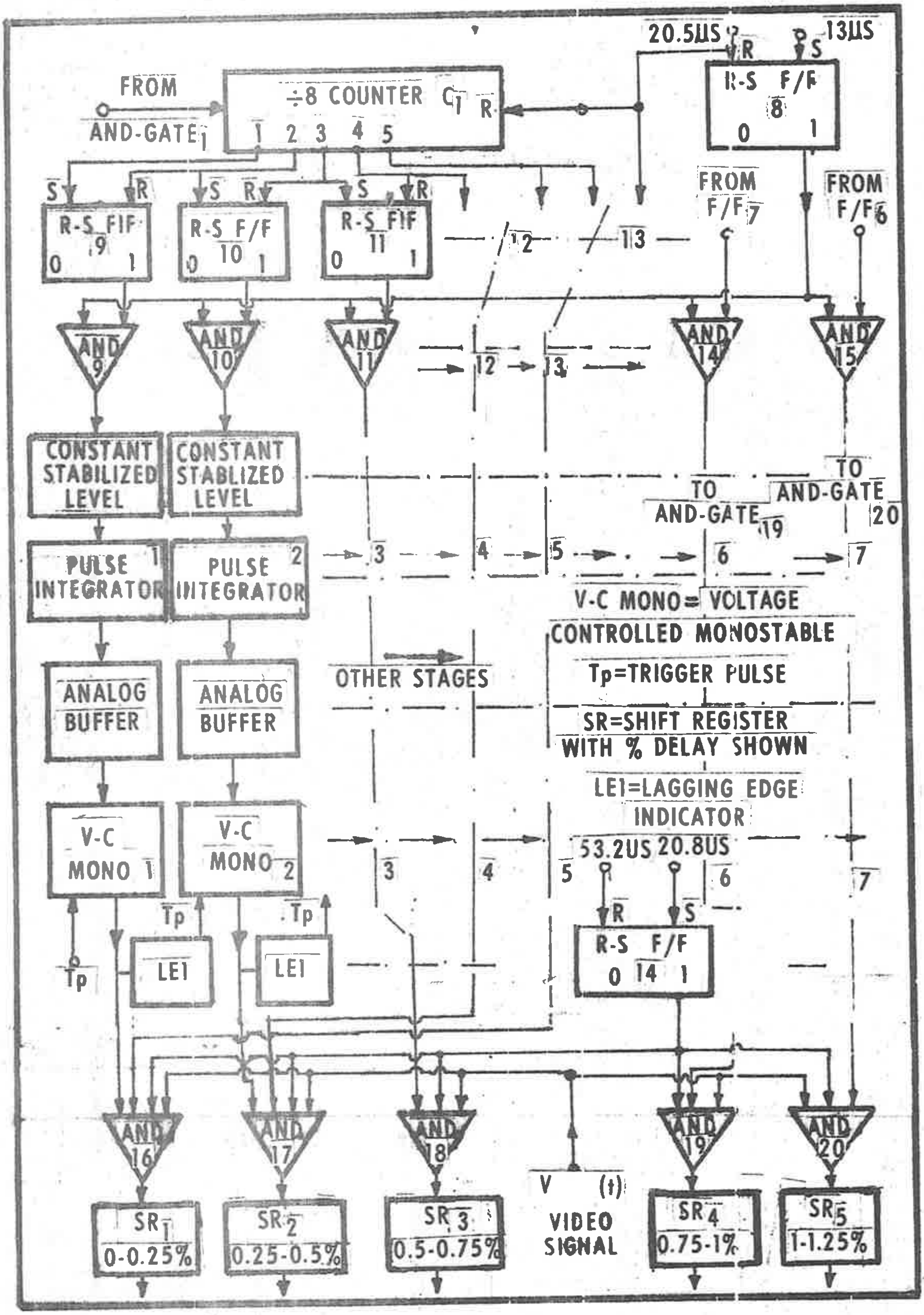


Figure 110. Timing Control Logic and Circuits Defining Distortion Regions in the Vidicon.

(3) the 3rd line defines the "-0·5% Distortion Line."
(4) the 4th line defines the "-0·5% Distortion Line."
(5) the 5th line defines the "-0·25% Distortion Line."
(6) the 6th line defines the "0% Distortion Line."

All of these 6 lines may or may not be present, but the sequence of lines and the resulting pulses define the distortion regions in the above sequence.

These pulses defining these lines are fed into a 3-bit Counter "C_1", and then each input pulse is extracted by the resulting serial-to-parallel conversion; two consecutive pulses are fed into a number of S-R Flip/Flops F/Fs "9-13" (Fig.110), with the result that each of these Flip/Flops has a "1" output of duration proportional to the time interval between two successive distortion correction lines.

Moreover,

(1) F/F "9" is associated with 0 to -0·25% correction, i.e. with the "up to $\frac{\Delta t}{2}$" correction Shift Register.
(2) F/F "10" is associated with the "between $\frac{\Delta t}{2}$ to Δt" correction Shift Register.
(3) F/F "11" is associated with the "between Δt to $\frac{3\Delta t}{2}$" correction Shift Register.
(4) F/F "12" is associated with the "between Δt to $\frac{\Delta t}{2}$" correction Shift Register.
(5) F/F "13" is associated with the "between $\frac{\Delta t}{2}$ to 0" correction Shift Register.

The output from each of these F.F's is fed into a set of Constant Output Level Circuits (see Fig.110) which are temperature-and supply-voltage-variation stabilized. The output of these is further fed into a set of linear

Pulse Integrators "1-7". The resultant output voltage at each Integrator is directly proportional to the intervals between the distortion correction lines. Because these intervals are scaled down by a ratio of 4·32:1, with respect to the actual active display area, the Integrator Output Voltage is proportional to the corresponding active display correction line intervals.

The outputs of these Integrations are fed, via high-input impedance Buffers, to 7 linear Voltage Controlled Monostables "V-C Monos 1-7". When a trigger pulse initiates the quasi-stable state, the resulting duration of this output pulse is directly proportional to the control voltage and thus, by appropriate scaling, can be made identically equal to the H-sweep time duration between the two corresponding distortion lines on the active display area.

At "t = 20·8us" ("T_{AS}"), the L.H. boundary of the active display area, a H-clock pulse triggers V-C Monostable "1". The lagging edge of the quasistable "1" output pulse is detected and triggers V-C Monostable "2" whose lagging edge of the "1" output pulse subsequently triggers Monostable "3" and so on.

Thus in synchronism with the horizontal scanning beam (synched by the "T_{AS}" pulse), the Monostables in turn define the regions on the active display region associated with the required Shift Register correction.

These Monostable outputs are AND-ed (gates "16-20") with the Vidicon video output and fed as input into the appropriate Shift Register. As at any instant only one Monostable is "on", only one Shift Register has an input and only one type of correction is performed.

The above circuit arrangement is valid for "symmetrical" distortion distributions about the centre axis of the active display area i.e. where a distortion contour can be "closed" by a line just outside of the L.H edge of the display distortion correction area. This symmetry of distortion is the usual distortion distribution under normal conditions. However the CRT under consideration with the distortion map in Fig.104, shows asymmetry in the bottom R.H. corner as evidenced by the "-0·75%" and the "-1·0%" contours present (see cross-section BB'). "Contour closure" cannot be implemented and yet this case must be differentiated from the above; otherwise the "-0·75% contour" would be read as a "-0·5% contour" and the "-1% contour" would be read as a "-0·25% distortion contour" etc, by the above logic decoding circuits. For this reason the "control lines" in the interval "t = 11μs to t = 12μs" are present, one line each for the presence of each additional contour over that allowed for in the "normal" correction region.
The "control lines" generate signals and control logic via F/F "2" (Fig.109) which extracts the required correction lines from the sequence switching the 3-bit counter "C_1".

The first pulse occuring within this "control line" interval indicates the presence of a "-0·75% contour" and hence a subsequent region where a "$\frac{3}{2}\Delta t$ to $2\Delta t$" Shift Register correction need be applied.

The 4th Distortion Line pulse normally associated with a "- 0·5%" line is extracted from the 3-bit Counter "C_1" via the R-S F/F "3" and is used to control separate Flip/Flops R-S F/F "5" and "T" F/F "7", with subsequent Pulse Integrator "6", Voltage Controlled Monostable "6" and so on. If no second "control line" pulses occurs, it implies that the next (5th) Distortion Line, if present, (see contour BB') is also a "-0·75% distortion contour." If so, control returns to the 3-bit Counter "C_1" as F/F "7", having detected the two pulses corresponding to the -0·75% contours enables the Counter input again; the two consecutive distortion lines reset F/F "7" back to its "0" state and reset F/F 3 also to its "0" state.

If two "control lines" are present, the sequence of the contour lines are ...." -0·75%, "-1%" respectively; again the Counter "C_1" is inhibited as in the "-0·75% detection" circuit . The Fig.109 shows a circuit arrangement catering for 2 "control lines".
For very distorted displays, requiring more Distortion Lines in the Graphic Distortion Information, added gating logic stages of the form as AND-gate "2", R-S F/F "4", AND-gate "8" and "T" F/F "6" , is added in parallel. Again, such control and distortion lines define intervals, which when fed into further Pulse Integrators, generate in the above fashion, the required display correction in synchronism with the scanning beam.

The timing diagram in Fig.108 shows the nature of the timing signals and resultant Monostable intervals for the line AA' in Fig.104(b).

8.3.3.2 Variable Delay Shift Registers

The bank of Shift Registers required to perform the variable correction delays on the Vidicon output pulse train is shown in Fig.112.

The Shift-Registers are built from R-S, or J-K, I-C Flip/Flops, and must be capable of operating up to clock rates of 15 Mhz. Fairchild RTL Micrologic, or better

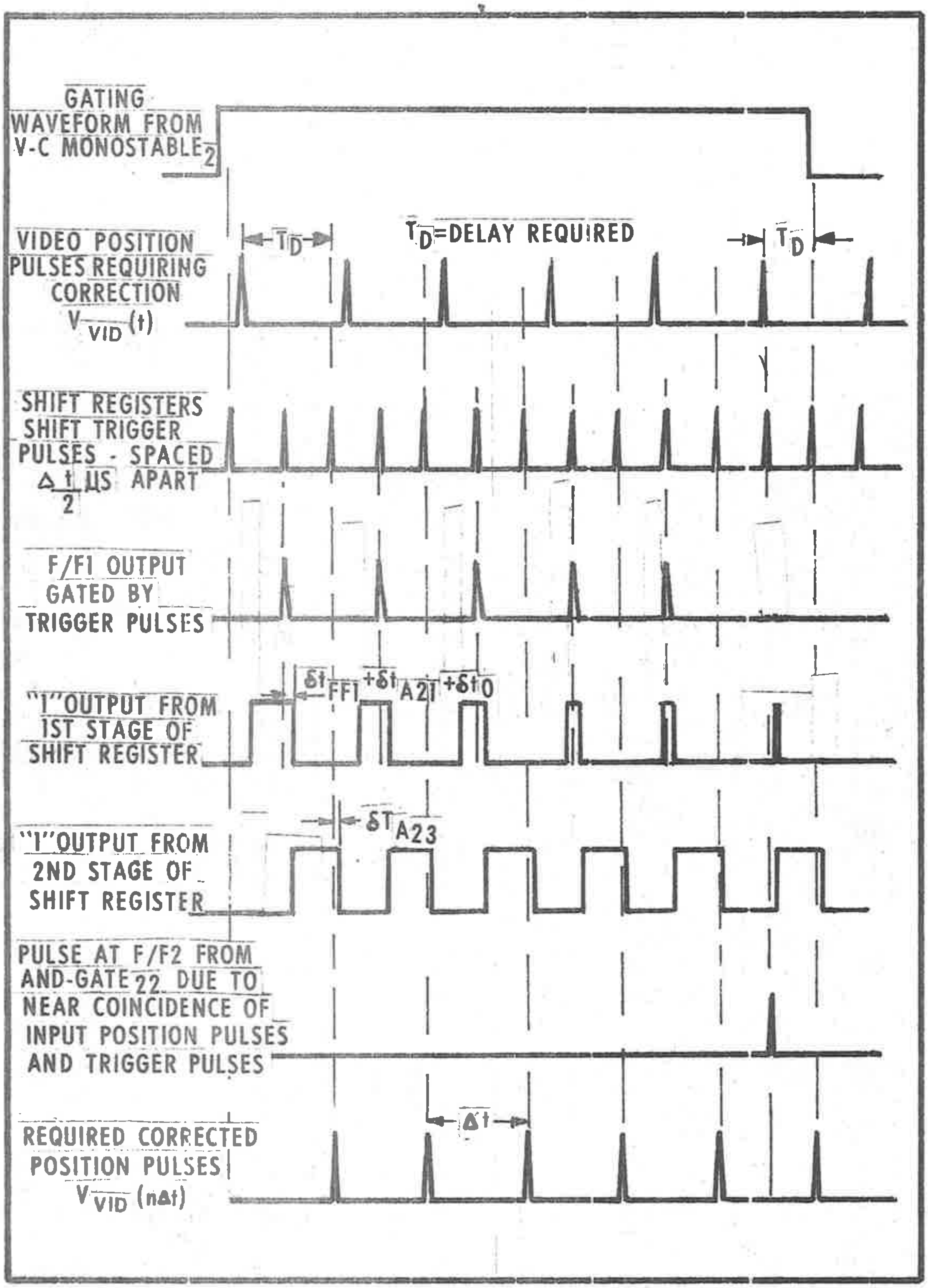


Figure 11.1. Correction Shift Register Signals Showing Corrected H-Coordinates in Vidicon.

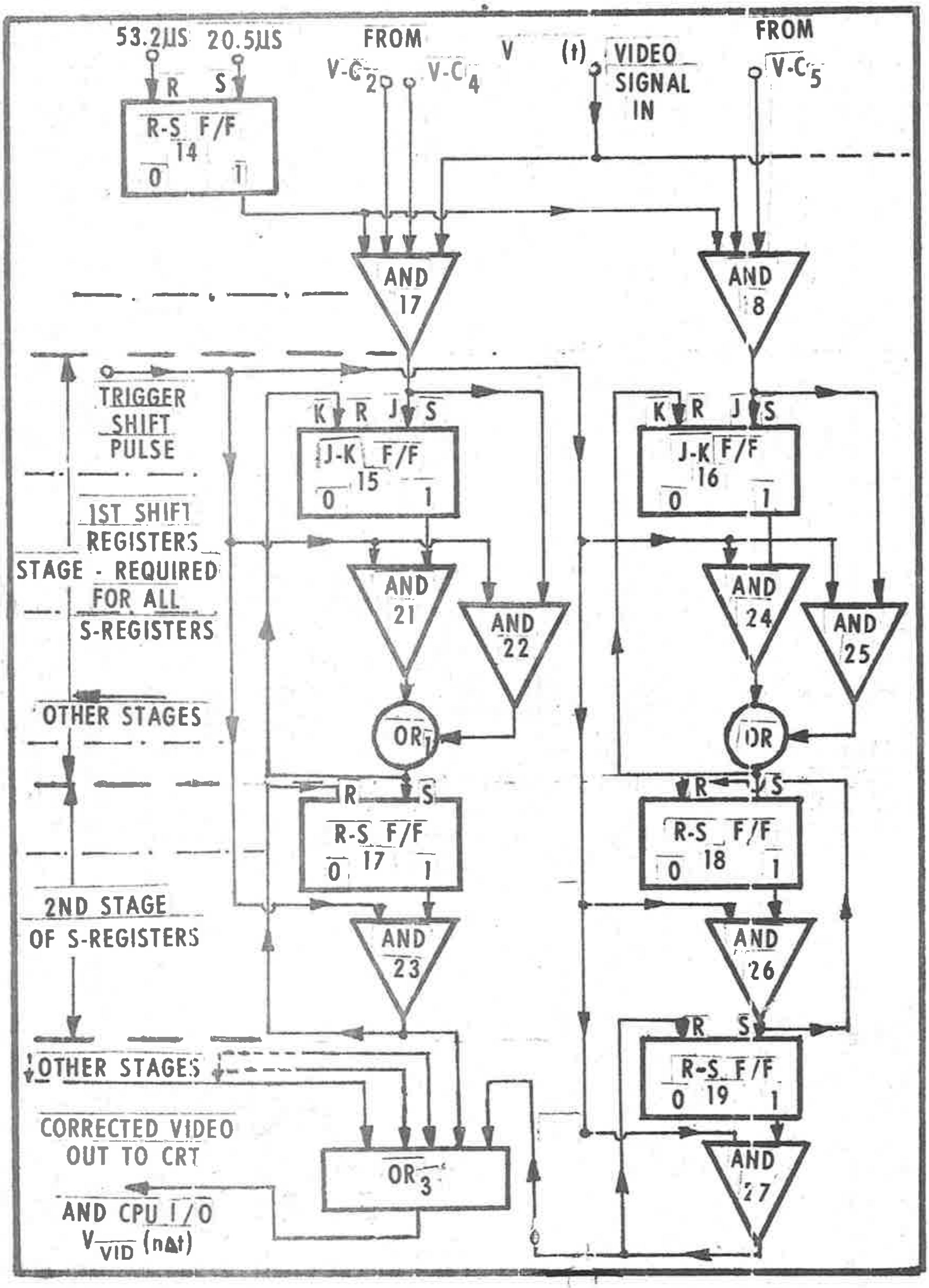


Figure 112. Variable Delay H-Correction Shift Registers.

(Only 2 are shown giving 0.25-0.5% and 0.5-0.75% correction) still TTL are suitable from this viewpoint and are also cheap enough.

The Video input pulses requiring delay, even with the distortion present, have a minimum inter-pulse time interval of the order of "$\Delta t \approx 0{\cdot}16$us." The shifting of these pulses from Register-location to successive Register-locations and the clearing of previous locations occurs at a H- clock derived pulse rate of repetition rate of "$\frac{\Delta t}{2} \approx 0{\cdot}081$us." Thus no possibility can occur of a video input pulse being inserted into an uncleared Register-location; any two consecutive video pulse are two Register-locations apart.

However the Vidicon response may be such that two adjacent position pulses may not be displayed as two separate pulses but as one pulse of double the pulse width. Consequently for a R-S Flip/Flop, an ambiguous "1" would result if the "Set" and "Reset" pulses are present simultaneously, as "Reset" pulses are presented after each single pulse input. A J-K Flip/Flop on the other hand, has a true "1" output after a "Set" pulse regardless whether a "Reset" pulse is present or not simultaneously. Thus a J-K Flip/Flop is used as the first stage of each Correction Shift Register.

Referring to Fig.112, when a location is shifted from the previous location to the successive location, it is delayed by "δt_A", the "AND-gate propagation delay" (i.e. AND-gate "21", "22" etc) and in the case of shifting between the first register location of each shift register and the second register locations, by an additional "δt_O", the "OR-gate propagation delay").

As

$$\delta t_A + \delta t_o < \frac{\Delta t}{2} \quad \ldots\ldots\ldots\ldots \quad 8.1$$

that shift pulse sets to "1" the successive F/F stage of the Shift Register prior to the next clock pulse. Simultaneously that shift pulse is fed back to clear the previous F/F; the gate-delays "δt_A" ensure that no race problems in the cleared F/F occurs. The AND-gate (e.g. AND-gate "21", "24" etc) ensures that a true pulse is propagated by the simultaneous presence of the H-clock pulse and the video pulse in the previous register-location.

Each Shift Register is enabled on by gating in "$V_{VID}(t)_{out}$" with the corresponding Monostable time interval indicating the region within which that correction must be carried out. Since such an interval defines a correction region from say -0·25% to -0·5% (the Shift Register on Fig.112, fed by AND-gate "17") equivalent to Register delays of from 1 to 2 Register-location shifts, the input pulses within "$V_{VID}(t)_{out}$" require delays from

$$"2\frac{\Delta t}{2} - \Delta T" \text{ to } "\frac{\Delta t}{2} + \Delta T". \quad \ldots\ldots \quad 8.2$$

where $\Delta T \rightarrow 0$. "$\frac{\Delta t}{2} - \Delta T$" to "$\Delta T$" is the delay correction performed by the first F/F of each Register. Consequently the possibility exists of video input pulses being coincident or near-coincident with the H-clock shift pulses; with the F/F switching and propagation delays "δt_{F1}" taken into account, a pulse requiring only a 'ΔT' delay may be instead delayed by $\Delta T + \frac{\Delta t}{2}$ instead. This is because for pulses corresponding to display locations adjacent to distortion boundaries $\Delta T \rightarrow 0$, and thus

$$\delta t_{F/F} > \Delta T \quad \ldots\ldots\ldots\ldots \quad 8.3$$

resulting in the "1" output of F.F "15", say, being presented to the AND-gate "21", after the H- clock pulse! Only at the following H-clock pulse (and thus after an added "$\frac{\Delta t}{2}$" delay) will that pulse be shifted to the following register location. Thus display locations near distortion region boundaries may be displaced by half a location position, and at the subsequent CRT-Vidicon cycle, will be rejected. The visible display may thus have a "ghost" image of the H-distortion map as on Fig. 104(a) (or parts of it) visible by some required display locations not displayed at those points.

The AND-gate " 22", in parallel to the first stage of the Shift Register circumvents this undesirable effect. The AND-gate "22" is enabled only when the H-clock pulse and the input pulses within "$V_{VID}(t)_{out}$" are coincident, or near-coincident enough to enable it on. It thus **sets** the second Register F/F of each Shift Register (in this case F/F "17"), (or else is output directly when only a delay of up to "$\frac{\Delta t}{2}$" us is required) with the OR-gate-delay "δt_o" (which approaches ΔT) later. This OR-gate, output pulse also clears F/F "15" which by this time interval has been set to "1".

The output of all the correction Shift Registers is OR-ed, the output being the required corrected output.

The timing diagram in Fig.112 illustrates this more clearly.
Only the pulse shifts in the first two stages of any Shift Register have been given as these race problems occur in the first F/F of each register. No truth tables and state tables are given for the Shift Register circuits, as meaningful information for such continuously varying

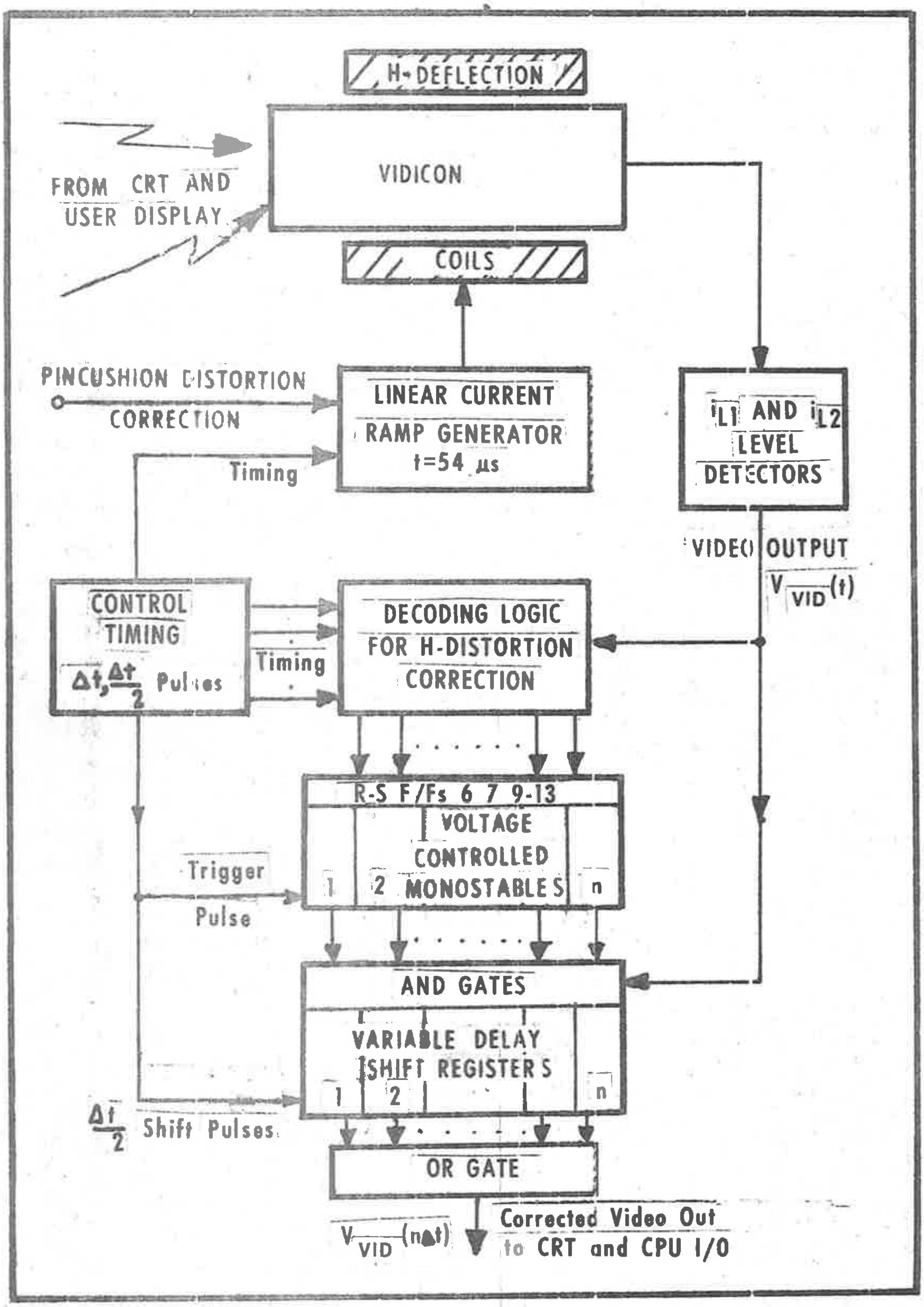


Figure 113. Functional Block Diagram of Vidicon Horizontal Scanning Generation and Correction Circuits.

'asynchronous' input pulses tends to be marginal; the timing diagram is more illustrative.

The complete Vidicon H-correction and deflection system is shown in Fig.113.

8.3.3.3. Accuracy of Correction System

The possibility of two Shift Registers being enabled on at any given instant (particularly during the transition from one distortion region to another) does not occur, as the lagging edge pulse of one Monostable triggers the following Monostable, the edge being detected by a "Lagging-edge Pulse Detector"; the overall delay during this transition between shift registers is much less than "Δt", the separation between two adjacent video pulses prior to correction.

The accuracy of specifying the lagging edge of a Monostable depends on the linearity of the "control voltage / output quasi-stable state duration" relationship; this (see chapter 11) is better than 0·3%. The absolute accuracy in specifying the boundary is to be better than "Δt" (to fall in between 2 display locations).

As the accuracy of a Monostable is better than 0·3%, it is clear that the longer the duration of the quasistable state, the more likely is 0·3% of the pulse duration approach "Δt".

In the worst case the maximum pulse duration of a Monostable is 32·4us, the width of the active display area; as this contains 200 display locations, with location separation being "Δt," then 0·3% accuracy corresponds to a boundary specification with an uncertainty of some "0·6Δt", which is of the order required. In practice, Monostable pulse duration is equivalent to less than 200 display location time intervals; thus the % non-linearity in pulse length duration equivalent to "n" display locations which can be tolerated is

$$\frac{\Delta t}{n.\Delta t}.100\% = \frac{1}{n} . 100\% \quad . . . . . 8.4$$

Thus to specify a display region of $\frac{1}{3}$ of the active display width (a typical distortion region - see Fig.104), $n \simeq 50$ and thus the monostable lagging edge position uncertainty which can be tolerated is 2%.

However the accuracy of the Pulse Integrators generating the control voltage for the Monostables, and of the Monostables themselves (particularly in the ability to specify the position of its lagging edge and hence of the pulse duration when fall times become appreciable with pulse duration), depend on the absolute pulse duration, and decrease as pulse duration decreases.

The decrease in Pulse Integrator linearity and Monostable "control-voltage/pulse length" linearity with decreasing pulse length are adequately accomodated in the relaxed conditions for accurately specifying the lagging edges of the monostables.

The circuits described above thus perform the variable Horizontal-coordinate correction for the Vidicon. For a "non-linear" Vidicon output "$V_{VID}(t)_{out}$" evidenced by the "asynchronous" video pulse train, the output of the bank of Shift Registers is the required corrected 'linear' (or "synchronous") video pulse train "$V_{VID}(n\Delta t)$" and is suitable as direct CPU input via the CPU I/O interface unit.

More usually it is recirculated back into the CRT for display refreshing.

8.4. H- SCANNING WAVEFORM GENERATION AND CORRECTION FOR CRT

8.4.1 Introduction

The video input pulse train to the CRT "$V_{CRT}(n\Delta t)m$" consists of constant period pulses originating either from the corrected Vidicon output pulse train or else from the CPU I/O unit. The resultant CRT screen display would appear distorted unless correction on this input pulse train is performed. The CRT H-coordinate Correction Circuits reposition these input pulses by selectively delaying them; the resultant corrected pulses actually entering the CRT beam-modulation circuit consist of an apparently "distorted" pulse train (i.e. interpulse time intervals are no longer constant) which results in a linear H-coordinate CRT display; this is "$V_{CRT}(t)_{out}$." This is in contradistinction to the action of the Vidicon H-coordinate Correction Circuits where the periods between the video pulses prior to correction were non-constant, and after correction, were constant resulting in a "synchronous" pulse train. The H-coordinate correction requirements in the CRT are the opposite to that required in the Vidicon.

For the Vidicon as stated above in section 8.3, the corrected, repositioned pulses "$V_{VID}(n\Delta t)$" are made coincident with H-clock pulses; <u>the exact distortion correction which corresponds to the amount of time delay required, is not required to be known exactly</u>, so long as it is known within which correction range a given position pulse falls i.e. whether, say, between 0·25- 0·5% delay is required, or not. The video position pulse is then gated into the appropriate Correction Shift Register;

the time interval between its entry into that Shift Register and its exit and read-out by an H-clock pulse, corresponds to the required time delay correction.

For the CRT on the other hand, the positions of each pulse within the input video pulse train is known since it is a "synchronous" pulse train, "$V_{CRT}(n\Delta t)_{in}$" ; each such pulse must be repositioned individually by a different amount of delay by the Correction Circuits. These differing corrections for each pulse are analytically non-describable and are only described by "distortion maps" analogous to the H-correction maps for the Vidicon; yet such maps only specify correction increment regions and not point by point dorrection information. Hence in CRT H-coordinate correction some degree of approximations must be tolerated.
Overall, the H-coordinate correction in CRTs is more complex than in the Vidicon.

8.4.2 Interpretation of Graphic Distortion Correction Information.

8.4.2.1 General Interpretation

The identical H-distortion map as for the Vidicon is used to illustrate an actual case of distortion correction. It was, after all, derived for the 14" TV monitor under test (77). It must be remembered that for this particular distortion map, pincushion distortion was not removed by analytically describable correction wave-forms (see section 9.4) as would normally be the case. The distortion shown and to be corrected, is thus much greater than would normally be expected; however, it may be taken as the "worst case" distortion. The resultant Correction Circuits will help to show that, in principle, any degree of distortion can be corrected.

The distortion convention (referring to the original distortion map in Fig.101(a) states that within display areas bounded by positive signs, locations are displayed behind their "no-distortion ideal" locations, and thus need be advanced in time, while within display areas bounded by negative signs, locations are displayed prior to their "no-distortion ideal" locations, and thus need be delayed in time.

As the remanent distortion requirements for the CRT are identical to those of the Vidicon, and since for both devices, corrective delays need be implemented, the previously derived distortion map, with 0·25% distortion contours as shown in Fig.104(a) is valid for the CRT. It is shown redrawn, and with slight modifications, in Fig.114(a).

The meaning of the distortion contours is also identical to the meaning for the Vidicon.
Thus for the line AA':

(1) locations to be displayed in the region defined in the H-scanning time interval by "T_{AS}" to "T_{AS} + 3·5"us need be progressively delayed from between "$\frac{\Delta t}{2}$" to "Δtus" where $\Delta t \approx 0{\cdot}162\mu s$. ($T_{AS} = 20{\cdot}8\mu s$, the time indicator from the start of a H- scanning interval, corresponding to the start of the active display area).

(2) locations to be displayed in the region defined by "T_{AS} + 3·5"μs to "T_{AS} + 20·2"μs need be progressively delayed from between "Δt" to "$\frac{3}{2}\Delta t$" μs and thence back to "Δt"us again.

(3) locations to be displayed in the region defined by "T_{AS} + 20·2"us to "T_{AS} + 28us" need be progressively delayed from between "Δt" to "$\frac{\Delta t}{2}$"us.

(4) the remaining display locations located between "T_{AS} + 28"µs to "T_{AS} + 32·4"µs need be progressively delayed from between "$\frac{\Delta t}{2}$" to 0us.

Thus the distortion contours, as before, specify regions where the delay is given by an integral number of "0·25% correction increments" and a variable delay of magnitude less than a "0·25% correction increment."

The near identical distortion requirements for the CRT to those of the Vidicon and the very similar H-distortion maps in both cases (in actual cases the two H-distortion maps are very different but the distortion contours specify identical distortion increments), suggests that at least the Distortion Information Graphics Storage is identical in form for both the Vidicon and the CRT, as shown in Fig.104(b). In fact only slight differences, mentioned below, exist.
The location of this graphics information is in the R-H section of the CRT scanned area as shown in Fig.105.

A further consequence of the similarity between the CRT and Vidicon distortion graphical information is that the logic and circuitry decoding this graphical information will be very similar to that required for the Vidicon H-correction decoding circuitry.

8.4.2.2. Approximations

Fig.120 shows the delay provided to several equi-spaced pulses, corresponding to the input video pulse train, "V_{CRT} $(n\Delta t)_{in}$" resulting in the corrected pulse train giving the linear CRT display "$V_{CRT}(t)_{out}$". The example shown corresponds roughly to a section of the AA' line in Fig. 114(a), in the vicinity of the maximum distortion line (the broken line in the figure). Several facts are readily seen from this:

(i) within each region defined by two consecutive distortion lines, the required correction delay gradually increases (or when moving away from the centre of the display, decreases), with the increase in delay (or decrease) between the first and last location within the distortion region being a time interval of "$\frac{\Delta t}{2} \approx 0{\cdot}081$us".

As a first approximation, then, it may be assumed to vary linearly, corresponding to a linear increase (or decrease) in the delay required. The linear rate of increase being such that the resultant location pulse delay increases (or decreases) between any two consecutive distortion lines by "$\frac{\Delta t}{2} \approx 0{\cdot}081$us".

(ii) Within the "central" region, defined in the distortion map on Fig.114(a) by the 2 distortion lines of "-0·5%" distortion, and in other distortion maps, by any 2 consecutive distortion lines of the same distortion, a maximum distortion occurs for any H-line. For the line AA', this maximum distortion is about "-0·63%" occuring at approximately "T_{AS} + 12"µs. Within the region "T_{AS} + 3·5"µs to "T_{AS} + 12"µs the distortion (and hence correction delay) increases to this maximum distortion. Past this maximum distortion, within the region "T_{AS} + 12"us to

"T_{AS} + 20·2" us, the distortion (and hence correction delay) decreases back to "-0·5%."

This "trace of maximum distortion" is required and is shown drawn in a broken line (for emphasis) in Fig.114(a); it is treated by the Graphics Distortion Information Decoding Logic and Circuitry as just another distortion line. The value of this maximum distortion changes from horizontal line to horizontal line, from a maximum of some "-0·75%" at the "-0·75% contour" to a distortion of "-0·6%" near the centre of the display area. It is thus a function of the vertical coordinate. As the magnitude of the maximum distortion is also required, an added "Vertical Correction Line" of similar form to the "Vertical Coordinate Correction Line" (see section 7.6) is provided. This is further explained below in section 8.4.3.5.2.

8.4.3 H- Correction Implementation

8.4.3.1 Introduction

The variable correction delay can be provided by feeding "$V_{CRT}(n\Delta t)_{in}$" into a set of Shift Registers in parallel, one Shift Register of which is enabled "on" at any instant. The "$V_{CRT}(n\Delta t)_{in}$" pulses are shifted pulse by pulse by a trigger or shift pulse train of nominally "Δt" separation, but in fact, of variable interpulse time separation, of the required corrected time spacing. The input is thus the "synchronous" video pulse train, while the output is the "asynchronous" pulse train "$V_{CRT}(t)_{out}$" to result in a linear H-coordinate CRT display (see Fig.120). The variable period shift or trigger pulse train is obtained from Voltage Controlled Astable Multivibrator (V.C.A), whose leading edges are detected and provide an impulse train. The V.C.A can be synchronized or preset to have its leading edges start at any required instant by external reset pulses, such as the pulse indicationg the start of the active display area "T_{AS}" or by Distortion Line pulses etc.

8.4.3.2. Correction by Voltage Controlled Astable Multivibration.

For a Voltage Controlled Astable, the resultant frequency is given by

$$f = V_o + K.V$$

where "V" is the control voltage

"V_o" and "K" are constants.

The period "Δt" between the leading edges of two adjacent pulses is clearly

$$\Delta T = \frac{1}{f} = \frac{1}{V_o + KV} \quad \ldots\ldots\ldots .8.5$$

For a change in the period from "ΔT" to some "$\Delta T + \delta T$"

then $$\Delta T + \delta T = \frac{1}{f + \delta f} \quad \ldots\ldots\ldots\ 8.6$$

which, if $\delta f \ll f$, reduces to

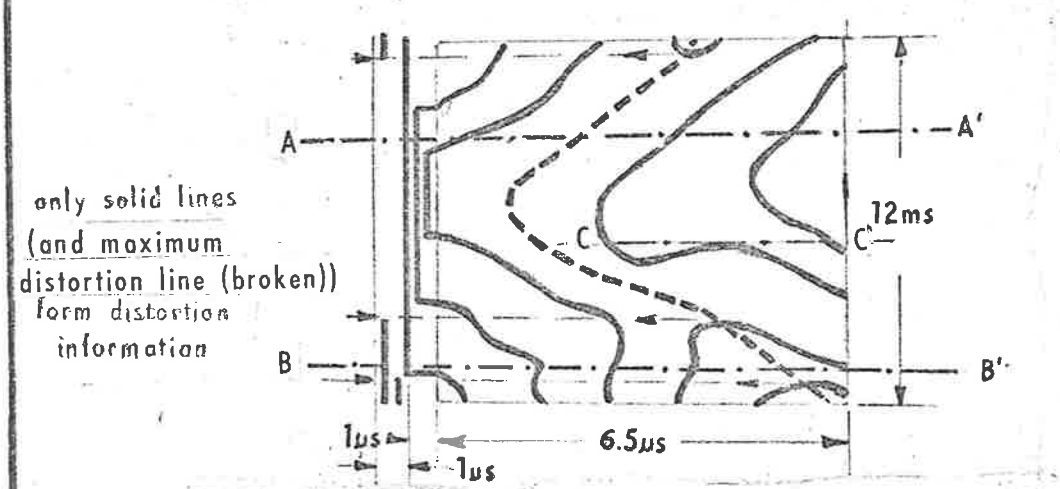
$$\Delta T + \delta T = \frac{1}{f} - \frac{\delta f}{f^2} \quad \ldots\ldots\ldots\ 8.6(a)$$

Hence the % change in the period "$\frac{\delta T}{\Delta T}$" is clearly given by

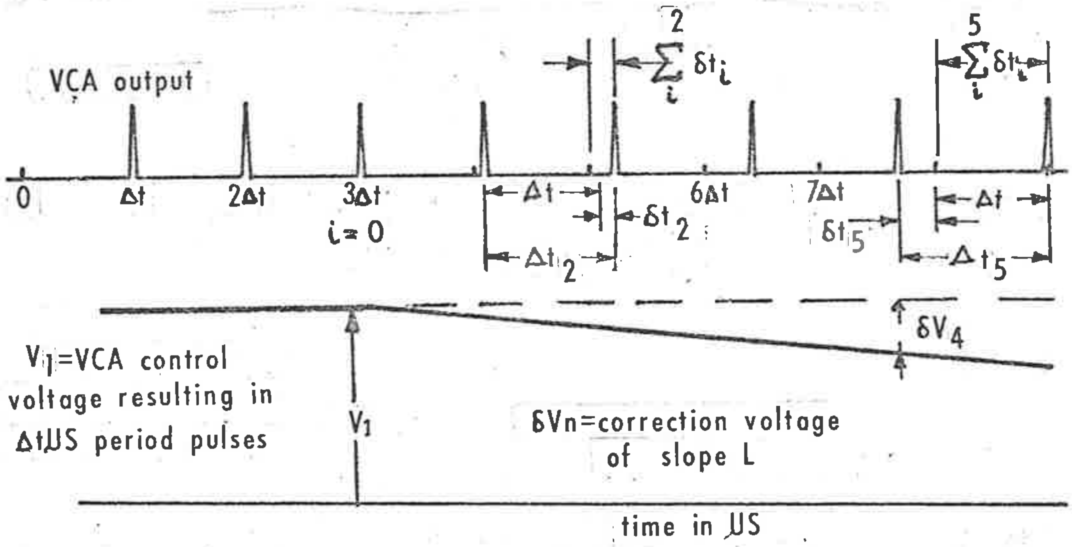
$$\frac{\delta T}{\Delta T} = - \frac{\delta f}{f^2} \bigg/ \frac{1}{f} = - \frac{\delta f}{f} \quad \ldots\ldots\ldots .8.7$$

$$= - \frac{\delta V}{\frac{V_o}{K} + V} \quad \ldots\ldots\ 8.7(a)$$

showing that a % change in the period is given an equivalent



(a) Graphical format of CRT correction information. It is essentially of the same form as that shown in Figure 104(b) except for the inclusion of the maximum distortion line (shown broken for emphasis) This storage area of 6.5 μs is compressed in a ratio of 1:4.99 with respect to the CRT active display area.



(b) The Voltage Controlled Astable output pulses under varying control voltage, showing the notation used, including the difference between "accumulative time delay $\sum \delta t$" and "interpulse time delay δt".

Figure 114. Concepts for CRT H-coordinate Correction

% change in the frequency of a V.C.A if the frequency deviation is less than, say, 20%.

For a "very distorted "CRT, assume a distortion corresponding to "0·5%"($\Rightarrow \Delta t \approx 0{\cdot}161$us), will occur within a scanning time interval as short as, say 2μs (in practice as can be seen from Fig.104, this normally will occur within a time interval of normally, say, 5-10μs). Within 2μs, approximately 12 display locations may occur, each separated by "Δt" secs. Within that interval, the 12th pulse will be shifted ("delayed") by an extra "Δt" with respect to the 1st pulse, over and above the normal "$12\Delta t$" pulse intervals; as that extra "Δt" shift has been introduced gradually in a linear fasion over the 12 pulses, the period of the final pulse "ΔT_{12}" is given by

$$\Delta T_{12} = \Delta T + \delta T_{12}$$

where $$\delta T_{12} = \frac{12}{\sum_{1}^{12} n} \cdot \Delta T,$$ the change in period from its nominal value "ΔT"

Hence $$\frac{\delta T_{12}}{\Delta T} = \frac{12}{78} \approx 0{\cdot}15,$$ satisfying the requirement of $\delta f \ll f$.

Thus even in the unlikely case of the distortion gradient quoted above, the V.C.A gives the required time delay correction correctly.

Fig.114(b) illustrates the resultant output pulse periods under varying control voltage for a Voltage Controlled Astable.

A simple ultra-linear VCA with a very linear range of about 4:1 is described in chapter 11. To obtain a range of 1:1·15 in such a VCA poses no problems.

8.4.3.3. Requirements of Correction Voltages for the VCA

Now the separation between any two adjacent distortion lines implies that shift pulses into the Shift Register, from the VCA, have an added accumulated time delay between the first and last shift pulse, in the distortion range defined by the distortion lines, equal to "$\frac{\Delta t}{2}$" us.

If it is assumed that this added time delay due to the decrease of VCA frequency is introduced gradually in a linear fashion (as is is assumed distortion between 2 adjacent distortion lines increases (decreases) linearly), such that the first location pulse within such a distortion region is least (most) delayed while the last location pulse is delayed most (least), then

$$\frac{\Delta t}{2} = \sum_{i}^{n} \delta t_i \quad \ldots\ldots\ldots\ldots \quad 8.8$$

where "n" is the number of location pulses within that distortion region

and "δt_i" is the delay of the "ith" pulse within that region.

If "δt_i", the added (decreased) delay due to the VCA frequency decreasing (or increasing), is provided by a linear decreasing ramp correction voltage, then according to expression 8.7(a)

$$\delta t_i \propto \delta V_i$$

or

$$\delta t_i = \left(\frac{-\Delta t}{\frac{V_o + V}{K}}\right) . \ \delta V_i \quad \ldots\ldots\ldots\ldots \quad 8.9$$

$$= C \, . \, \delta V_i \quad \ldots\ldots\ldots\ldots \quad 8.9(a)$$

Where "C" = $\left(-\dfrac{\Delta t}{\frac{V_o + V}{K}}\right)$

"δV_i" is the instantaneous ramp correction voltage.

Thus from expression 8.8,

$$\frac{\Delta t}{2} = C \sum_{i}^{n} \delta V_i$$

Since "δV_i" is a value of a ramp correction voltage

$$\delta V_i \propto n \Delta t \qquad n = 1, 2., i, .. n$$

or

$$\delta V_i = L.n \Delta t \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ .8.11$$

where "L" is the slope of the ramp correction voltage.

Thus $$\frac{\Delta t}{2} = C.L. \Delta t . \sum_{i}^{n} n \quad . \ . \ . \ . \ . \ . \ . \ . \ 8.12$$

$$= C.L. \Delta t . \frac{n(n + 1)}{2} \quad . \ . \ . \ . \ . \ 8.12(a)$$

or $$1 = C.L . n (n + 1) \ . \ . \ . \ . \ . \ . \ . \ .8.13$$

As the distance between any two consecutive distortion lines is proportional to the number "n" of display locations within that region, and as "$\delta V_i \propto n$" from above, it can be seen that, from expression 8.13, to keep "$\frac{\Delta t}{2}$" constant, for a varying "n", "L", the slope of the correcting control ramp voltage must be varied. Clearly for constant "$\frac{\Delta t}{2}$", the ramp slope variation must be

$$L \propto \frac{1}{n^2 + n} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ .8.14$$

As this voltage ramp performs the correction, it must be known prior to the implementation of the correction.

Thus in addition to specifying the regions where given Distortion Correction Regions are required, the information derived from the Graphic H-distortion Curves must also specify information to generate the slope of the 'ramp correction voltage' into the VCA.

8.4.3.4. Generation of Correction Voltages fro the VCA

The method of deriving this ramp slope information is as follows:

(i) from expression 8.14, the slope "L" is clearly dependent on "n", the number of possible display locations within the region specified by two adjacent distortion lines, and hence, as display locations are nominally equispaced in time, the slope "L" is dependent on the time interval defined by two adjacent distortion curves.

(ii) If H-clock derived pulses are gated with such a time interval when the H-distortion CRT lines are scanned from the CRT graphics stored information in the R-H portion of the CRT scanned area, the number of such H-clock pulses gives this time interval directly. The pulses may be fed into a "Ripple Counter", one such Ripple Counter for each expected distortion region. A stored, digital representation of the time interval corresponding to each distortion region is thus available.

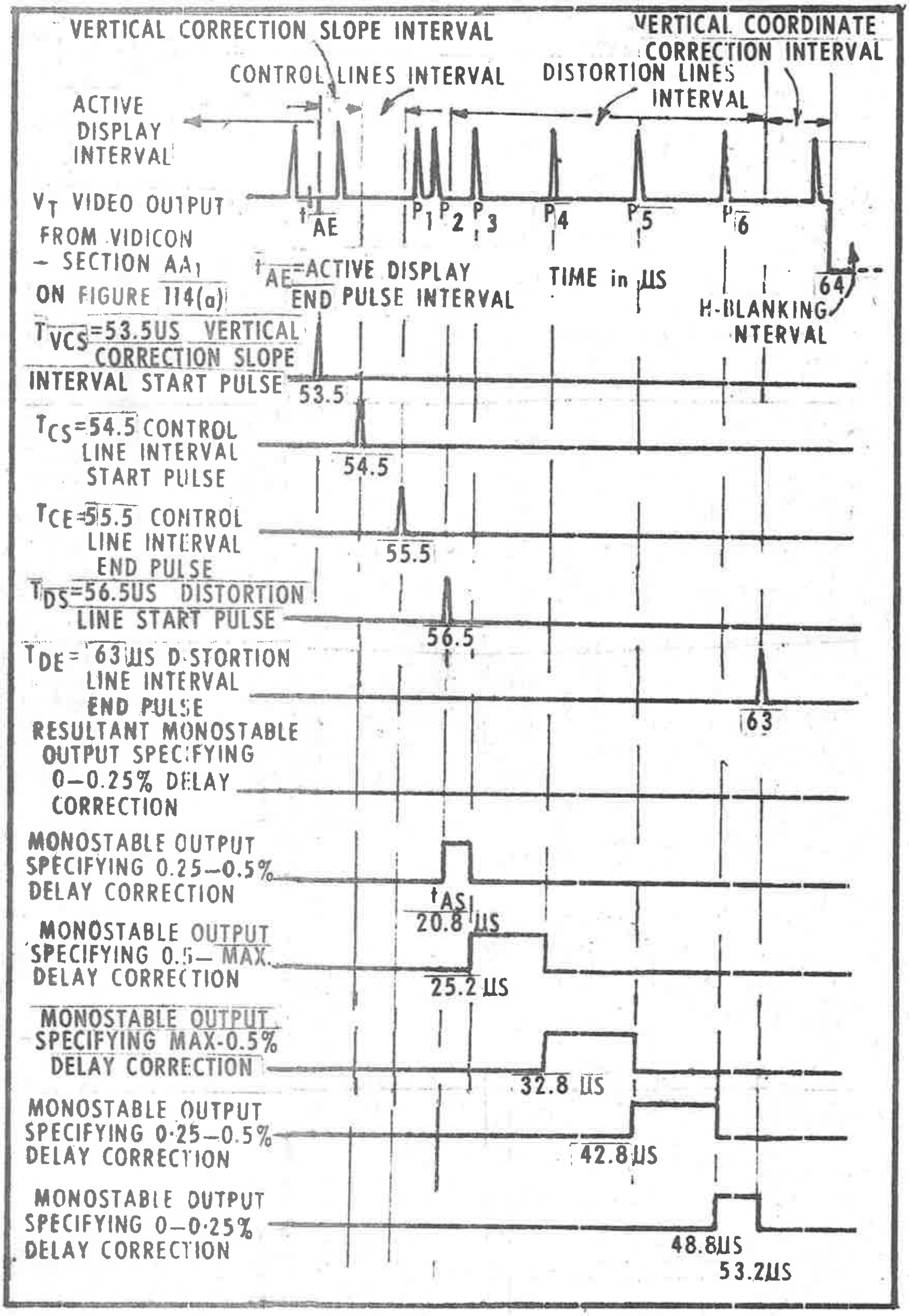


Figure 115. Timing and Control Signals from the H-Distortion Information for CRT Display Correction

For the case shown in Fig.114(a), distortion ranges from 0 to "-1·25%," and with "0·25%" distortion regions requireing specifying, 5 such regions are expected. Moreover, since each distortion increment has, in a symmetrically distributed distortion map, two distortion regions (one, where distortion increases, say from "-0·25% to -0·5%," and another region where distortion decreases, from "-0·5% to -0·25%"), 10 such distortion regions can be expected. In the actual case shown, due to the unsymmetrical distortion map in the lower Right-hand region, only 7 such distortion regions are thus present. Hence 7 Registers or Ripple Counters" must be provided to define the time interval of these distortion regions. Since in theory, a distortion region can vary in width from about 1 to 200 location time-intervals and thus can be specified by up to 200 H-pulses, each ripple counter would need to be up to 8-bits long.
As each of these counts (up to 200 possible counts) would need to be associated with a different correction voltage ramp slope, (expression 8.14), greatly increasing the amount of logic and hybrid circuitry required, some form of compromise need be made.

(iii) In practice thus, each such counter is a 4-bit counter. Thus the active display region is effectively quantized into up to 16 regions, each of $\frac{32\cdot 2}{16} \approx 2$us length and consequently there will be up to 16 different voltage ramp slopes possible. In our case, as seen in

Fig.114(b) ,the longest distortion region "CC'" is approximately 16µs long. Consequently only a "3-bit Ripple Counter" is required. The distortion regions will also be quantized into 2µs increments rather than into the "continuous" time increments before. However the same "continuous" distortion map as before still can be used with the quantitizing being hardware-implemented.
The upper half of the circuit in Fig.116(down to CSL "1- 7") accomplishes this.
The CRT H-distortion correction information takes "6·5us" to scan horizontally (as distinct from "7·5us" for the Vidicon H-distortion information). This "6·5us" need be quantized into 16 regions corresponding to the 16 quantized regions of the active display area. Thus indicator pulses of $\frac{6\cdot5}{16} = 0\cdot406$us are required. As "$\frac{\Delta t}{2} \approx 0\cdot081$us" clock-pulses are available for the Vidicon H-correction Shift Registers, and as $5 \times \frac{\Delta t}{2} = 0\cdot405$us, then dividing the "$\frac{\Delta t}{2}$ pulse train" by "5" provides the necessary quantized region indicator pulses.

The distortion line pulses "P_i" occuring within the $(6\cdot5 + 1)$us interval, from "55·5 to 63" us, are gated into a Ripple Counter labelled "$\div$ 8 Counter, C_2", similar to the Vidicon H-correction gating circuit "Counter "C_1"" in Fig.109. The serially-to-parallel decoded pulse counts, are fed into a set of R-S Flip/Flops "1-7" (corresponding to R-S F/Fs "9-13" in Fig.110), with the first Distortion Line pulse "P_1", fed into the first R-S F/F "1",

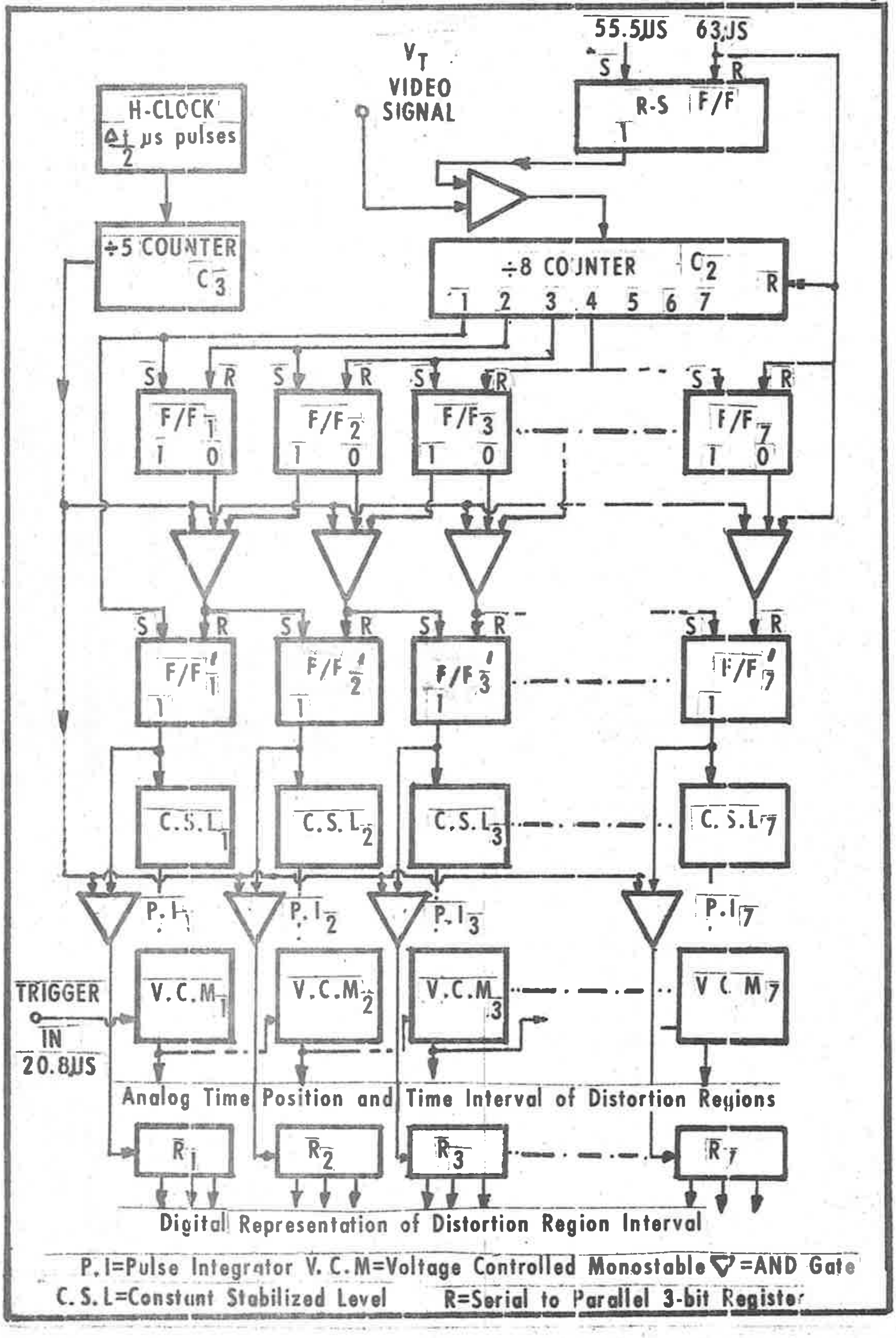


Figure 116. Block Diagram of Logic Defining Distort-Regions in 2us Increments Digitally and in Analog Form.

which is one of a set of FF's in parallel with the first, and labelled R-S F/Fs "1'-7'".

The additional AND-gates, in between, ensure that the subsequent Set and Reset pulses for F/Fs "1'-7'" occur at the required 0·406us time markers, derived from the "÷ 5 Counter, C_3". The time outputs specified by F/Fs"1'-7'", corresponding to the Distortion Regions are thus approximated into quantized 0·406us increments which when scaled up by a factor of "4·99:1" (=32·4:6·5) during the active display region scanning interval, result in the required 2µs quantized distortion regions.

The outputs from the FFs "1'-7'" then specify the distortion intervals by being gated with the ($\frac{\Delta t}{2}$ ÷ 5) pulses, and are then fed serially into the corresponding 3-bit Ripple Counters R"1- 7" to specify the time distortion interval digitally.

Also, as for the Vidicon H- distortion Correction Circuits, the F/Fs"1'- 7'" specified time intervals are fed into Pulse Integrators PI "1 - 7", to specify the same time intervals, in an analog form by having the Integrator output voltage control Voltage Controlled Monostables", VCMs "1 - 7" in a similar fashion as the VCMs "1 - 7" in Fig.110.

Similar modification to the gating circuits enabled by the "control lines", defining the assymmetrical distortion regions of "-0·75", - "1·25%, need also be made. (This is left till Section 8.4.3.6).

(iv) For the Section AA' in Fig.114(a) the modified or 2µs-interval quantized distortion regions become:

(1) corresponding to the region "T_{AS}" to "T_{AS} + 3·5"us ,the region is defined as from "T_{AS}" to "T_{AS} + 4"us.

(2) corresponding to the region "T_{AS} + 3·5"us to "T_{AS} + 11·8"us,the region is defined as "T_{AS} + 4"us to "T_{AS} + 12"us.

(3) corresponding to the region "T_{AS} + 11·8"us to "T_{AS} + 20·2"us, the region is defined as from "T_{AS} + 12"us to "T_{AS} + 22"us.

(4) corresponding to the region "T_{AS} + 20·2"us to "T_{AS} + 28"us,the region is defined as from "T_{AS} + 22"us to "T_{AS} + 28"us.

(5) the region from "T_{AS} + 28"us to "T_{AS}+32·4"us the region is defined as from "T_{AS} +28"us to "T_{AS} +32 us".

The small differences between the actual correction required and the correction implemented due to the resultant correction boundaries not being exactly coincident with the measured correction boundaries can be neglected,as they fall well within the permissable remanent distortion after correction of less than 0·25%.

(v) The 3-bits in each Register "R 1-7" specify a number up to "8",each corresponding to one of the 8 possible lengths or durations of distortion regions.

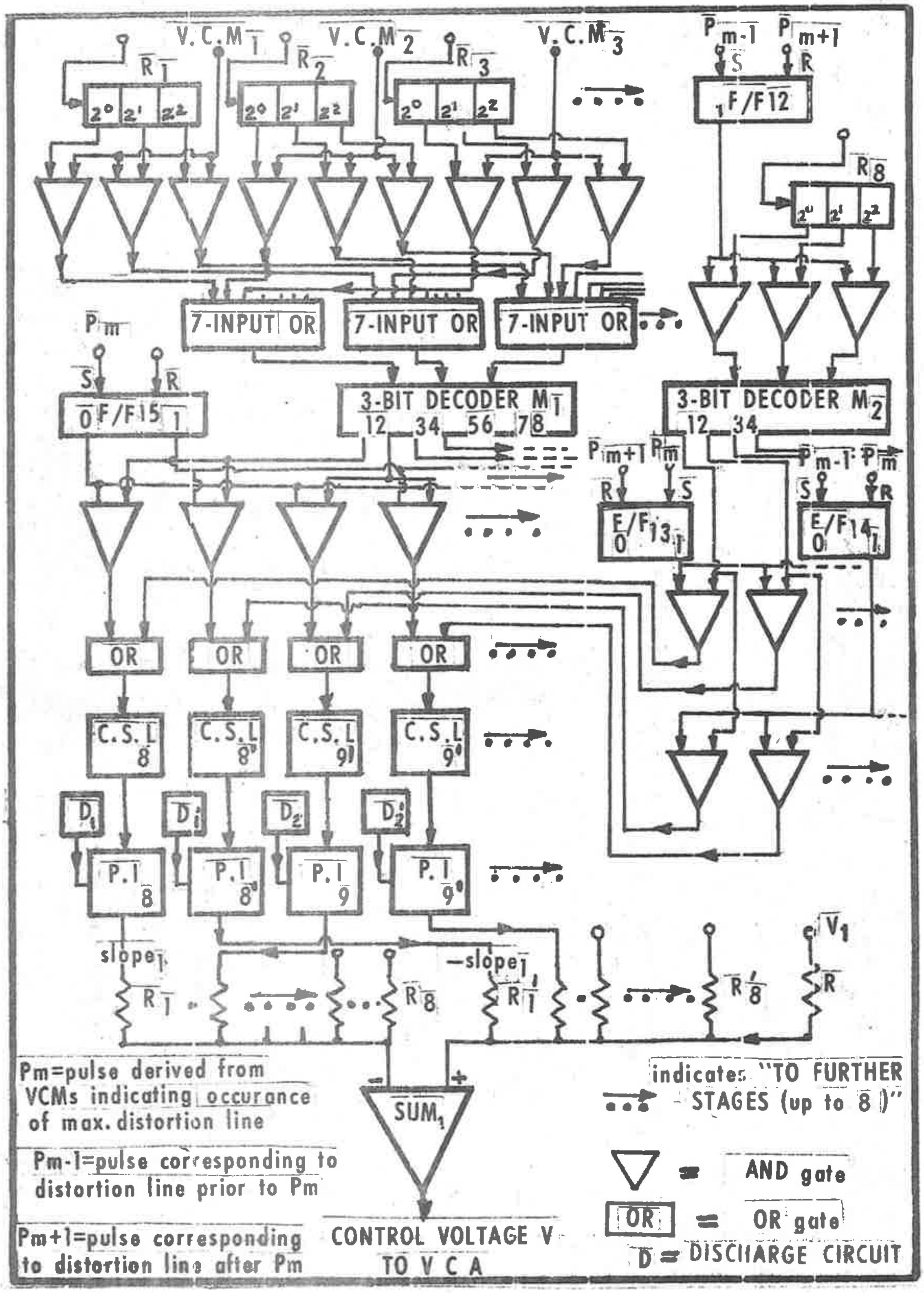


Figure 117. Block Diagram Showing the Generation of Correction Ramp Voltages of Varying Slope.

Associated with each of these 8 possible integers is a Pulse Integrator PI "8 - 15", each having a different slope of the resultant ramp output when a constant level pulse is integrated.

This can be achieved by a simple 3-bit Decoder labelled "M_1" in Fig.117, which makes available all of the 8 possible outputs, individually enabling its corresponding Pulse Integrator. As there are 7 Registers, the 3-inputs to Decoder M_1" is via 3 "7-input OR-gates", from the corresponding bit positions from all of the registers, "R_i". At any instant only one Register "R_i" is enabled "on".

By suitable logic and gating, each of these numbers is gated to its corresponding Pulse Integrator, and integration is initiated at the appropriate instant by the "1" output from its corresponding Voltage Controlled Monostable VCM "1 - 7" and for the appropriate length of time corresponding to the distortion region - refer to Fig.117.

The output of the Integrator, to a constant level input pulse, is a ramp voltage, whose slope can be controlled by the value of its "control" resistor or "control" capacitor (see section 11.5.3). The output voltage at any instant of the Integrator depends on the slope and the previous duration of the integrated pulse. These ramp voltages are the "Correction Voltages" to the control voltage governing the frequency and hence period of the VCA which gives the trigger shift pulses to the Shift Registers performing the required pulse delays.

The required output slopes for the various interval length distortion regions can be found as follows:

If the count in one of the Registers is "1", it specifies a distortion region of "2us" width; similarly a count of "2" specifies a distortion region of "4us" width and so on; a count of "8" thus specifies a distortion region of "16us".

Within a width of 2us there are

$$\frac{2}{32\cdot 4} \cdot 200 \approx 12\cdot 3 \text{ pulses, say 12 pulses nominally}$$

corresponding to 12 H- coordinate locations.
Similarly within a width of 16us there are some 98 pulses.
Now from expression 8.13,
the slope "L" of the ramp voltage is given by

$$L = \frac{1}{C.n.(n+1)}$$

where "C" $= -\left(\frac{\Delta t}{\frac{V_o}{K}+V}\right)$, from expression 8.9(a),

"n" is the number of pulses within an interval giving an accumulated pulse delay of "$\frac{\Delta t}{2}$"

Thus

$$L = -\frac{V_o + KV}{K(\Delta t.n)(n+1)} \quad \ldots\ldots\ldots 8.15$$

Now "Δ t.n" is the length of the distortion interval which contains "n" display locations.
Thus the required output voltage ramp slope of the Integrator to be used for a "2us" distortion interval is

$$L_1 = -\frac{(V_o + KV)}{13.K} \cdot \frac{1}{2} \text{ Volts}/\mu s \quad \ldots .8.15(a)$$

where "V" is the voltage into the VCA resulting in a pulse train of period "Δ t"us,

"13" because within 2us there are 12 pulses,

"2" because the time interval is 2us duration.

Similarly for the "4us" distortion interval, the slope required is,

$$L_2 = -\frac{(V_0 + KV)}{25.K} \cdot \frac{1}{4} \text{ Volts/us} \quad . . . .8.15(b)$$

For the 16us distortion interval, the slope required is,

$$L_8 = -\frac{(V_0 + KV)}{100.K} \cdot \frac{1}{16} \text{ Volts/us} \quad . . . . . 8.15 (c)$$

The ratios of the ramp slopes of the Integrators corresponding to the 2,4,6...16us distortion range Integrator respectively are

$$\frac{1}{13.2} : \frac{1}{25.4} : \frac{1}{37.6} : . . . . . 8.16$$

i.e.

$$\frac{1}{6.2.13} : \frac{1}{6.4.25} : \frac{1}{6.8.3} :$$

$$\frac{1}{n(n+1)} : \frac{1}{2(n)(2n+1)} : \frac{1}{3(n)(3n+1)} : . . . . 8.16(a)$$

where n = 12, the number of pulses in a 2us time increment. This is as expected from the expression 8.14.

The ramp outputs of these Integrators, PI "8-15" is summed in an analog Summer along with the voltage "V_1", which is the nominal voltage required to generate the pulse train of period "Δt" at the VCA. The summed result is the actual input control voltage to the VCA (see Fig.117). Because the summer SUM "1" is present, the slope variation, rather than be performed within the Integrators can be achieved by varying the input summing resistors in the above ratios given by 8.16(a), with each Integrator now

being identical in all respects.
Because of the negative sign of the slope the inputs of these "correction ramp voltages" are fed into the inverting input of the OP-amp. Summer while the "V_1" input is fed into the non-inverting input.

Each distortion region contributes a cumulative pulse delay of "$\frac{\Delta t}{2}$" µs and these "$\frac{\Delta t}{2}$" µs delays from these regions are themselves cumulative as successive distortion regions are entered.
In the above, all successive pulses within a new distortion range will be delayed by the cumulative delay just prior to this new distortion range. The Pulse Integrator ramp voltages corresponding to all prior distortion ranges must thus be disabled, otherwise they will continue to generate unwanted increased pulse delays. The disabling of the Integrator (see Fig.117) is achieved by discharging each integrator via the Discharge Circuits "D 1-8" and "D 1'-8'" by a pulse corresponding to the lagging edge of the "1" output of the VC Monostable specifying the integration period (and hence the distortion range), within a period of less than $\frac{\Delta t}{2} \approx 0{\cdot}081$ us. (The conditions for speed of discharge are given in section 11.5.4).

8.4.3.5 Distortion Correction within "central" distortion region.

8.4.3.5.1 Charge in sign in Distortion

Due to distortion symmetry about the centre axis of the active display area, pulses corresponding to display locations are progressively delayed more when scanning is in the L-H side of the active display area and going towards the centre, and progressively delayed less when scanning in the R-H side of the active display area.

The actual transition point occurs at the "Maximum Distortion Line" (shown broken in Fig.114(a)) and is thus indicated by the 4th Distortion Line pulse "P_4" from the " 8 Counter C_2" in the "Distortion Line Gating Logic" of Fig.116. As the accumulated delay progressively decreases past that line, it implies the slope of the Correction Ramp Voltage changes in sign. Consequently from expression 8.7(a),

$$\delta t = -\frac{K.\delta V}{(V_o+KV)^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 8.7(b)$$

A second set of 8 Integrators PI "8'-15'" is provided, identical in all respects to the first set, and gated with the distortion line pulse numbers "P_i", for "i" greater than "4" (i.e. those occuring after the Maximum Distortion Line). The output of these Integrators now is fed into the non-inverting input of the Analog Summer "SUM_1" as thence

$$\frac{1}{V_o + K(V_1 + \delta V)} \Longrightarrow T - \delta T \quad . \; . \; . \; . \; . \; . \; 8.6(a)$$

i.e. a nominal control voltage "V_1" and correction voltage "δV" summed give rise to a <u>decreased</u> time delay.
In Fig.117, the S-R Flip/Flop "15", is set by the pulse corresponding to the maximum distortion line "P_m" (and hence sign inversion); this pulse is derived from the VCMs "1-7" (see Fig.118(a)). The PI "8'-15'" are thence capable of being enabled on, while PI "8-15" will become inhibited.

<u>8.4.3.5.2. Change of Distortion Slope in Central Distortion Region</u>

The above scheme is satisfactory for defining and implementing the correction within a distortion interval defined by two consecutive distortion lines resulting in a cumulative delay of "$\frac{\Delta t}{2}$" us. For distortion regions such as the "central" distortion region defined by the two "-0·5%" distortion lines in Fig.114(a), containing the Maximum Distortion Line within it, the required cumulative delay, for section AA' say, is only about "-0·13%" at the location specified by the Maximum Distortion Line (the other "-0·5%" being provided by the two previous distortion regions). Moreover this added cumulative delay at the Maximum Distortion Line varies from some "-0·25%" to some "-0·10%" from near the -0·75% distortion contour to the centre of the active display area.

The maximum distortion, and thus the added cumulative correction delay, introduced within the interval defined by the "-0·5%" Distortion Line and the Maximum Distortion Line, varies and is a function of the vertical coordinate.

The simplest way to accomplish this variable peak accumulated delay is to treat all Distortion Lines including the Maximum Distortion Line as though each interval defined between two consecutive lines defines a "0·25%" distortion interval.
Call the correction voltage ramp for the H-line at vertical coordinate y_1, "$L_y(0{\cdot}25)$".

Call the slope of the ramp voltage which for the same time interval gives the required added accumulated time delay of say -0·13%, for section AA', "$L_y(0{\cdot}13)$".

Hence a "Correction Ramp" voltage must be subtracted from "$L_y(0{\cdot}25)$", to give the net slope "$L_y(0{\cdot}13)$".

This y-dependent "Correction Slope" information may be provided by an extra "Vertical Distortion Line" which may be drawn in an interval of up to "1us" wide. As the H- distortion Graphic Storage for the CRT is located within a H- time interval of "6·5us" (whereas "7·5us" were used for the H- distortion Storage for the Vidicon), this extra "1us" time interval is available. The position of the interval and line is shown in Fig.115.

The time interval defined by the horizontal location of the line within this "1us" time interval, and the instant of start of this time interval, is gated with "$\frac{\Delta t}{2}$ = 0·081us" clock-pulses; thus a pulse count up to "8" can be registered and stored in a 3-bit Register R "8". This stored number provides the required "Correction Slope" Information. It specifies and enables on one of the Pulse Integrators of a slope, whose output ramp voltage is input simultaneously to the Control Voltage Analog Summer SUM "1", with the ramp voltage giving a cumulative delay corresponding to -0·25%. The nett ramp voltage output of these two input ramps to the Summer is the required Ramp Slope giving the required accumulated delay at the Maximum Distortion Line. The "Correction Slope" Ramp is fed into the Summer "1" terminal of opposite polarity to the "-0·25%" delay Voltage Ramp.

Since the Maximum Distortion Line is taken as being located midway between the two "-0·5%" Distortion Lines, the two distortion intervals on either side of the Maximum Distortion Lines are equal in time width (this is in fact only an assumption but a reasonable one to make). As the cumulative distortion at both "-0·5%" Distortion Lines are equal, the increase and decrease of cumulative distortion within the two central time intervals are equal. Hence the same number in the 3-bit Register R "8" specifying the "Correction Slope" can be used for both regions. The S-R Flip/Flops "13,14" in Fig.117, set by the

distortion boundary prior to the Maximum Distortion Line, "P_{max-1}" and reset by the distortion boundary after the Maximum Distortion Boundary "P_{max+1}" thus defines the time during which slope correction is defined. Only the signs of the slopes change in both regions; as there are two sets of Pulse Integrators feeding the inverting and non-inverting inputs to the control voltage summer, the sign inversion is accomplished by gating the "Register Control Numbers" to the corresponding pairs of Pulse Integrators. The "control pulse" indicating that slope inversion, and hence interchanging the Pulse Integrators from PIs "8-15" to PIs "8'-15'", is set by the VCM lagging edge corresponding to the maximum distortion line "P_m".
The S-R Flip/Flops "13,14" in conjunction with their AND gates, perform this sign inversion.
These two Flip/Flops are themselves "Set" and "Reset" by pulses corresponding to the distortion boundaries on either side of the Maximum Distortion Line.

The resulting interval during which a particular PI is enabled on to generate a slope correction is gated in via the OR-gates just prior to CSL "1-7". This is shown in Fig.117.

If the region between the "-0·5% Distortion Line and the Maximum Distortion Line contains "n" display locations (n = 12, 24, ...), then the required Slope of the Voltage Ramp of the specified Integrator is (according to expression 8.15)

$$L_y(0{\cdot}25) = \frac{-(V_o + KV)}{K(n+1)\frac{n}{6}} \text{ Volts/us} \quad \ldots . 8.15(a)$$

$$= \frac{-(V_o + KV)}{K.\frac{n^2}{6}} \text{ Volts/us} \quad \ldots 8.15(b)$$

as "n" > 12

for the cumulative delay of -0·25%.
If the Maximum Distortion Line corresponds to an added cumulative delay of some

$$\left| D_y \right| < \left| -0{\cdot}25\% \right|$$

(for the line AA' in Fig.113(b), $D_y \approx -0{\cdot}13\%$) , then from expression 8.12(a) the required slope "$L_y(D_y)$" is derived. Thus

$$D_y(t) = C.L_y.\Delta t.n\,(n+1) \quad \ldots\ldots\ldots \quad 8.17$$

or

$$L_y(D_y) = \frac{D_y(t)}{\Delta t} \cdot \frac{(V_o + KV)}{K(n+1)\frac{n}{6}} \text{ Volts }/\text{us} \quad \ldots 8.17(a)$$

where "$D_y(t)$" is the time delay corresponding to distortion "D_y". Hence the "Correction Slope"

$$L_y(C_y) = L_y(0{\cdot}25) - L_y(D_y)$$

$$= \left(1 - \frac{D_y(t)}{\Delta t}\right) \cdot \frac{(V_o + KV)}{K.(n+1).\frac{n}{6}} \quad V/us \quad \ldots\ldots 8.18$$

Since $n > 12$,

$$L_y(C_y) = \left(1 - \frac{D_y(t)}{\Delta t}\right)\left(\frac{V_o + KV}{K.\frac{n^2}{6}}\right) \quad V/us \quad \ldots\ldots 8.18(a)$$

$$\therefore \quad L_y(C_y) = \frac{(V_o + KV)}{K.\frac{n_1^2}{6}} \quad \ldots\ldots\ldots \quad 8.18(b)$$

where

$$n_1 = \sqrt{\frac{\Delta t}{\Delta t - D_y(t)}} \cdot n \quad \ldots\ldots\ldots\ldots \quad 8.19$$

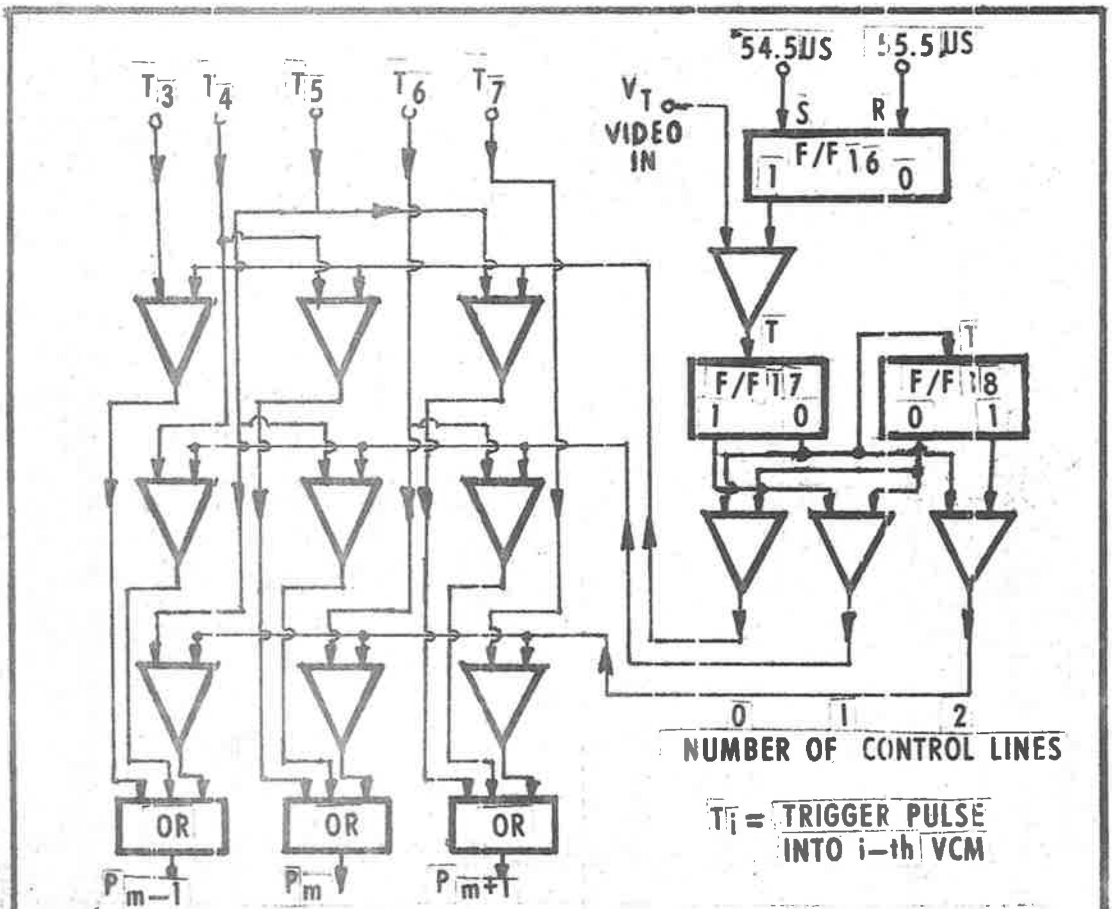
Thus if an interval corresponding to "n_i", is specified by the second "Vertical Distortion Line" and specifies a number fed into the register R "8", to control a Pulse Integrator corresponding to the distortion range duration given by "n_i" the above required cumulative delay "$D_y(t)$" is obtained.

Fig.118(a) shows the Gating and Selection Logic to accomplish this.

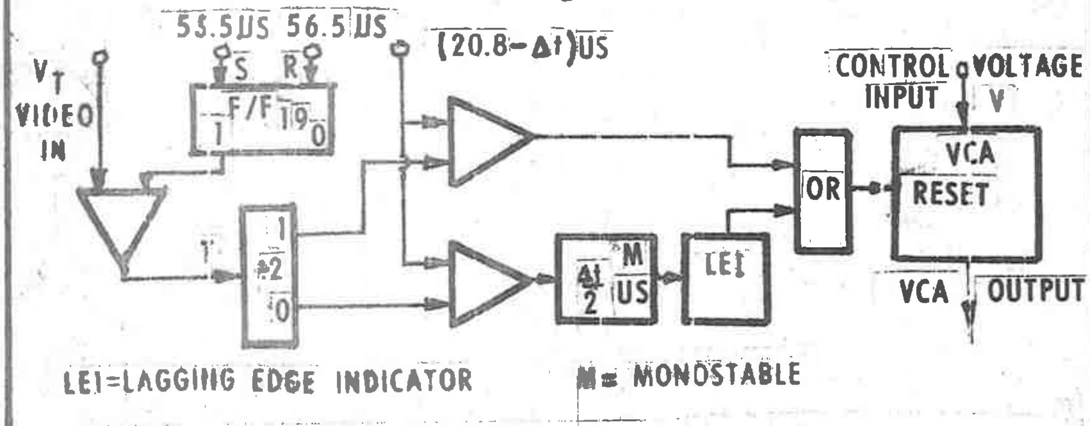
8.4.3.6 "Unsymmetrical " Distortion Correction.

The above implementation for H-coordinate Distortion Correction is suitable for "symmetrical distortion "regions i.e. where the "3rd" distortion line pulse "P_3" corresponds to "-0.5%" distortion, the "4th" distortion line pulse "P_4" corresponds to the maximum distortion line, the "5th" distortion line pulse "P_5" corresponds to "- 0.5%" distortion and so on. Within the "symmetrical distortion area" of the active display area, "P_4", corresponding to the maximum distortion line, indicates a reversal of sign for the correction voltage ramp slopes, as in regions occuring after the Maximum Distortion Line in the active display area s, distortion decreases and hence so do the cumulative correction time delays for the video input pulses, "$V_{CRT}(n\Delta t)_{in}$."

In "unsymmetrical" distortion regions, specified by the presence of "control lines" within the "1us" wide Control Line Time Interval (from t = 53.5us to t = 54.5us see Fig.115), "P_4" defines the "-0.75%" Distortion Contour (and which during the active display area scanning interval is defined by the trigger pulse into VCM "4" derived from the lagging edge of the "1" output from VCM"3")



(a) Circuit generating timing signals which determine the instant of maximum distortion during the scanning time interval and signals for the 'slope correcton' circuits in Figure 117.



(b) Circuit generating the resynchronizing pulse (Reset) for the V.C.A.

Figure 118. Circuits Generating Added Control Signals Signals for CRT H-coordinate Correction.

while "P_5" (if only one "control line" is present-for section BB' in Fig.103(b)) specifies the Maximum Distortion Line (i.e. the trigger pulse into VCM "4" defines the maximum distortion). If two control lines are present, "P_5" specifies the "-1·00%" Distortion Line. Consequently for the presence of 1 "control line", sign-reversal of "correction slopes" is specified by the 5th trigger pulse into the VCM "5", while the trigger pulse into VCM "4" enables on the Register R "8" specifying the "Correction Slope" Voltage Ramp for the particular maximum distortion value. The trigger pulse into VCM"6" specifies the end of the "correction slope enabling interval".
Similarly for the presence of 2 "control lines" sign reversal is specified by the trigger pulse into VCM "6", while trigger pulse into VCM "5" enables the "correction slope" circuits.

Otherwise, the distortion correction intervals and the method of correction are unchanged; two consecutive Distortion Lines still specify an added (or decreased) cumulative "$\frac{\Delta t}{2}$"us delay interval.

Figure 118(a) shows the relatively simple Gating and Decoding Logic Circuit under control of the VCM trigger pulse. It merely determines which Distortion Line "P_i" enables the "Correction Slope" Register R "8" and which enables voltage ramp sign-reversal. It is self explanatory.

Clearly the gating and control logic for the control information defining the necessary H-coordinate correction for the CRT is simpler than the corresponding gating and control logic in the Vidicon.

8.4.3.7 Variable Delay Shift Registers

Thus far the theory and implementation of generating the appropriate correction voltages has been described.

These Correction Ramp Voltages are switched in a sequence corresponding to the "$\frac{\Delta t}{2}$" correction intervals defined by consecutive Distortion Lines, into an analog Summer SUM_1 together with the Voltage "V_1". The output of the Summer is a slightly varying voltage which is the control voltage to the Voltage Controlled Astable Multivibrator, labelled VCA on Fig.119; its output frequency, and thus the pulse repetition rate, is a function of this voltage. The repetion rate is nominally set at "Δtus", the video input "$V_{CRT}(n\,\Delta t)_{in}$" repetition rate. The leading edge of the pulses in "$V_{CRT}(n\,\Delta t)_{in}$" is detected, resulting in an impulse train of variable spacing, nominally of "Δtus" spacing. This impulse train is used as the shift or trigger pulse input into a set of Shift Registers S"1-5" in parallel, only one of which is enabled on at any one instant.

The input to these Shift Registers is "$V_{CRT}(n\Delta t)_{in}$" from the Vidicon output or the CPU I/O interface. The input pulse repetition rate is "Δt"us while the shift trigger pulses have a repetition rate of "$\Delta t + \delta t_i$", with "δt_i" being the correction delay for each pulse, contributing to the additive delay. With a one-bit Shift Register, the output of the Shift Register will be delayed by "δt_i", with the time position of successive output pulses being cumulatively delayed. In some regions of the active display area, trigger pulses may have been shifted by "Δt" or up to "$2\Delta t$", corresponding to -0·5% and -1·0% distortions, implying that trigger pulses may be coincident with the video input pulses with the possibility of errors

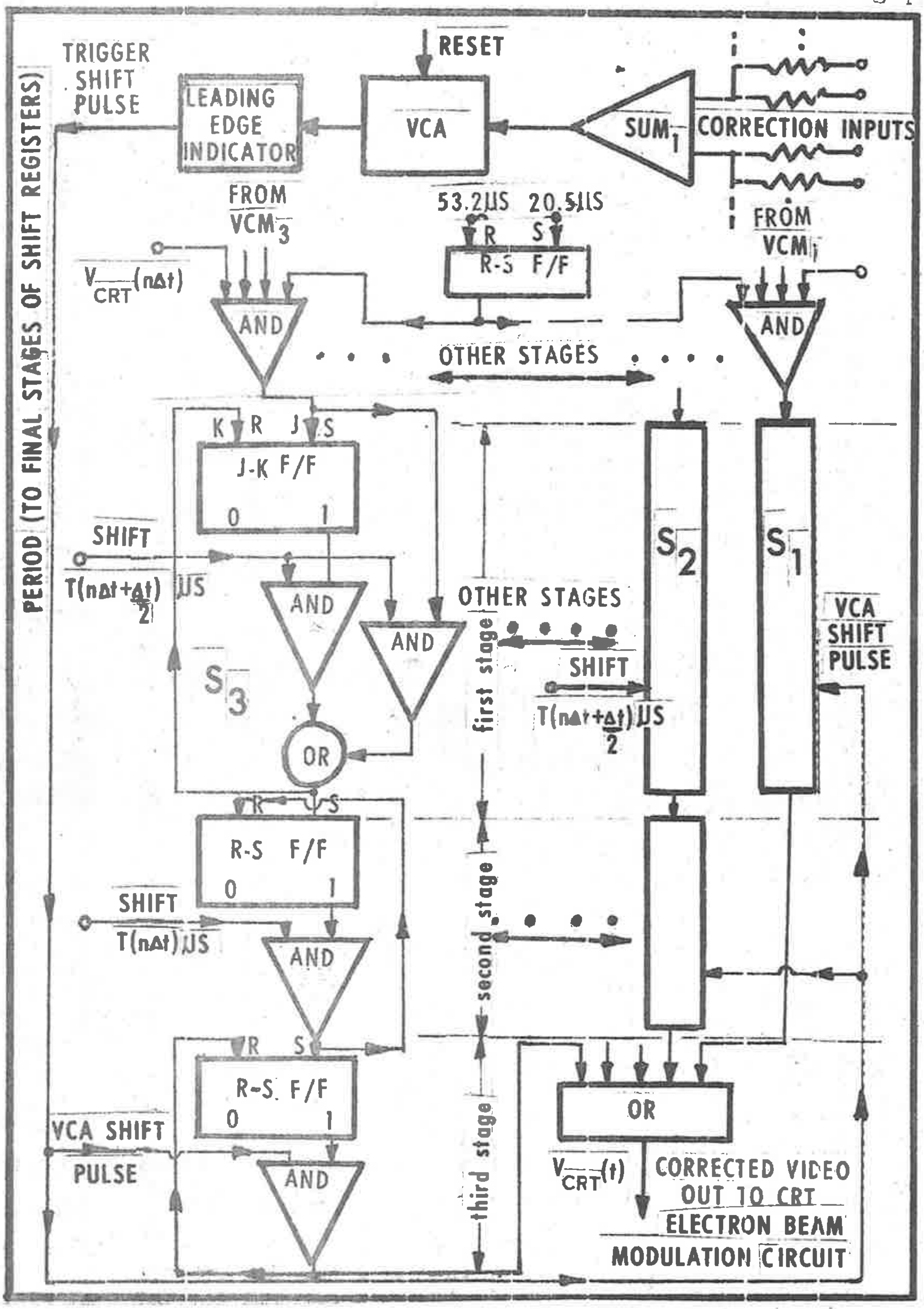


Figure 119. Variable Delay CRT H-correcton Shift Registers Only One Stage is Shown in Detail, Giving a Correction from -0.5% to max. Distortion.

resulting, in that pulses instead of being delayed by "$\Delta t + \delta t$," will instead be delayed only by "δt." Consequently such locations may be lost.

The parallel set of Shift Registers . S"1-5" is very much in that respect, like those required for the H-coordinate Correction for the Vidicon. Indeed the individual stages, one of which is shown in Fig.119, are identical, including the provision for the non-occurence of "race problems." The Shift Register stage shown in Fig.119, performs the delay within the region from "-0.5%" to maximum distortion (about -0.7%) - it thus is required to delay from "Δt" up to "$\frac{3\Delta t}{2}$" us.

The waveforms and result of corrective delay within this stage is shown in Fig.120. The effect of the shift registers is as follows:

(i) Within the distortion region defined by Distortion Line pulses "P_1" and "P_2" (and hence defined by VC M"1") within which a cumulative shift pulse delay of from 0 to "$\frac{\Delta t}{2}$" is expected (corresponding to $\pm 0.25\%$ "correction), the shift pulses occur with a spacing of "Δt" to "$\Delta t + \delta t_i$" max ,

where $$\sum_i^n \delta t_i = \frac{\Delta t}{2} \qquad \text{. . . . . .8.8(a)}$$

Consequently if the initial video input and the initial trigger pulses are coincident, successive pulses within that distortion region are progressively delayed by "$\sum \delta t_i$"

where $$0 < \sum_i^i \delta t_i < \frac{\Delta t}{2} \qquad i = 1 \ldots n$$

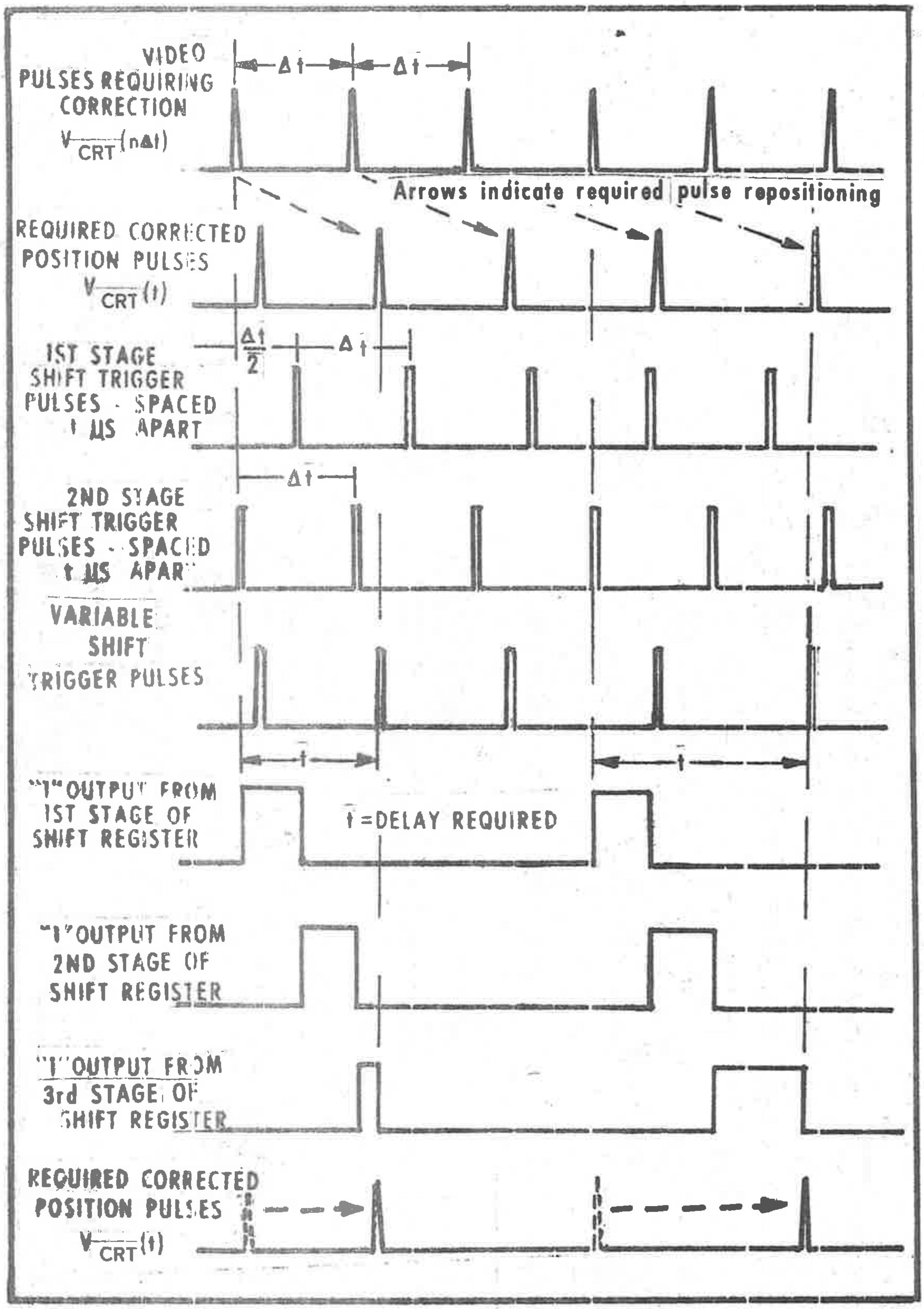


Figure 120. Correction Shift Register Signals and Outputs Showing Corrected H-coordinates in the CRT.

(ii) Within the region defined by Distortion Line pulses "P_2" and "P_3" (and within which a cumulative shift pulse delay of from "$\frac{\Delta t}{2}$" to "Δt" is expected (corresponding to "- 0·25% to -0·5%" correction)), the video input is gated into a 2-bit Shift Register "S"2". The first stage has its shift trigger pulse train of "Δt" period, but delayed by "$\frac{\Delta t}{2}$" with respect to the video input pulse train, also of "Δt" period. The shift trigger pulses into the second stage of the Shift Register are the impulse train from the VCA which are progressively delayed with respeet to the video input pulses by "$\frac{\Delta t}{2} + \delta t_i$" us.

The successive output pulses within that distortion region are thus progressively delayed by

$$\frac{\Delta t}{2} < \frac{\Delta t}{2} + \sum_{i}^{i} \delta t_i < \Delta t$$

(iii) For the region defined by Distortion Line pulses "P_3" and "P_4" (defined by VCM" 3") within which a cumulative shift pulse delay of from "Δt" to "$\frac{3}{2}\Delta t$" is expected, the video input is gated into a 3-bit Shift Register, S"3".
The shift trigger pulse input into the first stage is, as before, a pulse train of "Δt" period but delayed by "$\frac{\Delta t}{2}$" with respect to the video input pulse train. The shift trigger is a pulse train of "Δt" period in synchronism with the video input pulse train. The shift trigger pulses into the third stage of the Shift Register are the impulse train from the VCA which is progressively delayed with respect to the video input pulses by "Δt" to "$\frac{3}{2}\Delta t$" us.

Fig.119 shows the action of a 3-stage Shift Register delaying input-video by 1 pulse shift or more."$V_{CRT}(n\Delta t)_{in}$" is gated to the appropriate Shift Register by gating it via AND-gates with the "1" output from the V.C Monostables specifying the corresponding distortion regions.

The outputs from all of the Shift Registers is OR-ed together and fed into the video input of the CRT, to intensity modulate the electron beam of the CRT.

8.4.3.8 Synchronizing VCA pulses with H-System Timing.

The final requirement of the CRT H-correction circuits is to ensure that the shift pulses into the delay Shift Registers S"1-5", are in synchronism with the input video pulses requiring corrective delays, at locations (or time instants) where the distortion is stated to be 0%.

The VC Astable being a relaxation oscillator is inherently "free running", that is, its output pulses are not synchronized to any external timing unless this is explicitly introduced as a "synchronizing" or "reset" pulse. Moreover there is no correlation between the resultant VCA frequency at the end of one H-scanning line and the beginning of the next H-scanning line, as the distortions in those two regions are uncorrelated. Consequently the VCA has to be synchronized or reset at the beginning of each H-scanning line. This is performed by the pulse defining the beginning of the active display area i.e. at "T_{AS} = 20·8us" from the beginning of the pulse defining a H-blanking interval, in conjunction with the Distortion Line pulses giving distortion contour closure; these are the pulses within the "1us" time interval immediately prior to the Distortion Graphics Storage Area corresponding to the active display area in Fig.114(a), (on Fig.115 this is the interval defined from T_{CE} = 55·5us to T_{DE} = 56·5us).

The approximation is made that the Right Hand (and Left Hand) edge of the active display area themselves define Distortion Lines.
For example for section AA' in Fig.114(a), the L.H. edge defines the "-0.25%" Distortion Line while the R.H. edge defines the "0%" Distortion Line. For the section BB', the L.H. edge defines the "0%" Distortion Line while the R.H edge defines the "-0.75%" Distortion Line.

In fact as can be seen from Fig.104(a), from which the distortion graphics storage information in Fig.114(a) was derived, the actual distortion contours corresponding to the above values are not coincident with the R.H. and L.H. edges.

The errors thus introduced by this approximation, however, fall well within the allowable remanent distortion.

(i) If within the "1us" interval containing distortion contour closure line pulses, (from T_{CE} = 55·5 to T_{CS} = 56.5), only one pulse "P", is present, it specifies that the L.H. display edge corresponds to "0%" distortion, with the result that video input pulses and VCA originating shift trigger pulses need be coincident. Hence the VCA need be synchronized by a trigger pulse from the H- clock (of period "Δtus), one "Δt" period prior to the "20·8us" time-indicator pulse ("T_{AS}") specifying the L.H. edge of the display area;

call this the "T_{SYNC}" pulse. Since at that instant, the input to the VCA is "V_1" volts, with a resultant pulse frequency of period "Δt" us, the VCA output pulse leading edge will be coincident with the subsequent first pulse of the video input pulse train at the L.H. edge of the active display area. Thus "0%" distortion occurs there as specified by the distortion information.

(ii) If two distortion line pulses occur within the "1us" time interval, the L.H. edge must be coincident with the -0·25% distortion contour. Thus the correction Shift Register shift trigger pulses need be delayed with respect to the first video input pulse at the active display area edge, by "$\frac{\Delta t}{2}$" us, via a Monostable. The "1" pulse of "$\frac{\Delta t}{2}$" us duration has its lagging edge detected and this resultant pulse is the synchronizing trigger pulse to the VCA. The first shift trigger pulse to the Correction Shift Register occurs "$\frac{\Delta t}{2}$" after the first video input pulse corresponding to the active display area, implementing the required "0·25%" distortion correction as specified by the distortion information.

(iii) For 3 distortion line pulses detected within the "1us" time interval, the L.H display edge is to correspond to the "-0·5%" Distortion Contour. The resultant VCA derived shift pulse is to be delayed by "Δt" us with respect to the first video input display pulse. Thus again the "T_{SYNC}" pulse can be used for synchronizing the VCA.

(iv) In general, if an even number of pulses is detected within the "1us" time interval, defining "-0·5%," "-1·0%," "-1·5%" etc distortion intervals corresponding to "Δt," "$2\Delta t$," "$3\Delta t$," time delays, the "T_{SYNC}" pulse is delayed by the "$\frac{\Delta t}{2}$" us - Monostable before being used to reset the VCA.

As only an odd or even number of pulses need be separated out, a "÷ 2" counter "C 4", fed by the pulses occuring within the "55·5-56·5" us, "1us" time interval. Fig.118(b) shows the circuit required to perform the VCA re-setting; it is self explanatory.

8.4.3.9 Summary of CRT H-Correction System

To recapitulate, the H-coordinate CRT correction circuits consists of the following:

(i) a linear Horizontal Scanning Waveform Generator.

(ii) Control and Logic Circuitry which select out the required control signals (Fig.115) to generate the degree of correction required and to specify the scanning time intervals where these corrections are to be implemented. Four distinct regions in the graphics information storage are identified for CRT H-coordinate correction :

(a) the "1us" time interval (from t=53·5us to t=54·5us) containing the Vertical Slope Correction Line pulse "P_V" (section 8.4.3.5) which when gated with "$\frac{\Delta t}{2}$" period clock pulses, generate a number specifying the correction slope for the distortion regions on either side of the Maximum Distortion line.

(b) the "1 us" time interval (from t=54·5us to t = 55·5us) containing the Control Line Pulses (if any) which specify the presence of asymmetrical display area distortion around the central axis of the display area. The pulses detected within this interval, "P_{Ci}", control and change the Distortion Line pulse count at which Correction Voltage Ramp Slopes reverse signs.

(c) the "1us" time interval (from t=55·5us to t =56·5us) containing the Distortion Contour Closure Line pulse "P_{CLi}". These pulses feed the circuit shown in Fig.118(b) which determine the synchronising or reset pulse instant to the V.C.A.

(d) the "6.5us" time interval (from t=56·5us to t=63us) corresponding to the active display area (and hence scaled down by a factor of $\frac{32 \cdot 4}{6 \cdot 5}$ = 4·99), which define the Distortion Lines pulses "P_{Di}". These pulses along with pulses "P_{CLi}", are fed into a "÷ 8" counter "C 2", which specify the distortion region intervals quantized into 2μs time interval (see circuit in Fig.116 and description in section 8.4.3.4(iii)). The intervals thus defined are then:

(1) fed via Constant Level Output Circuits into Pulse Integrators P.I "1-7", which, via V.C Monostables VC M"1-7" define the length corresponding distortion regions and instant of occurance.

(2) gated with the "$\frac{\Delta t}{2}$" µs period pulse train via a "Divide by 5" Counter "C 3" and fed to Registers R"1-7" to specify digitally variable Correction Voltage Ramp Slopes corresponding to these distortion intervals.

(iii) A set of Constant Level Output Circuits, Pulse Integrators P.I"1-7", Buffers etc, which are fed into Voltage Controlled Monostables VCM"1-7". These Constant Level Output Circuits etc are controlled by the intervals defined by the "÷8 Counter C"2". These perform the functions mentioned in (ii) and above. (This is shown in Fig.116).

(iv) A set of 3-bit Registers, R"1-7", each corresponding to a distortion region defined by two consecutive Distortion Line pulses "P_{CLi}", "P_{Di}". Each Register contains a number from "1" to "8", obtained by gating in, in ripple-counter mode, every 5th "$\frac{\Delta t}{2}$" µs clock pulse, for a time interval defined by two consecutive Distortion Line pulses. The output from each Register, taken as the parallel output from each 1-bit stage of the Register, and decoded, enables "on" one of 8 (actually 16) Pulse Integrators P.I"8-15" and P.I"8'-15'", each corresponding to one of the "8" possible decoded numbers. The Register outputs enables "on", for the appropriate period and time instant (by the V.C Monostable), in sequence, their corresponding Pulse Integrators.

(v) A set of 8 "matched" pairs of Pulse Integrators P.I"8-15" and P.I."8'-15'", oneset feeding the inverting input to an Op-amp. Summer SUM"1",the other set feeding the non-inverting input (This is shown in Fig.117).

Each of these Pulse Integrators has its integrating function"control" resistors and capacitors chosen so that the resultant output ramp slopes, for a constant level input pulse, are in the ratios and of magnitudes given in section 8.4.3.4(v).

The various Pulse Integrators are enabled "on" successively, a particular Integrator at any instant being "on", depending on whatever register R"1-7" is in control.
One set of the matched pairs P.I."8-15" is fed into the inverting input of the OP-amp summer SUM_1, while the second set of integrators P.I.8'-15' " is enabled "on" by the Maximum Distortion Line Pulse "P_m" , the overall result being that the sign of the Correction Voltage Ramps as fed into the Summer is inverted, indicating the subsequent resultant time delays are reduced in magnitude, corresponding to distortion being decreased.

Each Integrator is discharged immediately after its enabling on period has ended by D "1-8"

(vi) An analog Summer SUM_1, where the Correction Voltage Ramps from the different Pulse Integrators are summed, together with "V_1", the voltage, which fed into the VCA alone generates a train of pulses of "$\Delta t = 0{\cdot}161$us"period, is also required.

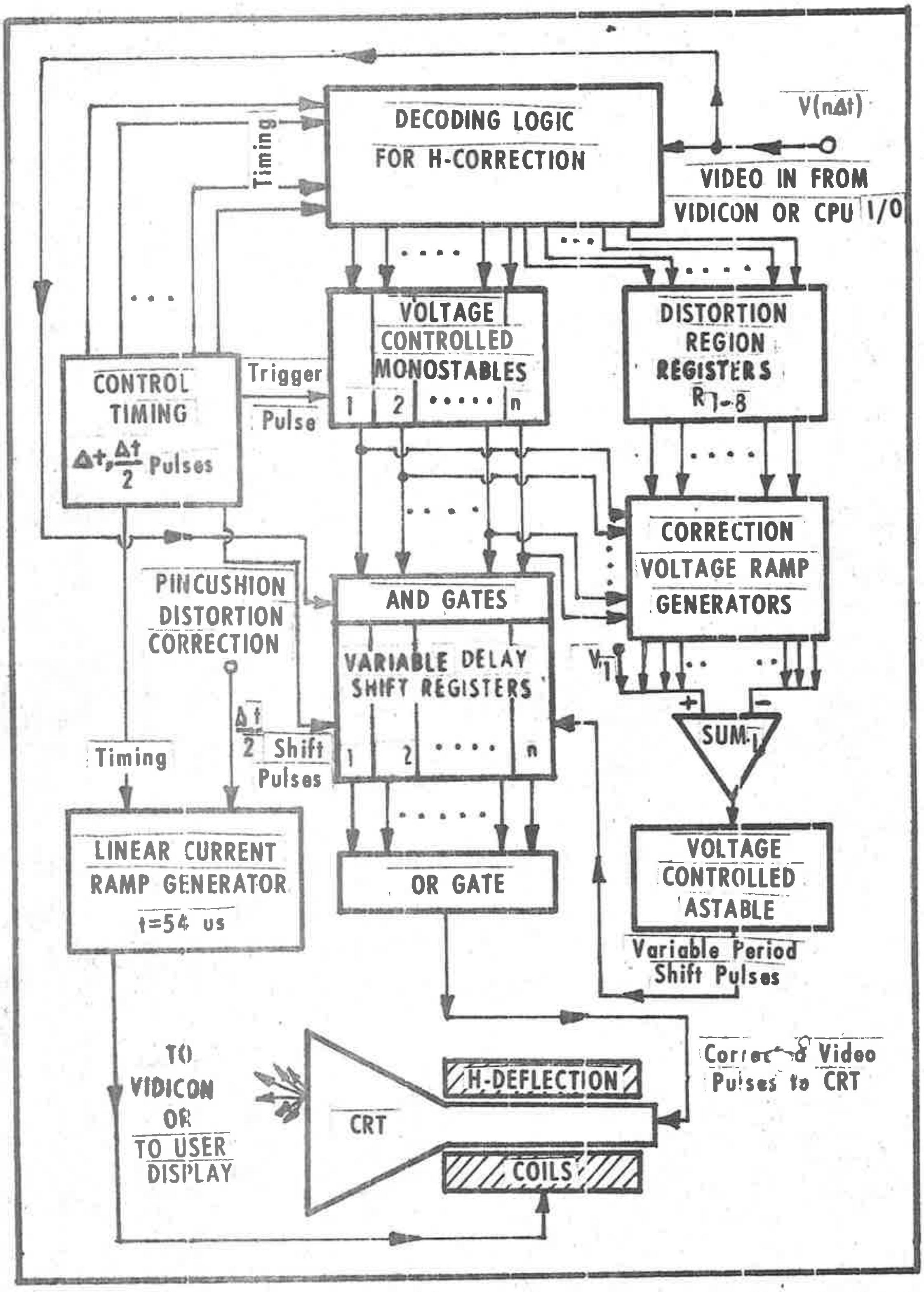


Figure 121. Functional Block Diagram of CRT Horizontal Scanning Generation and Correction Circuits.

(vii) A Voltage Controlled Astable Multivibrator, VCA, is required. Its control voltage is the output from the previous Summing Amplifier. It is reset or resynchronized each new horizontal scanning line, by the "R" pulses (section 8.4.3.8) to bring the first video input display pulse at the L.H. edge of the active display area, into "synchronism" with the distortion required at the L.H. edge of the display.

A V.C.A with the above requirements is described in section 11.5.6.

(viii) A set of "Variable Length" Shift Registers S"1-5" joined in parallel, any one of which is enabled "on" by its corresponding V.C Monostable defining its corresponding distortion regions, are required. (This is shown in Fig.119). The input to the Shift Registers is the Video input "$V_{CRT}(n\Delta t)_{in}$" from the Vidicon corrected output or the CPU I/O display input, corresponding to the CRT display locations prior to correction. The shift trigger pulses in the multistage Shift Registers are either "Δt"us H-clock pulse trains or "Δt"us period delayed by "$\frac{\Delta t}{2}$" us relative to the H-clock pulse, pulse trains. The shift trigger pulses into the final stage of each Shift Register is the pulse corresponding to the leading edge of the VCA output pulses. (The resulting correction by variable delays is shown in Fig.120).

The Shift Register outputs are all OR-ed together and fed into the CRT Video input as the corrected CRT display input.

8.5. JOINT REQUIREMENTS FOR CRT AND VIDICON DISTORTION CORRECTION

Before concluding this chapter on correction of geometrical display distortions three points must be mentioned:

8.5.1 Actual Form of H-coordinate Input for Correction

The output from the Vidicon for correction "$V_{VID}(t)_{out}$" and the input to the CRT for correction "$V_{CRT}(\Delta t)_{in}$" were taken as pulse trains with a pulse occuring corresponding to every possible display location i.e. as though the displayed graphic data consists of the 200 x 200 point grid. This was to simplify the explanation of the circuits. In fact, of course, actual display information consists only of a selection of pulses within the pulse trains and thus a selection of the 200 x 200 display points. Thus in actual displays, signal pulses within the video pulse trains circulating in the CRT-Vidicon electric loop, may or may not be present at the expected pulse positions corresponding to the 200 x 200 point grid display; and consequently correction may or may not be performed at every time instant corresponding to expected pulse positions. But since the timing and selection sequence of appropriate correction circuits is derived from external timing signals and "read-only graphics information signals", and is not activated by the display information video pulses, the above explanation for circuit operation are equally valid for all possible display location combinations up to the maximum display of 200 x 200 point grids.

8.5.2. CRT- Vidicon Alignment

The CRT and Vidicon require to be aligned, with the centres or "axis" of their respective active display areas to be coaxial, and at a distance such that the active display area of the CRT is imaged and positioned on a nominally 1:1 geometrical basis onto the active display area of the Vidicon.

A rigid mounting, with "optical-bench" alignment precision, is required for this, along the lines of the "optical barrel" mounting used for the Schmidt optics shown in Fig.63. Alignment procedures and adjustments along the methods described in (270) need also be available.

It must be remembered that the Vidicon total scanned area is $\frac{3''}{8} \times \frac{1''}{2}$ in size, with the active display area being about 0·25" x 0·3".

For CRT image positioning better than a half a location away from the nominal centre of the active display area, the Vidicon photoconductor plane need be located to an accuracy of better than

$$< \pm \frac{1}{4} \cdot \frac{0{\cdot}25}{200} \text{ inches}$$

$$< \pm 0{\cdot}0003''$$

in the vertical coordinate and better than

$$< \pm \frac{1}{4} \cdot \frac{0{\cdot}3}{200} \text{ inches}$$

$$< \pm 0{\cdot}0004''$$

in the horizontal direction.

Micrometer gauges are required and precision aligning tests and methods are required. The resultant display stability of a full 200 x 200 point grid, when inserted into the CRT and imaged onto the Vidicon and inserted into the CRT-Vidicon loop, can be used in setting up and aligning the two devices for coaxiality and a CRT-Vidicon magnification of 1:1.

8.5.3 Finite vs Zero Distortion at centres of Active Display Areas.

For the H-coordinate correction in both the CRT and Vidicon, the correction was unidirectional; this was because H-scanning is unidirectional and for pulses which need be synchronized or relocated with respect to the H-scanning waveform, selectively "time delaying" them is the simplest way, rather than "time advancing" them. As a consequence of this unidirectional time delaying, significant distortion apparently became "apparent at the centre of the CRT and Vidicon active display area, when the distortion contours have their "origin" shifted as explained in Fig.104(a)(in other CRTs or Vidicons this may not necessarily be the case). Consequently the central region of the display area are time delayed and become displaced to the night of the display area. Yet in practice it is assumed and required that zero distortion, zero correction and hence zero display shift, occurs at the centres of the display area. Properly speaking, effective display corrections to locations on either side of the centre must be shifted to the right and to the left of the centre.

To effectively achieve this and to obtain effective zero distortion at the centre, the H-scanning ramp current for both the CRT and the Vidicon is delayed with respect to the nominal starting instant, by a time interval equal to the time correction delay performed on the location at the nominal centre of the active display area.

This will effectively locate the "delayed" centre location back at the required geometrical centre of each active display area, and satisfy the requirement of zero distortion at the centres.

This delay is introduced to all of the H-scanning waveforms within a complete frame. As both H-scanning current waveforms are initiated and synchronized by H-clock pulses, the implementation of such delays poses no problem-delay is implemented by means of a Monostable.

A similar delay introduced to the vertical scanning current staircase equivalent to the vertical distortion at the centre of the display need also be made in both the CRT and the Vidicon.

8.6 GENERAL COMMENTS ON V- and H-COORDINATE CORRECTION

(1) The above description of the V- and H-Coordinate Correction Circuits for the CRT and the Vidicon, even though perhaps tedious in parts, serves to indicate that distortion correction, which is analytically non-describable, can be achieved by relatively simple digital, analog and hybrid circuitry. The simplicity of the resulting correction hardware is due to

(a) the unique way of storing the distortion correction information in graphical form on relatively unusable areas of the display scanned area (since in those areas, the expected distortion is such, that to correct it, much more complex circuits than the above would be required-hence these areas are unused).

(b) storing certain simple control signals in graphical forms ("Control Lines", "Distortion

Contour Closure Lines"etc).

This method of information storage can be seen to be a form of "fixed" and "read-only" storage, with the difference between the usual "read-only" memories being that data is read out at video rates and that information readout is in analog form.

(2) To compare this form of Graphics Distortion Correction Information, with the current methods of achieving the same ends, the following serves as the comparison example (78).
In that case example, display linearity of the order of 0·013% was required, with distortion prior to correction, being about 0·1%. The available display area was divided into a 64 x 64 matrix with the H- and V- correction required being associated with each matrix point, the same correction to be implemented between adjacent matrix locations. Thus $64 \times 64 \approx 4.10^3$ words of core store, for the H-coordinate, and 4.10^3 words for the V-coordinate were required; in addition the decoding and correction circuitry still had to be provided. The improvement of linearity was by one order (0·1% → 0·013%), the same order as for VIDIOGRAPHIC (from about 1% → 0·1% remanent distortion) described above.

(3) Lower remanent distortion could be achieved by starting out with initially higher precision, low distortion CRTs and Vidicon, say up to 0·5% distortion prior to correction.

Alternatively, "finer" distortion correction increments may be used, say 0·125% distortion increments, with a higher density of Distortion Lines, Control Lines etc. The correction circuitry will still be essentially the same, but more stages would be required, to go hand in hand with the increased number of distortion ranges and the greater number of lines to be decoded.

(4) The circuits described above make no pretence of being optimized (at least for logic circuitry optimization - for example the simplest R-S Flip/Flops were used continuously, only to emphasize the circuit principles, and not because R-S Flip/Flops may be the best Flip/Flops to use), nor even are they claimed to be the best or even unique solutions. They serve to indicate that in principle, relatively simple and straightforward circuits can be designed to implement a fairly demanding requirement of repositioning trains of pulses in an arbitrary manner, to a high degree of accuracy.

The components or subcircuits used are all available. The logic circuits require to be faster than at least 12Mhz. With TTL (Transistor-Transistor-Logic) with operating speeds of at least 25Mhz, becoming price-competitive with RTL (Resistor -Transistor-Logic), the implementation of logic poses no problems.

The analog and hybrid circuits such as the Pulse Integrators, Voltage Controlled Monostables and Astables and the scanning ramp and staircase currents are all described in Chapter 11, with the performance figures given. Their performance is well within the linearities required.

The remaining requirement for fast analog Summers are easily met due to the recent introduction of fast and economic I-C OP-Amps.

(5) The explanation of the circuits and even of the logic has been perhaps long and tedious. Logic equations rather than descriptions would normally have sufficed. But as these circuits controlled hybrid circuits, it was felt that a working explanation inter-woven with examples would clarify rather than confuse. Logic equations for logic circuits help to specify circuit components and signals required, but do not explain why the signals or componenets are required in the first case.

If some Gating and Logic circuits seem rather complex it is because the case example of distortion correction shown, is a "worst-case" one, in that the distortion map is unsymmetrical in the distortion regions, about the centre of the active display area. Normally the CRT and Vidicon would have the pincushion or barrel distortion removed by analytically defined waveforms (see chapter9.4), resulting in much lower distortion prior to correction than the above, and with no unsymmetry of distortion as in the lower part of the display area. To cater for any unsymmetry however, the control line signals "P_{ci}", were introduced. Normally it would be expected they would not be present. The presence of the pulses, "P_{ci}" consequently increase the complexity of decoding of the Distortion Information input pulses particularly for the H-coordinate Correction for the Vidicon as evidenced by the logic leading to the "toggle" F Fs 6 and 7 in Fig.109.

3.7. SUMMARY

(1) The Distortion Correction Information is stored in graphical form on both sides of the active display area, yet still within the normal

scanned area on the CRT; the left-hand area stores the Vidicon correction information, while the right-hand area stores the CRT correction information.

(2) As each raster line is scanned in succession, this correction information is available for each horizontal line (ie. for each V coordinate).

(3) This information is available to the Information Decoding Circuits as pulses; certain correction types of control pulses fall within certain time intervals and are gated to the appropriate correction circuits.

(4) The vertical coordinate is generated by a Staircase Current Waveform of some 300 steps with a scanning time interval of some 18ms. This vertical scanning staircase effectively generates a non-interlaced CRT display, and an interlaced raster for the Vidicon scanned area.

(5) The V-coordinate correction is analog in nature. A time interval defined by a H-blanking "start" or "end" pulse and the pulse defined by a "Vertical Coordinate Correction Line" generates, via a Pulse Integrator, a small additive increment to each current staircase step.

(6) The H-coordinate Correction is based on correction information which selectively delays the video pulses, which are the time coordinate representation of the CRT and Vidicon display

locations. These selective delays effectively reposition these video pulses in time and thus reposition them on the active display areas.

(7) For the Vidicon, the pulse train requiring pulse repositioning is effectively asynchronous in nature. On repositioning a synchronous pulse train of period "$\Delta t = 0{\cdot}161$us" results. Correction Circuits are primarily digital in nature- in this case, Shift Registers.

(8) For the CRT, the task is more complex. The pulse train requiring correction is synchronous in nature, of period '$\Delta t = 0{\cdot}161$us.' Repositioning is to result in a non-analytically describable asynchronous pulse train. The "irregularity" of this repositioning means that the Correction Circuits are primarily analog in nature, in this case consisting of "Variable Slope Correction" Voltage Ramp Generators (Pulse Integrators).

(9) The delaying of video pulses in the H-direction is unidirectional, with apparently significant distortions at the centre of the display area; similarly, the V-correction, by additive small step height correction increments, is also unidirectional, again with the apparent result of significant vertical distortion at the centre of the display area. The requirement is that display distortion is required to be zero at the centre of eachdisplay area. This is accomplished by delaying the H-scanning current waveforms and the V-staircase currents by a time interval corresponding to the correction time delay as given by the H-correction or V-

Correction Information, for the nominally central locations of the CRT and Vidicon Scan areas.

(10) The above correction methods and circuit implementation make no pretence of being a unique or optimized solution. They are used to indicate, occassionally perhaps in a painfully obvious manner, that in principle, H- and V- Distortion Correction can be accomplished with the required accuracy, with relatively simple circuits.

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CHAPTER 9

DISPLAY DISTORTION : CAUSES AND CORRECTION OF PRIMARY SOURCES OF DISTORTION

9.1. INTRODUCTION

9.1.1. General Requirements.

The formation of the CRT generated display is due to the accelerated electrons within the CRT electron beam striking the phosphor, which by cathodoluminescence, result in emitted luminous flux at required display locations. The cross-sectional area of the electron beam at the point of impact primarily determines the shape, size and hence luminance of the resultant display locations; factors affecting the beam cross-sectional area thus need be investigated. The "focussability"of electron beams thus needs be investigated.

The beam is deflected by time-varying magnetic or electric fields so that it can access all parts of the display area. Ideally the deflection should be such that the beam will generate a geometrically linear or undistorted display; unless this is so, or unless the remanent distortion is kept to less than the value given by expression 7. 7 , no steady or permanent display will result.

It was assumed in chapter 8, when distortion correction was implemented to reduce display distortion to acceptable levels, the distortion prior to this correction was of the order of 1%. This figure can be obtained with small extra effort with commercially available CRT's (for example the actual 14" PYE TV-Monitor on which the distortion tests were made); this is achieved by feeding linear current scanning waveforms etc.

The other major assumption made in chapter 8 was that "pincushion" or "barrel" distortion was also absent, or at least negligible. This is a more complex objective to satisfy; external "pincushion or barrel distortion correction" is required in addition to the corrections implemented in chapter 8.

The nature of electron beam deflection, and the resultant display distortion (and its effects on focussing) thus need be investigated, so as to identify the causes of distortion and take corrective action prior to distortion correction implementation as discussed in chapter 8.

In Vidicons also, a magnetically deflected electron beam discharges the stored charge pattern on the photoconductor target, due to the CRT luminance. For the same reasons as above, the distortion prior to the correction as in chapter 8 need be minimized. Again the distortion encountered is "pincushion distortion."

The same "first-principles" expressions can be used as a basis for deriving distortions expressions for both the CRT and the Vidicon, due to the similarity in the deflection mechanism. But the different magnitudes of the accelerating voltages, the different strengths of the focussing electromagnetic fields etc. in both of these devices, result in apparently different expressions for the beam deflections and hence different pincushion correction methods.

Since beam deflection deviations and beam cross-section deformation ("defocussing") can occur at all stages of the existance of the beam, the whole aspect of electron beam generation, focussing and deflection and effects near the CRT screen,or the photoconductor target,need be covered, and thus would involve such things as electron gun structure, the structure of accelerating and control grids, and the various aspects of focus and deflection coil design and so on. This however is not our province nor indeed is it a necessary requirement. Our stated aim was to use economic, readily available commercial sub-systems, and not to redesign CRT or Vidicons or any of their subcomponents. What will be done is to find expressions for the distortions or defocussing,or rather expressions for the distortion corrections in terms of readily available waveforms, such as the linear current sweep waveforms. These resultant correction waveforms are summed with the usual nominally linear sweep current waveforms and fed into the deflection or focus coils, resulting in the electron beams being located within the 1% or so of their ideal position prior to final correction as described in chapter 8.

9.1.2. Electron Optics.

The topic of electron beam focussing and deflection is called "Electron Optics" due to the similarity to "geometrical" optics where light beams are refracted ("deflected") and focussed by lenses; in "Electron Optics" electron beams are deflected and focussed by electro-magnetic fields ("electromagnetic lenses").

The literature on Electron Optics is large and appears to be comprehensive. However for our purposes little can be gleaned which is of direct use.

Most textbooks on TV or Electronics, or Electromagnetic Theory contain elementary derivations of beam deflection and focussing by electromagnetic lenses, but the approximations and assumptions used in deriving these do not give the required accuracy in expressing displays distortions or defocussing. Such expressions give distortions and defocussing of the order of 5% which are tolerable for viewing for everyday applications; for our purpose they are of little use.

On the other hand the technical or "professional" literature, much of which research was carried out in Germany, is useless for the exact opposite reason to the above. With typical thoroughness, the Teutons tackled this ticklish task! The resultant expressions for distortions and focussing "aberrations" are notable for the complexity and number of terms (often 10 or more) with very complex coefficiants. Their object was to identify the sources of distortions and defocussing, each term with each source of distortion or defocussing, rather than suggest or implement methods of eliminating these (see for example (294,295,296,297).

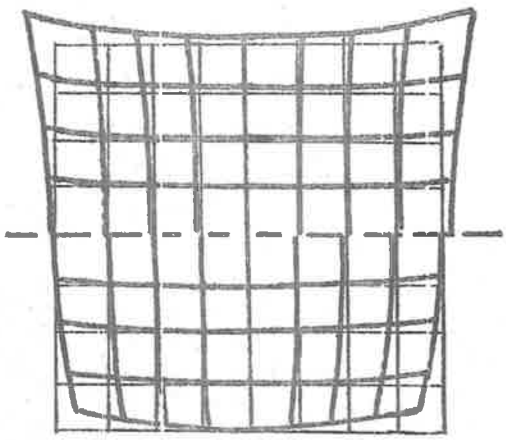
Thus expressions of a compromise nature between the above two approaches need be derived. This is done in the following sections.

9.2. GENERAL CONSIDERATIONS

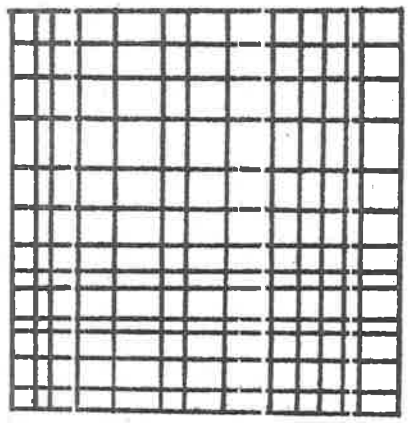
9.21 "Distortion" and "Pincushion" or "Barrel" Distortion.

The difference between what was termed "distortion" in previous chapters and "pincushion" or "barrel" distortion must be noted.

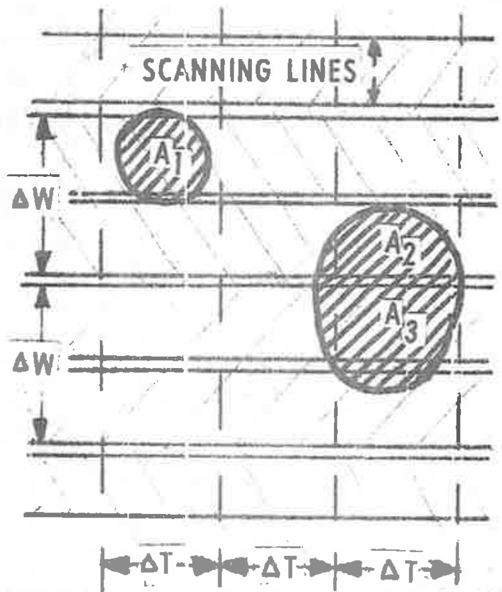
(i) "Distortion" as used previously means that horizontal scan lines are parallel to each other over the display area, even though the spacing between two adjacent scan lines varies



Top- "Pincushion distortion"
Bottom- "Barrel distortion"
on linear raster.
(a)

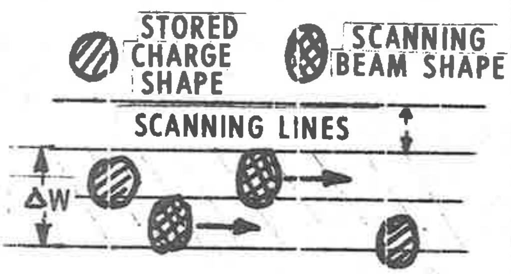


"Distortion"-the raster is square although H- and V-coordinates have non-constant spacing.
(b)



Defocussing in CRTs and Vidicons.
'A_1' is a focussed spot
The other would result in two locations 'A_2','A_3'.

Vidicon scanning by intentionally distorted beam- no interlacing.



Vidicon scanning by a focussed beam.
(d)

"ΔW"is the two scanning line width associated with each location.

Figure 122. Geometrical Distortion and Defocussing Effects.

from pair to pair of lines. This is the same as saying that no Vertical Pincushion or Barrel Distortion exists (see Fig.122(a)(b). A correction applied to any step height in the Vertical Scanning Current Staircase effectively repositions all the H-coordinate display locations within the corresponding scan line by the same amount.
If the H-scan lines were not parallel then different vertical correction steps would need to be applied to different sections of each H-scan line, greatly complicating the Vertical Distortion Correction.

Since locations within a given line can be individually corrected, and there need be no correlation between the same H-coordinate, for all V-coordinates, Horizontal Pincushion or Barrel Distortion can be tolerated, unlike the fact the Vertical Pincushion (or Barrel) Distortion cannot be tolerated.

(ii) "Pincushion (or "Barrel") distortion" on the other hand is distortion wherein H-scan lines are no longer parallel. It is of the form shown in Fig.122(a).

Pincushion distortion is invariably present to a greater or lesser degree in all CRTs and in Vidicons.

9.2.2. General Concepts of Beam Generation, Focussing and Deflection.

The Beam Generation and Deflection System consists of, in turn:

(i) an "Electron Beam Emission System," whereby a stream of electrons is emitted from a thermo-cathode, and accelerated to the required velocity by various anodes at various potentials. The requirement is to have a narrow beam of nominally the cross-sectional area required at the CRT screen or the photo-conductor target, leaving the electron emission assembly; this exit point is called the emission gun "aperture".

(ii) A "Beam Focussing System" whereby the beam, if divergent, is converged at the screen or target to the required focussed beam cross-section, even when beam is deflected.

The required beam diameter "D" at the screen or target is given by

$$D = \frac{\text{Height of display area}}{\text{Number of active display lines}} = \frac{H}{N_L} \quad .....9.1$$

With about 580 active lines in a 625-line system, then

(a) for the 3" x 4" display area on the projection CRT

$$D_{CRT} = \frac{3''}{580} \simeq 0{\cdot}005''. \; . \; . \; . \; . \; . \; .9.1(a)$$

(b) for the $\frac{3}{8}$" x $\frac{1}{2}$" display area on the Vidicon

$$D_{VID} = \frac{3''}{8.580} \simeq 0{\cdot}00065''. \; . \; . \; . \; .9.1(b)$$

Either "electrostatic" or "magnetic" focussing may be used.

(iii) A Beam Deflection System whereby the beam is deflected in a predetermined manner to be incident on the screen, in the predetermined raster scan; ideally the resultant display raster should be geometrically linear. Either "magnetic" or "electrostatic" deflection may be used.

(iv) The final requirement in the nature of the target for the electron beam and any added beam deviations at or near it.

For the CRT, the target is the phosphor, screen (described in chapter 4) - no added beam deflections occur, although the halation, described in section 6.5.5 , could be described as defocussing; this however is negligible as the resultant signal due to this is not detectable by the current Level Detectors.

For the Vidicon, the target is the photo-conductor; the signal defects (analogous to "defocussing"), and slight localized beam deflections have been described in chapter 5.

9.2.3. Electron Beam Emission

9.2.3.1 The Electron Beam Emission System

In both the CRT and the Vidicon, the electron beam is generated by a thermo-cathode, indirectly heated. The emitted beam is shaped by electrodes at certain potentials and certain shapes (forming preliminary "electric focussing lenses") and a "final aperture", out of which the beam exits the Emission System; the "aperture" diameter is approximately equal to the required beam target diameter.

Near the thermo-cathode are located control grids to cut off (or "blank off") the beam from reaching the target.

(i) For the CRT, this blanking-off is under direct input video signal control. For display locations to be displayed, the beam is enabled on by making the control grid approach the cathode potential. Whenever a display location is not required, the video signal makes the control grid much more negative than the cathode, inhibiting the beam from reaching the screen ("cutting the beam off").

The beam is also cut-off during "horizontal" and "vertical retrace time" i.e. during the time intervals that the scanning system repositions the electron beam to the L.H. edge of the display area for each new H-scan line and back to the top of the display area for each new display frame.

(ii) For the Vidicon, the complete display area is scanned continuously. The beam is only cut-off during the 10us (or thereabouts) "H-retrace" and the 2ms "V-retrace time" to reposition the beam for the raster scan.

For CRTs the accelerating potential varies from 10KV to about 25KV, the latter value required for Projection CRTs. The impact velocity of beam electrons is enough to cause secondary electron emission.

For the Vidicons the accelerating potential is in the order of 300-400V; the resultant beam electrons are "too slow" on impact to give rise to secondary electrons.

9.2.3.2 Emission System Abberations

Of particular interest are the defects in the beam which give rise to changes in the cross-sectional area of the beam and hence defocussing (294). These are

(i) "Chromatic aberration"
(ii) "Space-charge beam spreading"
(iii) Electron Emission Assembly component misalignment.

(i) Chromatic Aberration

Electrons are emitted from the thermo-cathode with different initial velocities. Since the focussing depends on electron velocities, focussing action will be different for electrons with differing initial velocities. The resultant defocussing, not very significant, is called "chromatic aberration", as it is analogous, in geometrical optics, to the chromatic aberration where light of differing wavelengths is refracted by varying amounts, giving rise to the defocussing of the above name.

(ii) Space-charge Beam Spreading.

Since the beam consists of electrons, charged particles of the same charge, mutual repulsion between them exists, giving rise to an increase in beam width and decreasing beam current density. It can again be neglected when compared with the other present defocussing effects.

(iii) Emission Assembly Component Misalignment.

To obtain an emitted beam of the required small diameter, with individual electrons having parallel trajectories to each other, the thermo-cathode is made small. For the emitted beam from the aperture to be coincident with the tube longitudinal axis, otherwise known as the "tube principal axis" or "optical axis", the exit aperture, the thermocathode, and various electrodes within the Emission Assembly need to be symmetrically located about the principal axis. Similarly the Focussing and Deflection Coils need also be symmetrically located about the principal axis. Any misalignment of these individual components results in the beam being, to a greater or lesser degree, misaligned with the principal axis, resulting in off-centering the undeflected beam from the display area centre, (a form of "constant" distortion) and in various defocussing effects which are present during beam deflection, as a misaligned beam can be considered to be a deflected beam.

Since the above factors depend on the structure of the Emission System or the physics of the Electron Emission from the thermo-cathode, nothing can be done by us. It is thus assumed that in the available CRTs and Vidicons, the above defects do not occur, or are negligible, or are correctable, their effect being within the remanent correction prior to correction.

9.2.4. Comparison between Electric and Magnetic Deflection and Focussing.

Although the Projection CRT required, as well as the Vidicon, are focussed and deflected by magnetic fields, "$\underset{\sim}{B}$-fields", the alternative of electrostatic beam deflection and focussing, "$\underset{\sim}{E}$-fields", will be briefly mentioned for comparison. The major difference between "$\underset{\sim}{E}$" and "$\underset{\sim}{B}$-field" Deflection and Focussing is that:

(a) with $\underset{\sim}{E}$-fields, the energy of the beam electrons changes within the $\underset{\sim}{E}$-field region.

(b) with $\underset{\sim}{B}$-fields, only the direction of the beam electrons is changed but not their energy.

Based on this, it can be shown (see for example (298) that:

(i) for equivalent deflection systems, defocussing aberrations are greater in $\underset{\sim}{E}$-field systems than in $\underset{\sim}{B}$-field systems.

(ii) for this reason, only small diameter electron beams can be tolerated in $\underset{\sim}{E}$-field systems, otherwise the aberrations become unacceptable. Consequently with such lower beam diameters, the resultant CRT intensity is much lower than in $\underset{\sim}{B}$-field systems.
For this reason, if for no other, $\underset{\sim}{E}$-field CRTs would not provide the high luminances required to maintain and regenerate the displayed information.

(iii) In $\underset{\sim}{E}$-field deflection, the generated display raster is nominally linear on a <u>flat</u> CRT screen; in $\underset{\sim}{B}$-field deflection, the resultant display raster is nominally linear on a <u>spherical</u> CRT screen. The latter screen shape is that required for the Schmidt Optics System focussing. Again for this reason $\underset{\sim}{E}$-field deflection cannot be used.

(iv) From the expressions relating the deflection to the $\underset{\sim}{E}$ and $\underset{\sim}{B}$ fields and the accelerating potentials, it can be shown that variations in the accelerating voltage "V_A", such as due to power supply variations, pickup etc, give greater deflection variation for the $\underset{\sim}{E}$-field system than for the $\underset{\sim}{B}$-field system.

(v) The cost of $\underset{\sim}{E}$-field tubes is usually greater than that of the $\underset{\sim}{B}$-field tubes.

$\underset{\sim}{E}$-field tubes however usually have faster response and are more economical, power-consumption wise. For Vidicons, only experimental $\underset{\sim}{E}$-field tubes have been reported thus far e.g.(299,300).

9.3. FOCUSSING OF ELECTRON BEAMS

9.3.1 Introduction

The focussing system of the CRT and of the Vidicon ensures that the electron beam, after emission and after deflection, is incident on the CRT screen or photoconductor target with the required beam diameter given by expressions 9.1(a) and (b).

The focussing action may be likened to that in lenses in geometrical optics,with analogous focussing defects or "aberrations" present in electron optics as in geometrical optics. Consequently, even though the electron beam may be sharply focussed (at "best focus") at say, the centre of the scanned area, away from this centre, the focussing deterioriates, and the electron beam diameter increases, while the cross sectional beam area may become distorted from its ideal circular shape. Consequently CRT display locations themselves appear distorted in shape while the Vidicon's output may result in spurious signals.

The object is to produce "best focus" or acceptable focus over the whole scanned area, or at least over the scanned area corresponding to the active display area.

9.3.2 Requirements of CRT and Vidicon Focussing.

9.3.2.1 CRT Requirements.

For the CRT, "best focus" is certainly required over the active display area, for the following two reasons:

(i) The active display area is to be observed by the user and thus must be of acceptably "good quality" for user-confidence and comfort.

(ii) More importantly, when the active display area is imaged onto the Vidicon photoconductor target, the individual locations must not be defocssed to such a degree, that any one imaged location would "spill over" into the display element area associated with a neighbouring location. During scanning, a signal may be generated/associated with this light incident onto the neighbouring location, of large enough amplitude to the detected by the "i_{L1}" Current Level Detector, resulting in an invalid display location being generated on the CRT. This spurious location will in turn be defocussed and generate yet another spurious location. Thus in consecutive frame-times, one display location may give rise to many spurious displayed locations merely due to defocussing (see Fig 122(c)).

To ensure that "best focus" is present, some form of "focussing correction," in addition to the existing focussing, may be required.

Focussing which varies from display location to display location on the display area, is called "dynamic focussing" as opposed to "static focussing", which is the focussing used which assumes that for a constant focus control parameter (usually the focus coil current), good focussing is achieved over the whole display area.

9.3.2.2 Vidicon Requirements

For the Vidicon, focussing requirements are not quite as stringent as for the CRT. The scanning electron beam discharges the CRT-originated charge pattern locations, which may be slightly distorted in shape and displaced from their geometrically linear positions by the Vidicon camera lens, which has itself some "pincushion", or "barrel" or other distortion. Distorted charge accumulations corresponding to the CRT display locations may thus feasably be "aligned" in "bowed" lines, typical of pincushion or barrel distortion (see Fig.122(a)). The scanning beam may thus itself have a larger (or "vertically elongated ")diameter than that given by expression 9.1(b), so that when the beam sweeps in a linear horizontal fashion (with no pincushion distortion), displaced charge locations will still be swept and discharged by the beam.
Alternatively, if no Vidicon beam defocussing is present, such displaced charge locations will be swept by the "fine focussed" beam, either during the first or the second field within a frame time, as a strip of the two H-lines width "ΔW" is associated with each Vertical coordinate (see section 8.1.2); the adjacent lines of course are scanned in interlaced fields of 20ms duration.
Consequently, for the Vidicon, two beam shapes could be used for scanning:

(i) a beam at "best-focus" over the whole active scanned area, with 2:1 interlacing required to read out all display locations which may have been distorted, or displaced, by the Vidicon Lens Pincushion or Barrel Distortion.

(ii) a beam of cross sectional area of "twice height to width" ratio, without interlaced scanning.

The scanned area would be completely scanned twice per frame time of 40ms, the scanning being done in the two normal H-scan-line wide strips.

The former is preferred here, as the availability of Vidicons with beam apertures shaped of the latter form is doubtful, while the generation and control of such a beam, although not unfeasable, is outside the scope of this thesis.
The two methods are illustrated in Fig.122(d).

9.3.3 Methods of Focussing.

Magnetic focussing of electron beams (electrostatic focussing being precluded - see section 9.2.4) can be achieved by two different methods:

(i) by a short, axial magnetic field, produced either by a permanent magnet or an electro-magnet. Focussing is achieved by the radial component (with respect to the CRT or the Vidicon tube axis) of the resultant magnetic field. The mechanism of focussing is similar to that of beam deflection by transverse magnetic fields. This is the usual method of focussing in CRTs (see Fig.123(a)).

(ii) In Vidicons, focussing is achieved by a long axial magnetic field of high intensity, such as that produced in a solenoid carrying a DC. Electrons emitted from the Emission Assembly Aperture at some small angle "γ" to the tube axis, will move in a circular motion around the lines of force of the axial field (see Fig.124(a)). The period of such a resultant circular rotation is independent of "γ", for small "Υ" and independent of any axial velocity of the electrons. Consequently all electrons emitted from the aperture will, after a certain time, all spiral back to another cross-over point of the same size as the Aperture. Since all electrons are considered to have the same axial velocity, the circular motion is in fact a helical motion, and if the photoconductor target is distant one such helix spiral away, the beam impacts the target with a diameter equal to the Aperture diameter i.e. the beam at the target is focussed.

The mechanism of focussing, imperfections of focussing or aberrations, focus coil assembly etc, even though complex, are well known and covered very adequately in the literature (for example 294,297,301). No great detail will be entered into here on these topics; the starting point will be the operating expressions for focussing in determining the primary, focussing aberrations and thence the required corrections.

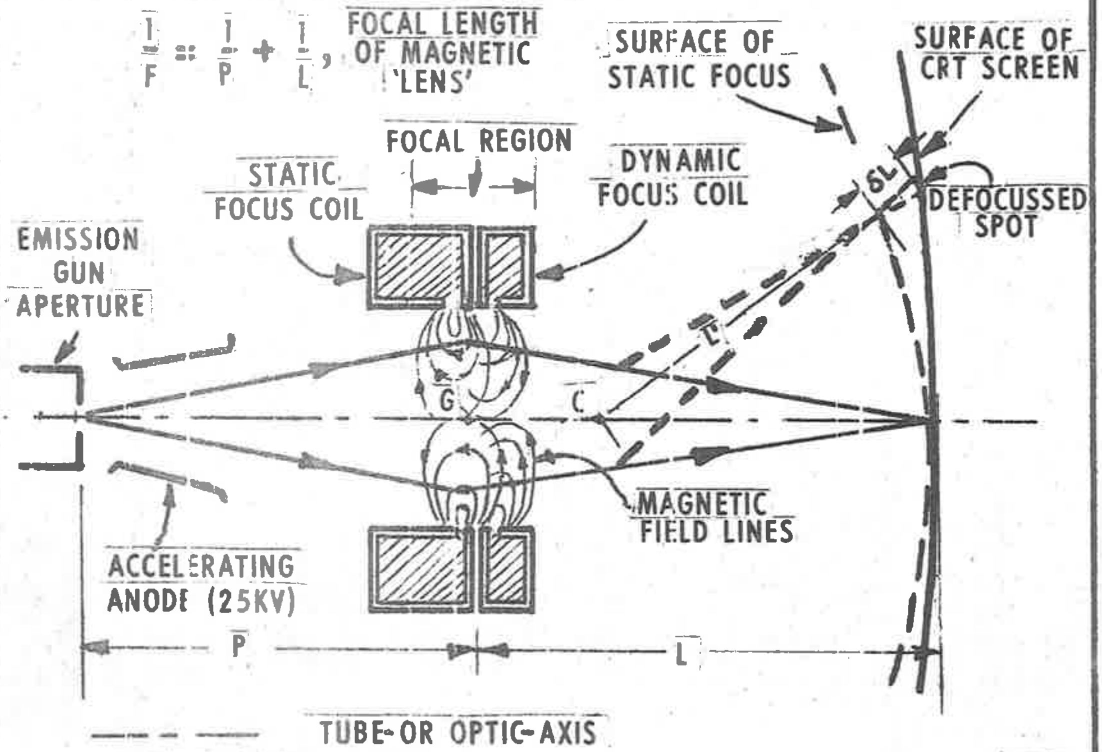
9.3.4 CRT Focussing and Correction

9.3.4.1 Defocussing due to Beam Length Variation

Referring to Fig.123(a) showing a typical short focus coil arrangement common to most CRTs (including Projection CRTs), and its relation to the Beam Emission System and the CRT screen, it is found that the distances "P" and "L", are related, analogously as in geometrical optics, by

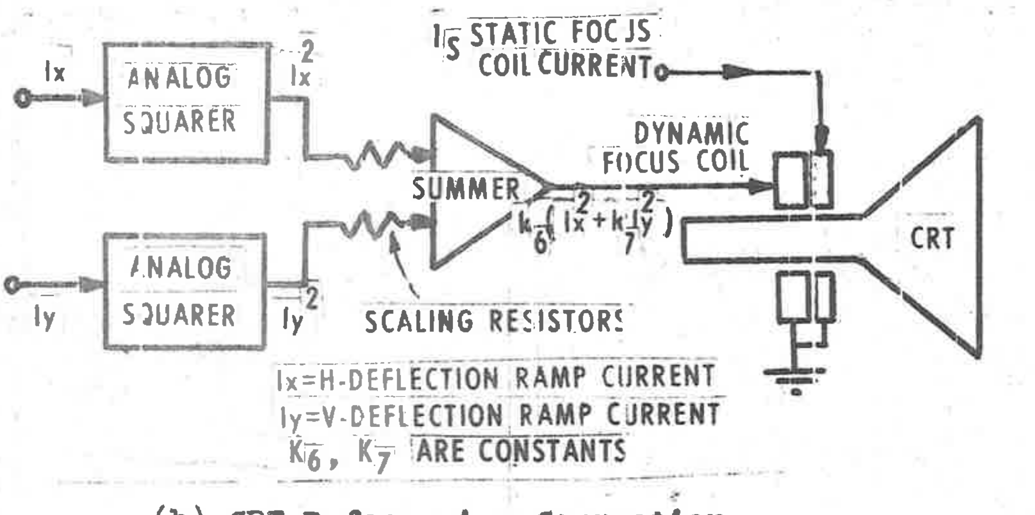
$$\frac{1}{F} = \frac{1}{P} + \frac{1}{L} \quad \ldots\ldots\ldots\ldots\ldots 9.2$$

where "F" is the "focal length" of the magnetic "focussing Lens" (301,302).



(a) Beam Fecussing by a "shert magnetic lens".

The Static Fecus Ceil previdos fecussing enly en the 'breken line' surface. The Dynamic Fecus Ceil lenght-ens the electren beam 'threw' frem 'L' te 'L + δL'.



(b) CRT Defecussing Cerrectien

Figure 123. CRT Magnetic Fecussing and Defecussing Cerrectien.

Further it is found, that if the focussing field region is short, and no electric field exists within this region, then

$$\frac{1}{F} = \frac{e}{8m} \cdot \frac{1}{V_A} \cdot \int_0^1 H_z^2 . d_z \quad . . . . . . \quad 9.3$$

$$= K_1 . \frac{I_S^2}{V_A} \quad . . . . 9.3(a)$$

where "e", "m" are the charge and mass of an electron,
"V_A" is the accelerating anode voltage,
"H_z" is the resultant axial magnetic field due to a focus coil DC current "I_S",
"z" is the distance along the axis,
"0 to 1" is the region where "H_z" is active and is considered to be constant.
and "K_1" is a constant.

Also as $H_Z = C . I_S$ 9.4

where "C" is a constant, then 9.3(a) is true.

Now as the beam is deflected across the screen, "L" varies. The "centre of beam deflection" is usually taken as the centre of the deflection coils which is not the centre of the focussing coil. Thus even for a CRT with a spherical screen whose radius of curvature is equal to the distance of the centre of deflection to the screen (as in the Projection CRT within the Schmidt Optical system -see section 6 .3.3), "L" will vary to "$L + \delta L$" during beam deflection.
For the general case where the radius of screen curvature, "R_S" is not coincident with the centre of deflection "C," and where the distance between "C" and the centre of focussing "G" is "ΔC," (see Fig.12 3(a)), then, it is found in Appendix A.6.1 that :

$$\delta L = \frac{x^2+y^2}{2(L-\Delta C)} \cdot \left(1 - \frac{L-\Delta C}{R_S}\right) \ldots\ldots\ldots 9.5$$

where "x", and "y" are the beam impact screen coordinates referred to the centre of the screen where x-0, y-0. For a flat screen CRT, the usual case quoted in the literature (303), $R_S = \infty$, and the above expression reduces to

$$\delta L = \frac{x^2+y^2}{2(L-\Delta C)} = K_2(x^2+y^2) \ldots\ldots 9.5(a)$$

Now from expression 9.2,

$$\frac{\delta F}{F^2} = \frac{\delta L}{L^2} \ldots\ldots\ldots\ldots\ldots 9.6$$

leading to $\delta F = \delta L \cdot \frac{F^2}{L^2}$

Similarly taking differentials in 9.3.(a) gives

$$-\frac{\delta F}{F^2} = \frac{2K_1}{V_A} \cdot I_S . \delta I \ldots \left(= -\frac{\delta L}{L^2}\right) \ldots\ldots 9.7$$

thus $$\delta I = -\frac{V_A}{2K_1 I_S} \cdot \frac{\delta L}{L^2} \ldots\ldots\ldots\ldots 9.7(a)$$

or $$\frac{\delta I}{I_S} = -\frac{1}{2}\left(\frac{V_A}{K_1 I^2{}_S}\right) \cdot \frac{\delta L}{L^2} = \frac{-F . \delta L}{2L^2} \ldots\ldots 9.7(b)$$

Substituting for "δL" from 9.5(a) gives

$$\frac{\delta I}{I_S} = \frac{-F\ (x^2+y^2)}{4L^2(L-\Delta C)} = -K_3 . (x^2+y^2) \ldots 9.7(c)$$

where $$K_3 = \frac{F}{4L^2(L-\Delta C)}$$

Now the Horizontal and Vertical Scanning Waveforms, being ramp or staircase currents themselves, are linear functions of time (and hence position) and thus

$$x = K_4 I_x \text{ and } y = K_5 I_y \quad . \; . \; . \; . \; . \; . \; . \; . \; 9.8$$

where "K_4" and "K_5" are constants and $K_4 I_{xmax} : K_5 I_{ymax} = 4:3$.

Consequently,

$$x^2 + y^2 = K_4^2 \left(I_x^2 + \left(\frac{K_5}{K_4}\right)^2 I_y^2 \right) \quad . \; . \; . \; . \; . \; . \; 9.9$$

Substituting gives,

$$\delta I = -I_S K_3 . (K_4)^2 \left(I_x^2 + \left(\frac{K_5}{K_4}\right)^2 I_y^2 \right) \quad . \; . \; . \; . 9.10$$

$$\delta I(x,y) = -K_6 (I_x^2 + K_7 . I_y^2) \quad . \; . \; . \; . \; . \; . \; . \quad 9.10(a)$$

where $K_6 = I_S . K_3 (K_4)^2$, $K_7 = \left(\frac{K_5}{K_4}\right)^2$ are constants.

This then is the correction current to be fed into the focus coil, in addition to the current "I_S", which by itself produces the normal static focus.

In practice a separate "dynamic" focus coil is provided, as close to the "static" focus coil, as possible. This is shown in Fig.123(a). This "dynamic focus coil" is usually a low inductance coil, so that the response in generating the field corresponding to the above input current in expression 9.10(a), is not delayed by the time constant due to the inductance and resistance of the coil. The total driving current into the dynamic focus coil is low enough to be supplied directly from I-C Op-amps which also acts as a Summer for the individual current components.

The block diagram to generate this dynamic focus correction is shown in Fig.123(b). The blocks labelled as "Squarers" can be "4-quadrant Analog Multipliers" with the two inputs into each being either the "I_x" or the "I_y" currents.

The peak expected amplitude "δI_{peak}" is derived as follows.

From the 5" projection CRT data (259), from which the tube dimensions and locations of focus coil are obtained, it can be found that $L \approx 8\frac{1}{2}"$, $P \approx 2\frac{1}{2}"$ and hence from expression 9.2, $F \approx 2{\cdot}0"$. For x = 3", y = 4" and $\Delta C \approx 1\frac{1}{2}"$, and $R \approx 7\frac{1}{4}"$ then "δL_{max}" from expression 9.5, is equal to 0·06" and thus "$\frac{\delta I}{I_S}$" (from expression 9.7(b)) is equal to about 0·001". As DC currents "I_S" for focus coils are of the order of 200-500mA (300), the actual "δI_{max}" is of the order of 0·2 to 0·5mA; hence the output directly from Op-amps can be used. This apparently small and negligible correction is due to the fact that the projection CRT has its centre of deflection almost coincident with the centre of curvature of the screen. Deflected beam lengths are thus nearly constant and "δL" $\rightarrow$ 0 according to expression 9.5. In flat screen CRTs with the above CRT dimensions (but $R \rightarrow \infty$) then $\delta L \approx 0{\cdot}9"$ and "$\frac{\delta I}{I_S}$" equals 0·0125. With $I \approx 200 - 500$mA, "δI_{max}" would be of the order of 2·5 - 6 mA.

9.3.4.2. Defocussing due to Non-normal landing of Beam

The other major "dynamic defocussing" effect is due to the non-normal landing of the beam on the screen. A beam landing normally, as at the centre of the CRT screen, presents its cross-sectional area "A_1" upon impacting on the screen. A beam landing non-orthogonally, at at some angle "φ" to the normal, presents a beam area of "$A_1 \sec \varphi$" on impact. For "φ" up to 20^0 off normal, "$A_1 \sec \varphi$." is only about 5% more than the nominal beam cross-sectional area, and thus this effect can be neglected as such non-normal beam landing is only encountered in flat screen CRT, which for our purpose are of no interest.

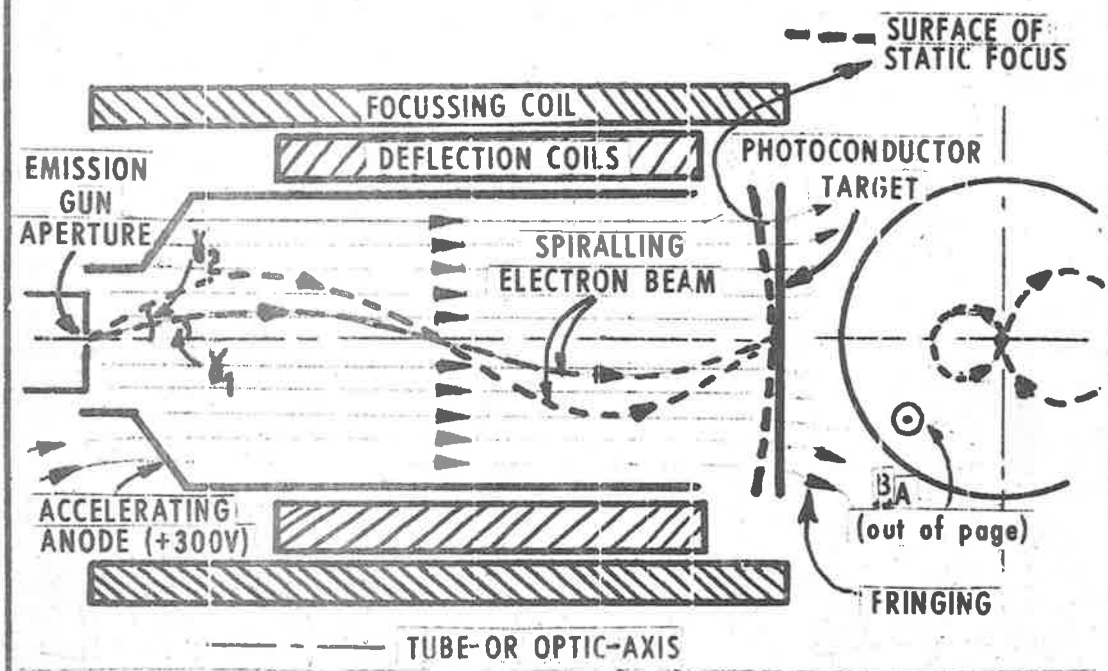
9.3.4.3 Conclusions

It can thus be concluded that Focussing Correction is unnecessary in the Projection CRT required, as beam length variations are negligible and beam landing is near-normal.

9.3.5. Vidicon Focussing Correction

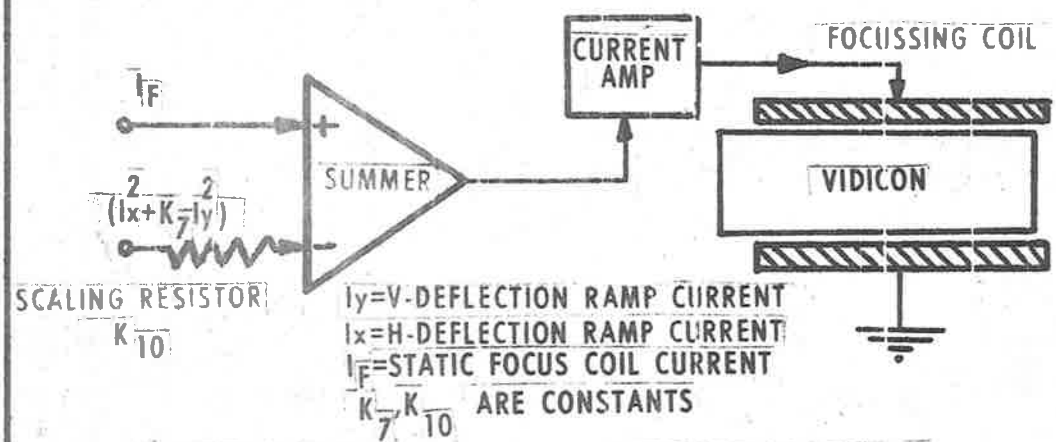
9.3.5.1 Vidicon Focussing.

In Vidicons focussing is carried out on beams consisting of "slow electrons" (accelerated by anode voltages of about 300-400V), the reason being to preclude any secondary emitted electrons from being generated upon beam-target impact. The focussing field is a long axial field produced effectively by a long solenoid, within which the Vidicon tube, including the deflecting coils, are inserted (see Fig.124(a)). Both the "object" i.e. the Beam Emission System Aperture and the image, i.e the photoconductor target, lie within the focussing magnetic field. As shown in most textbooks (see for example (295, 301), such "slow" electrons describe a spiral path around the axial magnetic lines of force, the "length" of a spiral (or "pitch length") under certain conditions being constant, for electrons emitted at various angles "γ" to the tube axis, i.e. for those electrons requiring focussing. Thus all electrons emitted from the Emission System Aperture, will after one spiral cross or meet again to form a "focussed" spot of Aperture diameter cross-sectional area. The same focussing occurs after 2,3,...n spirals.



(a) Beam Focussing by a "long magnetic lens".

The electrons at angle "γ" spiral along the axialfield lines, with the electron beam 'throw' being equal to one 'pitch' length of the spiral. The figure at right shows the projected end-view of the spiral trajectory of two electrons being focussed.



(b) Vidicon Defocussing Correction.

Figure 124. Vidicon Magnetic Focussing and Defocussing Correction.

9.3.5.2 Defocussing due to Beam Length Variations

The Axial Focussing Magnetic Field has superimposed within it, the "x" Direction and "y" Direction Magnetic Deflecting Fields. As an approximation these resultant magnetic fields add vectorially to form the resultant field as shown in Fig.126(a), and the slow electrons spiral along the nett "bent" axial lines of force. Near the photoconductor target, only the axial focussing field is operative (the deflecting magnetic fields being much "shorter" than the axial field), because the electron beam is required to land normally onto the phototarget to ensure that the stored target charge is fully discharged (see section 5.4). (The calculations in section 5.4. assumed the worst case that the deflecting field was operating near the target region also and hence beam landing was non-normal).

The angle of deviation "γ" of the emitted electrons from the emission assembly aperture is quite small (by suitably designing the emission assembly) and certainly less than about 12°, otherwise under maximum deflection, the dimensions of the spirals and of the location of the nett lines of force would be such that spiralling electrons would be incident on the sides of the 1" diameter Vidicon (a simple geometrical calculation will show this, taking into account the length of a 1" Vidicon deflection region and the dimensions of the scanned area).

The velocity of these beam electrons is derived from

$$eV_A = \frac{1}{2}m\ v_T^{\ 2} \quad \text{....(from expression 5.6)}$$

$$= \frac{1}{2}m\ (v_r^{\ 2} + v_z^{\ 2})$$

where "V_A" is the accelerating anode potential

"v_z" = $v_T \cos\gamma$ the electron velocity parallel to the tube axis.

"v_r" = $v_T \sin\gamma$, the electron velocity radial to the tube axis.

and "v_T" is a constant for any fixed V_A.

The force "$\underset{\sim}{F}$" on an electron within a magnetic field $\underset{\sim}{H}$ is given by

$$F = \mu \underset{\sim}{v} \times \underset{\sim}{H} \quad \ldots\ldots\ldots\ldots\ldots 9.11$$

Hence the electrons parallel to the $\underset{\sim}{H}_z$ axial field, with velocity "v", are unaffected by "$\underset{\sim}{H}_z$", while the electrons with a velocity radial to "$\underset{\sim}{H}_z$" are deflected in a circular direction (see Appendix A.6.3), with the radius "r" of resultant circle of deflection being,

$$r = \frac{m \underset{\sim}{v}_r}{e\mu \underset{\sim}{H}} \quad \ldots\ldots\ldots\ldots\ldots 9.12$$

Due to "v_z" being present, the resultant motion is a spiral. The period "T_S" for an electron to describe a circle is derived from the equivalence of distance travelled in a spiral

$$v_r . t = 2\pi r \quad \ldots\ldots\ldots\ldots\ldots 9.13$$

then $$T_S = 2\pi . \frac{m}{e\mu} . \frac{1}{\underset{\sim}{H}} = \frac{K_8}{\underset{\sim}{H}} \quad \ldots\ldots\ldots 9.13(a)$$

If the distance between the Emission Assembly Aperture (the "object") and the photoconductor target is "Z_K", then

$$T_S . v_z = Z_K = \text{constant} \quad \ldots\ldots\ldots 9.14$$

implying that both "T_S" and "v_z" need be constant.

"v_z" is nearly constant; for $-12^\circ < \gamma < 12^\circ$

"$\frac{v_z}{v_T}$" varies by about 2% from unity.

Under deflection, with the total angle between the direction of "v_T" and the tube axis, being "φ", then,

$$\varphi = \arctan\sqrt{\frac{x^2+y^2}{L}} \quad \ldots\ldots\ldots\ldots 9.15$$

$$\approx\sqrt{\frac{x^2+y^2}{L}} \quad \ldots\ldots\ldots\ldots\ldots 9.15(a)$$

(with less than 5% error for $\varphi \leq 20^\circ$), where "L" is the length where the deflecting field operates (see Fig.126(a)).

Now using the first two terms of the series expansion for "$\cos\varphi$",

$$v_T\cos\varphi = v_T\left(1-\frac{(\varphi)^2}{2}\right) \quad (= v_z) \ldots\ldots\ldots 9.16$$

$$\approx v_T\left(1 - \frac{x^2+y^2}{2L^2}\right) \text{ on substitution for "}\varphi\text{"}$$

$$\approx \frac{v_T}{1+\frac{x^2+y^2}{2L^2}} \quad \ldots\ldots\ldots\ldots\ldots 9.16(a)$$

As it is required that (expression 9.14)

$T_S.v_z$ = a constant, Z_K

then substituting for "T_S" and "v_z" results in

$$\frac{K_8}{\underset{\sim}{H}} \cdot \frac{v_T}{\left(1+\frac{x^2+y^2}{2L^2}\right)} = Z_K \quad \ldots\ldots\ldots 9.17$$

If the magnetic field $\hat{H}$ is such that

$$H = H_F\left(1 - \frac{x^2+y^2}{2\,L^2}\right) \ldots\ldots\ldots\ldots 9.18$$

with "H_F" fixed, then both sides of expression 9.17 are constant (except for a negligible 2-nd order term $(x^2+y^2)^2$. Since the static focus magnetic field "H_F", is caused by a DC current "I_F" flowing in the focus coil such that

$$H_F = K_9 I_F \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 9.19$$

then the required focus coil current "I_n" is given by

$$I_n = I_F\left(1 - \frac{x^2+y^2}{2L^2}\right) \quad \ldots\ldots\ldots\ldots \quad 9.20$$

And from expression 9.8,

$$x = K_4 I_x \quad \text{and} \quad y = K_5 I_y \quad \ldots\ldots \quad 9.8$$

then the nett required current into the Vidicon focus coil "I_n" is given by,

$$I_n = I_F - \frac{I_F (K_4)^2}{2L^2}\left(I_x^2 + \left(\frac{K_5}{K_4}\right)^2 . I_y^2\right) \ldots. 9.20(a)$$

$$= I_F - K_{10}(I_x^2 + K_7 I_y^2). \quad \ldots\ldots \quad 9.20(b)$$

where $K_{10} = \frac{I_F . (K_4)^2}{2L^2}$ and $K_7 = \left(\frac{K_5}{K_4}\right)^2$ are constants.

A block diagram of the circuit accomplishing this is shown in Fig.124(b). The block generating the term "$I_x^2 + K_7 I_y^2$" is the same as for the CRT dynamic focussing, and will recur still later for pincushion or barrel distortion elimination.

The scaling of the two input resistors to the differential amplifier is as follows:

Equating 9.20 and 9.20(b) results in

$$I_F\left(\frac{x^2+y^2}{2L^2}\right) = K_{10}.I_x^{\,2}\left(1+\left(\frac{K_5 I_y}{K_4 I_x}\right)^2\right) \quad \ldots .9.21$$

with
$$K_{10} = \frac{|I_F|}{|I_x|^2}\cdot\left(\frac{x^2+y^2}{2L^2}\right)\frac{1}{\left(1+\left(\frac{K_5 I_y}{K_4 I_x}\right)^2\right)}$$

From the equivalence expression of 9.8 this gives

$$K_{10} = \frac{I_F}{|I_x|^2}\cdot\frac{x^2\left(1+\frac{y^2}{x^2}\right)}{2L^2}\left(\frac{1}{1+\frac{y^2}{x^2}}\right) \quad \ldots .9.22$$

For the Vidicon "x_{max}" occurs at the scanned area corners and is equal to $\frac{1}{4}$", while "L" is of the order of 2 → 2.5". "x_{max}" corresponds to the horizontal sweep current ramp of

$$I_{x\ max} = \left.\frac{I_{peak\ to\ peak}}{2}\right]_H$$

$$K_{10} = \frac{|I_F|}{(I_{p-p})^2}\cdot\frac{4.\left(\frac{1}{4}\right)^2}{2.(2\cdot5)^2} \quad \ldots\ldots .9.22(a)$$

$$= \frac{1}{50}\cdot\frac{I_F}{(I_{p-p})^2} \quad \ldots\ldots\ldots 9.22(b)$$

"I_F" is normally about 200-300mA, while "I_{p-p}" is usually of the order of 100mA.

Hence $\quad K_{10} \approx \frac{200}{10}\cdot\frac{1}{50} = \frac{2}{5} \quad \ldots\ldots\ldots 9.22(c)$

9.3.6 Vidicon Beam Landing Correction

At this juncture the circuit enabling the cathode potential of the Vidicon to be varied to compensate for non-orthogonal beam landing (see section 5.4) onto the photo conductor target, and hence to compensate for varying degrees of output signal degradation will be described. In Section 5.4. the requirement was stated that a voltage "V_K'", of "$-V_A.\mathrm{Sin}^2\varphi$" was required at the cathode, where

$$\varphi = \arctan\sqrt{\frac{x^2+y^2}{L}} \quad \ldots\ldots\ldots\ldots 5.5$$

with "V_A", "L", "x" and "y" as defined previously and $\varphi \leqslant \pm 7^o$.

Expanding the above and substituting into the expression for the required voltage results that the cathode voltage must be given by

$$V_K' = -V_A . \frac{(x^2+y^2)}{L^2} \ldots\ldots\ldots\ldots 9.23$$

and substituting for "x" and "y" from expression 9.8 gives

$$V_K' = -\frac{V_A(K_4)^2}{L^2}\left(I_x^2 + \left(\frac{K_5 I_y}{K_4}\right)^2\right) \ldots\ldots 9.23(a)$$

$$= -K_{11}\,(I_x^2 + K_7 I_y^2) \quad \ldots\ldots 9.23(b)$$

The peak value $\pm V_{Kmax}$, for "$V_A \approx 300V$" and "$\varphi_{max} \approx 7^\circ$" is of the order of "$-4V$".

The circuit enabling the above to be implemented is shown in Fig.127 (with the Summer "11" and the Resistor "R_L" at the Vidicon Cathode).

9.3.7 Focussing Aberrations

The focussing defects or "aberrations" mentioned above and for which correction circuits have been derived, are due to "dynamic" effects i.e due to beam deflection across the scanned area. It has been assumed that undeflected beams i.e. those incident at the centre of the scanned areas where "x", "y" = o, are correctly focussed. This is not strictly true, as anologous to focussing aberrations in geometrical optics, "aberrations" still are present for such undeflected beams, in electron optics.

Specifically, these aberrations are called "3rd-order aberrations". As in geometrical optics, many expressions in electron optics, describing the individual electron trajectories within the electro-magnetic fields, contain terms of the form "sin α", where "α" is the angle between the trajectory direction and the optical or tube axis. Usually "sinα" is expanded into the Series $(\alpha - \frac{(\alpha)^3}{3} + ..)$.

In "first order" electron optics, "sinα" is approximated by "α". If the "$\frac{(\alpha)^3}{3}$" term is included, certain terms appear in the resulting trajectory expressions, indicating deviations from ideal trajectories. These "defect" terms are the "3rd-order aberrations". Clearly they become more significant as "α" increases. Particularly, when beams are deflected, "α" increases and so do the aberrations.

Compared with "dynamic" defocussing effects, the "3rd-aberrations" are not greatly significant. A brief mention of them will be made for completeness sake. References (294,296,297) contain a full treatment with excellent illustrations of these aberrations on beam spot size.

Analogous to geometrical optics, the aberrations are:

(i) "spherical aberration"

(ii) "Coma"
(iii) "Curvature of field"
(iv) "Astigmatism"
(v) "Geometrical distortion."

As magnetic fields are anistropic for electron beam deflections (beams traversing identical trajectories in opposite directions are deflected differently), their presence introduces three more aberrations:

(vi) "Spiral distortion"
(vii) "anisotropic coma"
(viii) "anisotropic astigmatism".

The effect of all of these aberrations is to increase the beam diameter or CRT display spot size, symmetrically or unsymmetrically to a greater or lesser degree. Illustrations of such distorted CRT screen spots are given in (294,296,297). The expressions derived in the literature (for example (305)) are cumbersome and unwieldy, due to the complexity of problems involving electron beam motion within 3-dimensional electromagnetic fields. Expressions of practical significance are even more difficult to obtain. The determination of aberrations (and hence corrections) depends on the exact knowledge of the electric and magnetic fields within the focussing, deflecting, and accelerating regions. These are difficult enough to measure to any degree of precision within the small confines of a CRT or Vidicon tube dimensions; the expressions for obtaining aberrations further require the first and higher order gradients of these electro-magnetic fields.

Assuming then that these have been derived from the field measurements, and assuming that within the "aberration expressions," the aberration coefficiants have been identified with each of the electric and magnetic fields, the corrections eliminating these aberrations still require to be made. Generating correction current and voltage waveforms, derived from these expressions, is too complex, requiring too many complex function generators.

The usual method is to shape the coils and electrodes giving rise to certain electro-magnetic field distributions and seeing the effect on trajectories by "ray-tracing." More recently, "Computer Generated Ray Tracing" techniques have been implemented (306). All this is, of course, outside the scope of this thesis.

9.3.7.2 Other Focussing Aberrations

The other major aberrations which may be present are:

(i) First Order Aberrations which occur when axial symmetry is absent between the Electron Beam Emission Assembly, the Focussing System and the Deflection Coils and the CRT, or Vidicon Target; thus all these components must be so aligned that their longitudinal or electro-optical axis are all collinear. Otherwise, a misalignment occurs between the undeflected beam and the centre of the scanned area of the target, which is equivalent to all of the electrons in the undeflected beam being aligned at some small angle "$\delta\gamma$" to the tube axis. The result is unsymmetrical, increased aberrations over the whole scanned area.

Beam centering assemblies, consisting either of permanent - or electro- magnets can be used and are commercially obtainable (302); they are usually provided with TV camera Focussing Assemblies or in CRTs. Theyrealign the electron beam with the optical axis of the tube.

Micrometer - controlled,precision Coil Positioning Assemblies are similarly obtainable for precisely positioning or rotating deflection coil assemblies (302).

It is assumed, with reasonable justification, that the commercially available projection CRTs and the Vidicon assembly of Tube and Deflection and Focussing Coils, have insignificant "1-st order aberrations" and "3rd-order aberrations" which are no more significant than the "dynamic defocussing", which as seen above, is correctable whithout much complex correction hardware.

This assumption is based on current technology capabilities and on the fact that the active display area over which the assumption is to be operative, lies within the central part of the scanned area (see Fig.105) where defocussing effects are much less than near the edges of the scanned area.

9.3.8 Summary.

(1) For CRTs the display locations need be sharply focussed and of constant size over the whole scanned area, or at the very least,over the active display area - otherwise spurious display locations may be generated due to electron beam "spread" or "defocussing".

(2) For the Vidicon, sharply focussed beams are also required over the active display area but the requirements can be relaxed over that required for the CRT.

(3) Defocussing is caused by the following reasons:

(i) "first-order aberrations" or aberrations due to any or all of the following components to be misaligned with the tube optical axis: Beam Emission Assembly, Deflection and Focussing Coils and CRT Screen or Vidicon Target. Commercially available "beam alignment devices" are available to eliminate these misalignments.

(ii) "Third-order aberrations", due to the non-constancy of electric and magnetic fields within the focussing region, and which make themselves apparent at large beam angles with the optical axis. Present day technology and the fact that the active display area is smaller than the total scanned area make these aberrations negligible.

(iii) Increased third-order aberrations due to beam deflection in generating the display raster, being present.

(iv) The variation in beam length from the centre of the focussing region to the CRT or Vidicon target, due to deflection. Normally focussing is usually static, "the best focus" being for a fixed beam length.
This is the major cause of "defocussing", and corrections are applied to eliminate this form of defocussing.

(v) the non-orthogonality of the beam to the target on impact causes an increase in beam cross sectional area.
This defocussing effect can be neglected.

(4) For both the CRT and Vidicon, simple "correction wave-forms" derived from the Horizontal and Vertical Scanning Current Waveforms, and feeding into the Focus Coils can be easily implemented.
For the CRT, a separate "Dynamic" Focus Coil (commercially available) is required. However, in the spherical screen Projection CRT correction is not usually required.
For the Vidicon, if the focus coil is of low enough inductance, the correction current can be summed with the Static Focus Current and the result fed into the existing Focus Coil.

9.4. DEFLECTION OF ELECTRON BEAMS & PINCUSHION OR BARREL DISTORTION CORRECTION

9.4.1 Introduction

Deflection of the electron beam to scan the display area in both the Vidicon and the CRT is caused by magnetic fields "H_x" and "H_y" whose intensity changes in a predetermined manner with the frequency of the H- and V-scanning. These magnetic fields are thus functions of time, with "$H_x = H_H(t)$" and "$H_y = H_V(t)$" where the subscripts "H" and "V" refer to the horizontal "x" and vertical "y" directions respectively. This time variation is only in relation to the scanning and hence to the beam deflection angle, and not to the time of transit of electrons within the beam between the beam emission assembly and the instant of impact on the target.

A simple sum will show that for the slowest beam electrons, those in the Vidicon, accelerated by an anode voltage of some 300V, this transit time is less than some 0·1uS. Hence deflecting magnetic fields for any deflection may be considered as quasi-static.

The deflection system must meet two requirements:

(i) the resultant generated display or raster must have geometrical fidelity - i.e. focussing must be retained and the raster must be geometrically linear.

(ii) It must have efficient power utilization. This requirement maybe relaxed in favour of the first.

The Magnetic Deflection System of both the CRT and the Vidicon consists of two pairs of deflection coils, one pair for Vertical deflection, the other for the Horizontal deflection. Between a given pair of coils the deflecting magnetic field is generated, by feeding into the coils a linear ramp current (for the horizontal deflection) and a linear staircase current (for the vertical deflection), which generates a linear varying magnetic field according to

$$H(t) = K.i(t) \quad \ldots\ldots\ldots \text{(as in 9.19)}$$

Ideally it is assumed that this resultant magnetic field exists within the whole of the coil region; in fact it exists on the coil axis, and varies slightly (decreasing) away from the axis, in a radial direction. Magnetic "field fringing" also occurs at the ends of the deflecting region, i.e. at the ends of the coils.

Any derivation of deflection expressed as a function of the linear scanning current, "I(t)", and any deviations from ideal deflection ,should take into account the form and distribution of the fields "$H_H(t)$", "$H_V(t)$", along the axis of the coils (the "Z-axis"), the radial variation of intensity,and the end fringing effects. Difficulty in measurement of these field distributions is one limiting factor which precludes this. The other major difficulty is the complexity of the equations themselves and their analytic solutions; numerical methods or approximating assumptions need be made before solutions can be obtained.

The predictable distortion which can be expressed with analytically defined coefficiants is the pincusion or barrel distortion, which is present even with linear deflection coil driving currents. Correction currents, analytically defined, can be derived from these distortion expressions to compensate for the distortions. The remanent distortion after correction will be of the order or less than 0·5 - 1·0% which can be corrected and eliminated by the distortion correction methods described in chapter 8.

The expressions derived here differ from those given the literature (e.g. 294, 296) in that emphasis is on simplicity of expressions and "correctability" of distortions, rather than expressions which identify the causes of distortion, which most textbooks and references on the topic seem to do.

On the other hand existing derived expressions suitable for correction analysis either give inadequate explanations of derivation (303,307) or else make assumptions which are too simplifying (308).

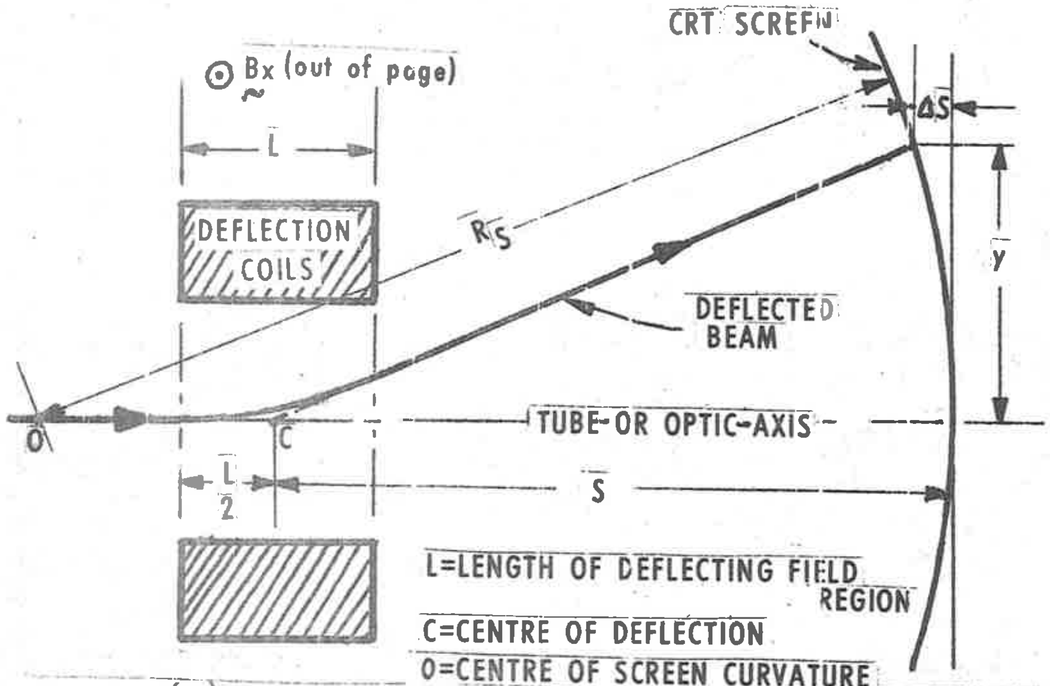
Magnetic beam deflection in a CRT is due to magnetic fields located in a region separate from the region containing the focussing magnetic field region. "Fast" electrons are deflected, that is, those accelerated by accelerating potentials of greater than 10KV; in Projection CRTs, the accelerating voltage is of the order of 25KV or more.
In Vidicons, the deflecting field is superimposed on the long axial focussing magnetic field. "Slow" electrons are deflected, accelerated by potentials of some 300-400V.

Consequently, the mathematical treatment for both of these cases would appear to be somewhat different, even though the final correction expressions will be shown to bear some similarity. The derivations must, of necessity, contain approximations, the main one being that the region within which the magnetic deflecting region is present be sharply defined by the deflecting coil boundaries; the field within this region is assumed to be constant, while outside the region the field is zero. Such approximations will result in correction expressions still accurate enough, so that when the correction is implemented remanent pincushion distortion is less than about 0·25%, while distortion is within 0·5-1·0%. Distortion without correction would be in the order of 3 - 5%.

9.4.2. CRT Distortion and Correction.

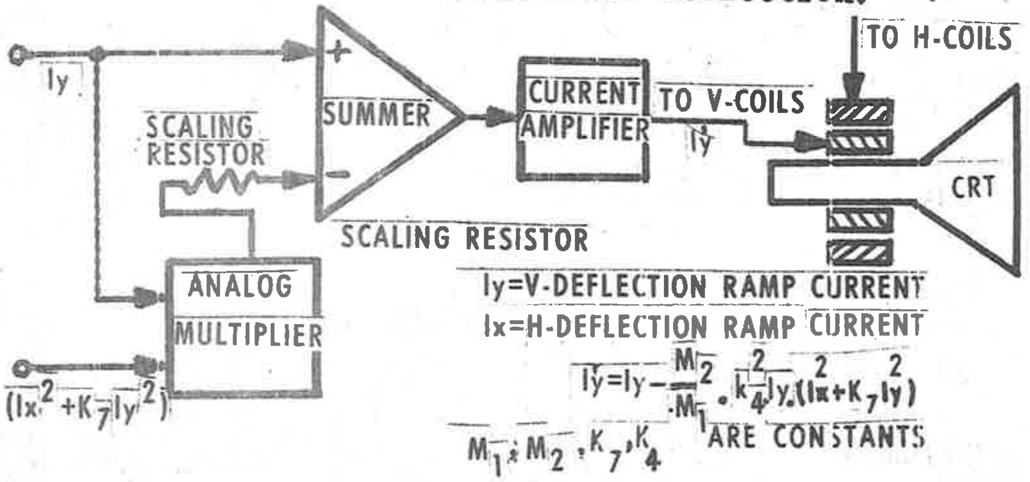
9.4.2.1 CRT Distortion

The derivation for pincusion distortion for arbitrary curved CRT screens is derived in Appendix A.6.3 in a paper submitted for publication. Therein is contained



(a) CRT Magnetic Deflection

The scanning magnetic field $\underset{\sim}{B}_x$ (out of page) deflects the electron beam upwards within the region of length 'L'. The beam appears to originate nominally from 'C', the 'centre of Deflection'. A second field $\underset{\sim}{B}_y$ (vertical in the plane of page) is necessary to produce the horizontal deflection.



(b) CRT Display Distortion Correction.

Figure 125. CRT Magnetic Beam Deflection and Display Distortion Correction

a short review of existing derivation for pincushion distortion and their shortcomings, for our correction purposes. The distortion expressions are derived from first principles.
For a curved CRT screen where the centre of beam deflection is not coincident with the centre of screen curvature, the "y" deflection is given, from expressions 40(a) in Appendix A.6.3 ,

$$y = -KB_xLS - K^3.\frac{L}{2}^3.S.\left[1-\frac{S}{R_S-\frac{\Delta S}{2}} - \frac{L}{4S}\right].B_x.\left[B_x^2+B_y^2\right] \quad (40(a))$$

where "B_x" is the transverse magnetic field causing "y" deflection and where $B_x = K_yI_y$.
where "K_y" is a constant.
and "I_y" is the ramp current causing y-deflection.
"B_y" is the transverse magnetic field causing "x" deflection. Again $B_y = K_xI_x$; "K_x" is a constant.
" K" is a constant and equal to $\sqrt{\frac{e}{2m V_A}}$
where "e","m" are the charge and mass of electron.
"V_A" is the accelerating anode voltage ($\approx$ 25KV).
"S" is the distance from the centre of the CRT screen and the "centre of deflection."
"L" is the length of the magnetic deflecting region.
"R_S" is the radius of curvature of the CRT screen.
"ΔS" is the deviation of the screen from flatness at the point where the beam is incident.

These distances are shown in Fig.125(a).
An analogous expression can be immediately written for the x- deflection.
Expression "40(a)" can be rewritten as

$$y = M_1 I_y + M_2 I_y\left[(K_x I_x)^2 + (K_y I_y)^2\right] \ldots\ldots 9.24$$

where

$$M_1 = -\sqrt{\frac{e}{2mV_A}} \cdot L.S\,K_y \quad \ldots\ldots\ldots 9.25$$

$$M_2 = -\left(\sqrt{\frac{e}{2mV_A}}\right)^3 \cdot \frac{L^3}{2} \cdot K_y \cdot S\left(1 - \frac{L}{4S} - \frac{S}{R - \frac{\Delta S}{2}}\right) \quad \ldots\ldots 9.26$$

9.4.2.2. Distortion Correction

Rewriting expression 9.24 as:

$$y = -M_1 I_y \cdot \left(1 + \frac{M_2 K^2{}_x}{M_1} \cdot \left[I_x{}^2 + \left(\frac{K_y I_y}{K_x}\right)^2\right]\right) .9.24(a)$$

then if a current of the form

$$I_y' = I_y\left(1 - \frac{M_2}{M_1} K_x^2 \left[I_x{}^2 + \left(\frac{K_y}{K_x} I_y\right)^2\right]\right) \quad 9.27$$

is fed into the deflection coils, the new deflection becomes

$$y = -M_1 I_y\left(1 - \left[\frac{M_2}{M_1} K_x^2 \left(I_x^2 + \left(\frac{K_y}{K_x} . I_y\right)^2\right)\right]^2\right) ..9.28$$

$\approx -M_1 I_y$, the required linear deflection as the second term is insignificant (less than 0·1%). Similarly a current into x-deflection coils of the form

$$I_x' = I_x\left(1 - \left[\frac{M_2}{M_1} k_y{}^2 . I_x{}^2 + \left(\frac{K_y}{K_x} . I_y\right)^2\right]\right) \ldots 9.27(a)$$

eliminates pincusion distortion in the horizontal coordinate.

As it is required that "$y \propto B_x$" and "$x \propto B_y$" and as

$$\left.\begin{aligned} y &= K_5 I_y \\ x &= K_4 I_x \end{aligned}\right\} \text{ expression 9.8 and } \quad \begin{aligned} B_x &= K_y I_y \\ B_y &= K_x I_x \end{aligned}$$

then $\frac{K_y}{K_x} = \frac{K_5}{K_4}$ 9.29

implying that the factor $\left[I_x^2 + \left(\frac{K_y}{K_x} . I_y\right)^2\right]$

is identical to the factor $\left(I_x^2 + \left(\frac{K_5}{K_4} I_y\right)^2\right)$ used in "defocussing expressions" for the CRT and the Vidicon.

The block diagram in Fig.125(b) indicates the correction implementation.

The expected amplitudes of pincushion distortion can now be calculated.

(a) For a flat screen CRT, $R_S = \infty$, and thus "M_2" is evaluated with the bracketed factor in 9.26 equal to $(1 - \frac{L}{4S})$. This is the usual case quoted in the literature.

(b) For the Projection CRT, then, as mentioned previously, to satisfy certain Schmidt Optics requirements, the screen is made a spherical section with the Centre of Deflection "C", coincident with the Centre of Curvature of the Screen. Under these conditions $R_S = S$ (see Fig.3 in Appendix A.6.3). With typical values for a 5" Projection CRT,

$R_S = 7\frac{1}{4}" = S$, $\Delta S_{max} = 0 \cdot 32"$ (from Table 1)

$L \approx 3"$, $\frac{\Delta S}{2} \ll R_S$ and can be neglected

It can be easily found (304) that

$$B_y = K_x I_x = \frac{1}{\sqrt{\frac{e}{2mV_A}}} \cdot \frac{\sin \varphi}{L} \quad \ldots\ldots .9.30$$

where $\varphi \approx \arctan \frac{\sqrt{x^2+y^2}}{S - \Delta s}$, the angle of deflection

$\approx \frac{\sqrt{x^2+y^2}}{S}$, correct to about 5% for angles less than 20°.

For maximum CRT deflection where $x = \frac{4''}{2}$, $y = \frac{3''}{2}$, then substituting into 9.24(a), and noting the equality given by 9.29 and 9.8, the maximum pincushion deviation from linearity is

$$\delta = + \frac{M_2}{M_1} \cdot (K_x I_x)^2 \cdot \left(1 + \left(\frac{K_5 I_y}{K_4 I_x}\right)^2\right) \quad \ldots \quad 9.31$$

and substituting the above values,

$$\delta = \frac{\left(\sqrt{\frac{e}{2mV_A}}\right)^3}{\sqrt{\frac{e}{2mV_A}}} \cdot \frac{L^2}{2} \left(\frac{-L}{4S}\right) \cdot \left(\frac{1}{\sqrt{\frac{e}{2mV_A}}}\right)^2 \cdot \left(\frac{x^2+y^2}{L^2 S^2}\right)\left(1 + \left(\frac{y}{x}\right)^2\right) \quad \ldots \quad 9.31(a)$$

The negative sign due to the "$\frac{-L}{4S}$" term indicates Barrel distortion. Expression 9.31(a) reduces to, for maximum deflection,

$$\delta = \frac{L}{8S^3} \cdot \left(\left(\frac{3}{2}\right)^2 + 2^2\right) \cdot \left(1 + \left(\frac{3}{4}\right)^2\right) \quad \ldots \quad 9.31(b)$$

and substituting for "L" and "S" from above

$$\delta = 1.0\% \quad \ldots \quad 9.31(c)$$

indicating barrel distortion of some 1% full scale distortion. The maximum error term or remanent barrel distortion after correction is derived from expression 9.28.

The nominal remanent barrel distortion error is

$$(\delta)^2 = 0{\cdot}01\%.$$

The suggested block diagram implementing correcton is shown in Fig.125(b).

9.4.3 Vidicon Distortion and Correction

The derivation of the expression for beam deflection on the photoconductor target of a Vidicon, including the distortion, is derived in Appendix A.6.4. Included therein is also a short explanation of the beam deflection in Vidicons and its difference between CRT beam deflection. Again the derivation was from first principles, as no easily interpretable expressions suitable for correction has been found in the literature. Some expressions do exist (309) but these are for the Image Orthicon, which though bearing superficial resemblance in the focussing and deflection systems, has some significant differences.

Some simplifying assumptions have been made in deriving the expressions, but the form of the expressions is essentially correct in specifying the barrel distortion, and hence will be correct in specifying the correction required.

Expression 13(a) in Appendix A.6.4 indicates the "x -deflection" on the photoconductor; it is

$$x = \left(\frac{Z_T}{B_Z}\right) \cdot B_x - \left(\frac{3}{2} \cdot \frac{Z_T}{B_z^3}\right) \cdot B_x \cdot \left(B_x^2 + B_y^2\right) \quad \ldots (13(a))$$

And similarly the "y-deflection" on the photoconductor is,

$$y = \left(\frac{Z_T}{B_Z}\right) \cdot B_y - \left(\frac{3}{2} \cdot \frac{Z_T}{B_Z{}^3}\right) \cdot B_x \cdot \left(B_x{}^2 + B_y{}^2\right) \quad . \; . \; . \; 13(b)$$

where "Z_T" is the distance between the beginning of the deflection magnetic fields region and the photoconductor target. In 1" Vidicons it is of the order of 8 - 10 cms.

"B_Z" is the Axial Focussing Magnetic Field and nominally constant at some 40-50Gauss ($4-5.10^{-3}$ Weber/m^2).

"B_X" is the time-varying deflection magnetic field in the "x"-direction causing beam deflection in the "x"-direction.

"B_y" is the magnetic field causing deflection in the "y"-direction.

These expressions are completely analogous to the expression 40(a) and 9.24 above , for the "x" and "y" deflection within the CRT.

$$\text{With } B_x = K_x I_x \text{ and } B_y = K_y I_y \quad . \; . \; . \; . \; . \; 9.32$$

the current required to be fed into the deflection coils is analogous to expression 9.26, 9.26(a).
Thus a current of the form

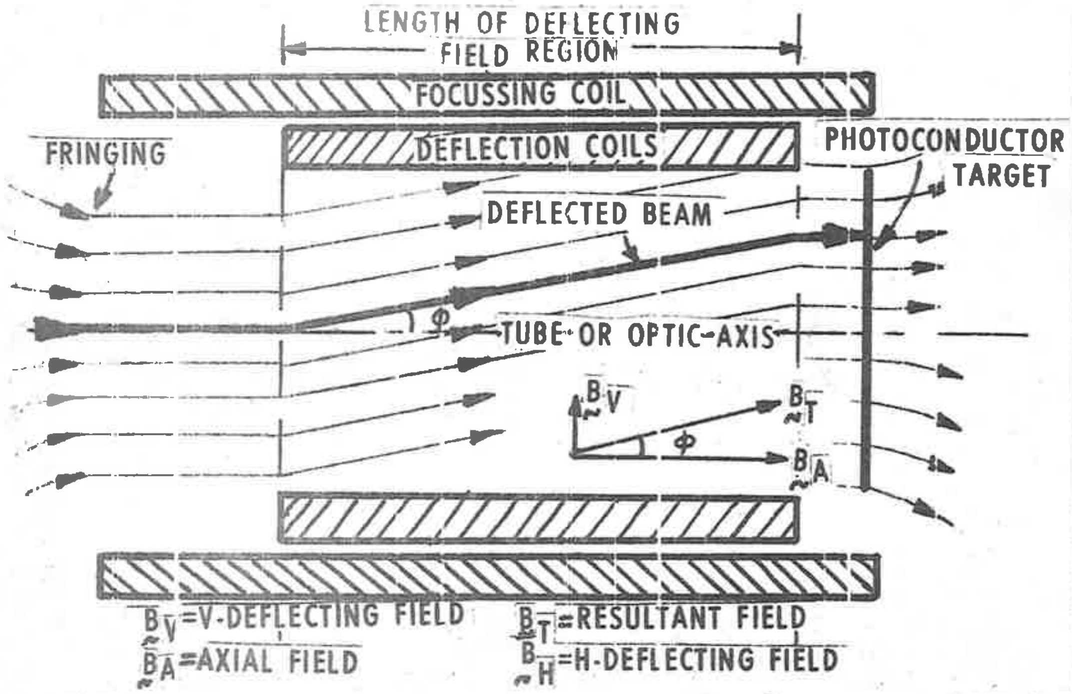
$$I_x' = I_x\left(1 + \left(\frac{3}{2} \cdot \frac{1}{B_z{}^2} K_x{}^2\right) \cdot \left[I_x{}^2 + \left(\frac{K_y}{K_x} \cdot I_y\right)^2\right]\right) \quad . \; . \; . 9.33$$

$$= I_x\left(1 + K_{11}(I_x{}^2 + K_7 I_y{}^2)\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; 9.33(a)$$

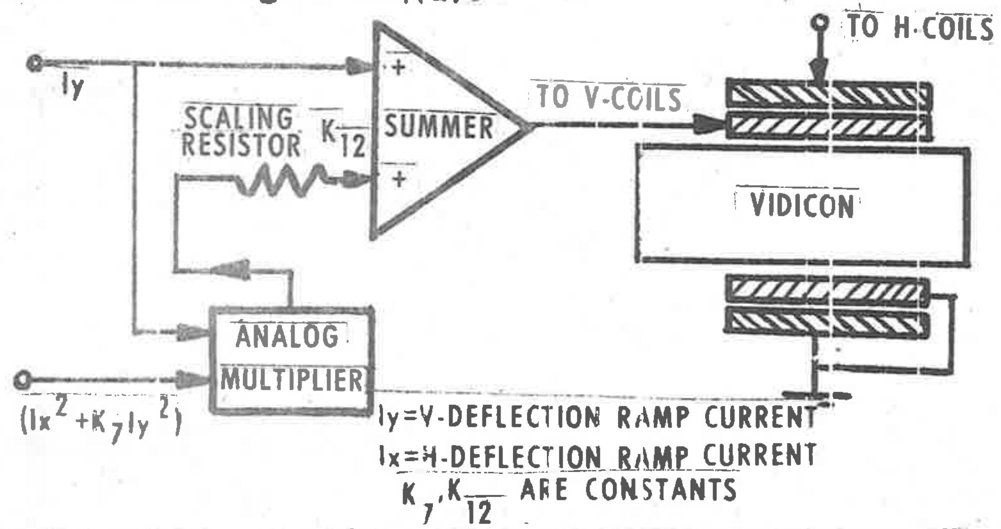
and

$$I_y' = I_y\left(1 + \left(\frac{3}{2} \cdot \frac{1}{B_z{}^2} \cdot K_y{}^2\right) \cdot \left[I_x{}^2 + \left(\frac{K_y}{K_x} \cdot I_y\right)^2\right]\right) \quad . \; . \; . 9.34$$

$$= I_y\left(1 + K_{11}\,(I_x{}^2 + K_7 I_y{}^2)\right) \quad . \; . \; . \; . \; . \; . \; . \; . 9.34(a)$$



(a) The axial and deflecting fields (only the vertical deflecting field is shown) add to form a resultant field which is still essentially an 'axial' field along whose field lines, the beam electrons still focus as in Figure 124(a).



(b) Vidicon Scanned Area Distortion Correction.

Figure 126. Vidicon Magnetic Beam Deflection and Scanned Area Distortion Correction.

eliminates barrel distortion in the Vidicon.
Again noting the identity 9.29, the factor,

$$" I_x^2 + \left(\frac{K_y}{K_x} . I_y\right)^2 "$$

is identical to the factor " $I_x^2 + \left(\frac{K_5}{K_4} . I_y\right)^2$ " used in CRT deflection and defocussing expressions.

The block diagram in Fig.125(b) shows the correction implementation in Vidicons.

The amplitudes of the expected distortion is as follows :

The ratio of the correction current to the nominal coil-driving current at maximum deflection is from expression 9.33,

$$" \frac{3}{2} . \frac{1}{B_z^2} . K_x^2 . I_{xmax}^2 \left(1 + \left(\frac{K_y I_y}{K_x I_x}\right)^2_{max}\right) "$$

$$= \frac{3}{2} . \left(\frac{B_{x\ max}}{B_z}\right)^2 . \left(1 + \left(\frac{y}{x}\right)^2_{max}\right)$$

from expressions 9.29 and 9.8;

and as " $\frac{B_x}{B_z}$ max " is approximately equivalent to the maximum deflection angle and of the order of " $\pm 7^\circ$ or 0·12 rads., the ratio of peak Correction Current to peak Ramp Scanning Current is 0·034 or 3·4%. With peak values of Vidicon Scanning Currents of 100-150 mA, the Correction Currents are 3-5 mA. These current magnitudes are such that direct summing of Scanning and Correction Currents at I C Op-amp. inputs can be used, along with the output feeding the Vidicon Deflection Coils directly.

9.5 COMMENTS

Both the Focussing and the Barrel or Pin-cushion

Distortion Correction in both the CRT and Vidicon, contain the common correction current term,

$$\left[I_x^{\,2} + \left(\frac{K_5 I_y}{K_4}\right)^2 \right]$$

This is not surprising as in both the Vidicon and the CRT:

(i) Focussing and Deflection is implemented by static or time varying magnetic fields which in turn are generated by currents feeding into the respective Focussing and Deflection Coils.

(ii) the corrections required are due to the electron beams scanning finite display areas, and as a result, the electron beam lengths and beam deflections are a function of the distance between some origin and the coordinates (x,y) of the screen or photoconductor location where the beam impacts. This distance is a function of

" $x^2 + y^2$ "

which is reflected in the expression

$$\left(\frac{1}{K_4}\right)^2 \left((K_4 I_x)^2 + (K_5 I_y)^2 \right)$$

as $y = K_5 I_y$ and $x = K_y I_x$ (expression 9.8).

Since linear deflection coil driving currents are required for both the CRT and the Vidicon, the function " $I_x^2 + \left(\frac{K_5 I_y}{K_4}\right)^2$ " can be derived from the one set of staircase and ramp current generators, say those from the Vidicon H- and V- current ramps. The various Defocussing and Deflection Distortion Correction Currents derived therefrom are by additional Scalers, Adders and so on.

The fact that the absolute values of the CRT and Vidicon H- and V- currents are different does not matter. If the Horizontal and Vertical CRT deflection (x,y) are given by

$$y_c = K_{yc} I_{yc}$$
$$x_c = K_{xc} . I_{xc} \qquad \ldots\ldots\ldots\ldots .9.35$$

where

"I_{yc}" is the V- deflection coil current
"I_{xc}" is the H- deflection coil current
"K_{yc}", "K_{xc}" are constant

and similarly if the Horizontal and Vertical Vidicon Deflection (x,y) are given by

$$y_v = K_{yv} . I_{yv}$$
$$x_v = K_{xv} . I_{xv} \qquad \ldots\ldots\ldots\ldots 9.35(a)$$

and since at any instant, both CRT and Vidicon are in synchronism, and the CRT is imaged onto the Vidicon target, then

$$y_c = y_v \text{ and } x_c = x_v \ldots\ldots\ldots .9.36$$

Now for the common term required in the CRT Defocussing and Pincushion Distortion Correction

$$\left[I_{xc}^2 + I_{yc}^2 \left(\frac{K_{yc}}{K_{xc}} \right)^2 \right] \ldots\ldots\ldots .9.37$$
$$= I^2_{xc} \left[1 + \left(\frac{I_{yc} K_{yc}}{I_{xc} K_{xc}} \right)^2 \right]$$

Substituting from expression 9.35,

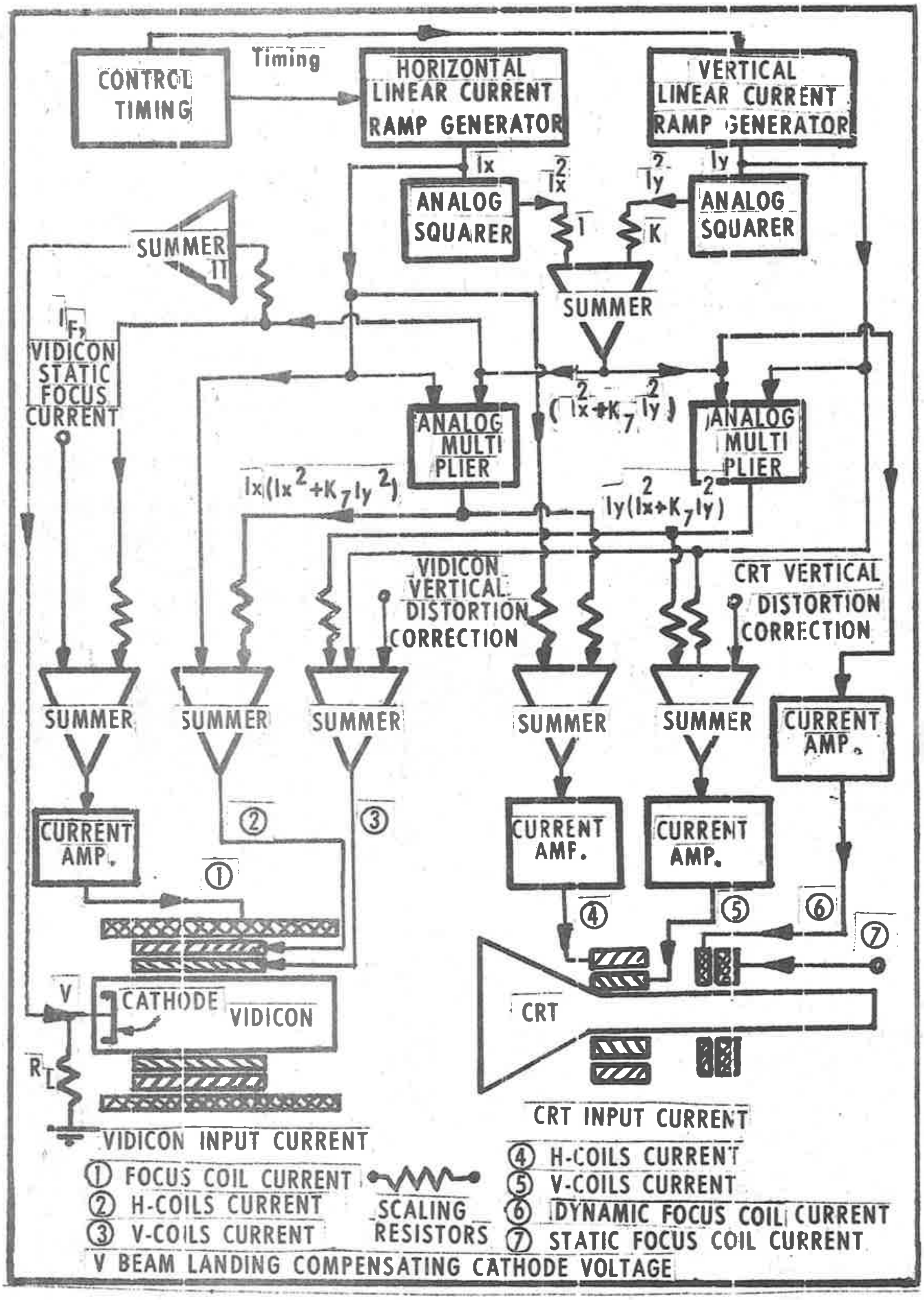


Figure 127. CRT and Vidicon Focussing and Deflection System with Correction Implementation.

$$= \left(\frac{x_c}{K_{xc}}\right)^2 \cdot \left(1 + \left(\frac{y_c}{x_c}\right)^2\right) \quad \ldots\ldots\ldots\ldots \quad 9.37(a)$$

and substituting from the identities in expression 9.36 and 9.33(a).

$$= I_{xv}^{\,2} \cdot \left(\frac{K_{xv}}{K_{xc}}\right)^2 \cdot \left(1 + \left(\frac{I_{yv}K_{yv}}{I_{xv}K_{xv}}\right)^2\right)$$

$$= K\left(I_{xv}^{\,2} + \left(I_{yv}\frac{K_{yv}}{K_{xv}}\right)^2\right) \qquad 9.37(b)$$

where $K = \left(\frac{K_{xv}}{K_{xc}}\right)^2$

showing that the required correction terms in both the CRT and the Vidicon differ only by a constant scaling term "K", implying only one generator is necessary for the term in 9.37, derived say from the Vidicon H- and V- scanning ramp currents.

The "cross-product" terms

$$I_x\left[I_x^{\,2} + K_7 \cdot (I_y)^2\right] \text{ and } I_y\left[I_x^{\,2} + K_7 \cdot (I_y)^2\right]$$

can similarly be shown to be similar for both the CRT and the Vidicon except for a constant scaling term.

The overall Defocussing and Deflection Correction System for both the CRT and the Vidicon is shown in Fig.127.

The above block circuits are only functional arrangements for implementing the required corrections, and serve to indicate the form of correction required and the feasability thereof. The actual implementation of the Multipliers, Squarers etc. is with commercially available I-Cs performing those functions, or on the other hand, from suggested circuits derived for CRT Defocussing and Distortion Corrections reported in (303,308,310,311).

For the Vidicon the problem is much simpler than indicated in the above references, as lower currents are present, implying that the output from I-C Op-amps can be used directly as the input to the coils. The accuracy of commercially available I-C Squarers or "4-quadrant Multipliers" is in the order of 1-2%. Since in the worst case, of distortion correction (for the Vidicon) some 4% distortion need be corrected to about 0.2% or less, an accuracy of some $\frac{0\cdot 2}{4} \approx 5\%$ is required, which is met by the above circuits.

The figures given in the above examples to calculate expected current amplitudes etc have been based on the worst case, that is values corresponding to the corners of the scanned area. In the actual case, for our requirement, these figures can be relaxed somewhat as the active display area where correction need be implemented is smaller than the total scanned area. Thus the (x^2+y^2) term is reduced with a consequent reduction in the peak values of the correction currents.

9.6 SUMMARY

(1) The correction of distortion as described in chapter 8 assumed that pincushion distortion or barrel distortion were absent. This meant that the H-scan lines could have non-linear separation but should essentially be parallel over the whole of the scanned area, or at least, over the active display area, for both the CRT and the Vidicon.

(2) Similarly the electron beams generating the CRT display or scanning the Vidicon photoconductor should be sharply focussed over at least the active display area.

(3) CRT and Vidicons, even with linear Scanning Current Waveforms, suffer from pincushion or barrel distortion.

(4) Simple expressions have been derived for the major Defocussing and Scanned-area Distortion. Even though these expressions are based on very simplifying assumptions, the form, if not the "exact" value of the coefficiants is sufficiently correct to express the distortion to the accuracy required for correction.

(5) From these expressions simple Correction Currents can be derived from available Horizontal and Vertical Scanning Currents.

(6) Common to all Correction Currents is the most "complex" of the correction terms required. This term

$$(I_x^2 + K_7.I_y^2)$$

is the reflection of the variation of the scanned area coordinates from the centre of the scanned area, which the electron beam must access, and is indicative that Defocussing and Distortion is a function of a scanned area position. A function generator generating this term may be made common to all the corrections in both the Vidicon and the CRT.

(7) Some circuits to achieve these correction have been reported (for CRTs) and for specific applications. However the precise expressions derived within this chapter ("precise" in the sense that coefficiants are determinable) enable coefficiants to be determined analytically, and ensure that the expressions can be used for all CRTs and Vidicons and not merely specific applications. Consequently commercially available I-C's performing "squaring", "multiplying" etc may be used.

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CHAPTER 10

"VIDIOGRAPHIC": SYSTEM OVERVIEW AND CONCLUSIONS

10.1 INTRODUCTION

10.1.1. General Remarks

In the previous chapters, the feasability of "VIDIOGRAPHIC" was established; suggested means of implementing its requirements were given. The chapter following this one contains the description and results of selected circuits and of other experimental work required to implement "VIDIOGRAPHIC." Rather than leave the overview of the feasability study and practicability of "VIDIOGRAPHIC" until after the experimental work has been described and thus break the trend of thought, the general considerations, overview, areas for improvement and conclusions will be described now.
Particularly the general requirements for "VIDIOGRAPHIC" as an IGC with the objectives as stated in Chapter 3, together with a comparison of how it meets the particular performance parameters of the Display, Graphics Input and Storage Subsystems as given in Chapter 2, will also be given.

A breakdown of estimated costs of the system will also be given to show that indeed an economic solution to the real problem of a low cost IGC is present in "VIDIOGRAPHIC".

And finally the area of applications and the areas and room for future improvement and development will be touched upon.

10.1.2 "VIDIOGRAPHIC" Subsystems Not Treated in Feasability Study

Only the major or novel requirements for "VIDIOGRAPHIC" were developed in previous chapters. Other obvious requirements and subsystems were not treated as the techniques for implementing them are well known and well developed.

Specifically these are, in the main, the video signal amplifying subsystem in both the Vidicon and the CRT, consisting primarily of multistage video amplifiers. The design and realization of these is no major problem; moreover they are usually supplied with the Vidicon camera or the RCA Projection TV Receiver.

(i) For the Vidicon, the video amplifier is a 3-4 stage, capacitivly coupled, high input impedance (50-100KΩ) amplifier, whose input is at the photoconductor target output and whose output is of some 1-2 V peak to peak; this output is "positive going", that is, 0V represents "black" or "no signal", while 1-2V is the bright display "highlight".
The gain is typically 40-60dB (a voltage gain of 100-1000), and is peaked in the range of 3-5Mhz to compensate for the "aperture effect" of the Vidicon; the finite scanning beam-width decreases the frequency response of the electro-optical system, causing loss or degradation of fine detail (312,313) Display locations spaced some 0·16us apart in time (i.e at 6Mhz) are "fine detail" and hence the above form of "aperture correction" need be implemented. In Appendix A.7.3,

showing the equivalence of a stationary finite electron beam with that of a moving or "scanning" beam, the effect of the finite aperture was indicated.
The overall response of the aperture-limited response and the compensated video amplifier is flat over the required frequency range.

(ii) For the CRT, the Video amplifier,(again of some 3-4 stages with the same bandwidth as above but no "aperture correction" being required), amplify the 1-2V Vidicon Video signal to some 30-50V(peak to peak) to feed the control grid input. Most text-books on TV Engineering (314, 315), or technical data supplied with the TV reciever, describe these.

In both cases the requirements for video amplifiers can be relaxed somewhat over the requirements for commercial TV receivers in the sense that only 2 luminance levels (3 for the Vidicon) are present, and thus various "gamma" correction circuits to compensate for or obtain true picture grey-level reproduction, are not required.

(iii) The Current Level Detectors "i_{L1}" and "i_{L2}" have not been described. As the video output from the Vidicon varies from OV (nominally) to about 1-2V for a detected signal, a simple Schmitt Trigger Detector may be used, to operate at the required speed of $>$ 6 Mhz.

(iv) In the Display Distortion Correction Circuits, various Summers, with single polarity inputs, and also requiring inverting and non-inverting inputs

are required. The voltages requiring summing are of low levels (several volts), being correction voltages, then I/C Op-amps, of which there is a large variety commercially available (316,317), can be directly used.
Other than the above points, the description in previous chapters covered the operation and suggested circuits for implementing VIDIOGRAPHIC in comprehensive detail.

10.2. VIDIOGRAPHIC AS AN IGC

10.2.1 "VIDIOGRAPHIC" Objectives.

In section 3.1 the requirements of VIDIOGRAPHIC as an IGC were stated as:

(i) a Graphics Display Subsystem
(ii) a Graphics Information Input Subsystem for user-specified graphics, capable of "pointability" to displayed features, using a pen or stylus.
(iii) a Display Refresh Store to maintain the display in a flicker-free mode.

These requirements are to be realized at the lowest cost possible. Alphanumeric and CPU-specified vector generation are outside the scope of this thesis, as these are readily available commercially in many forms (see section 2.3.3 - 2.3.5). Software support, including TV-mode formatting from what is essentially random vector specification in the CPU, to the TV raster display format, and the CPU I/O interface control, are also outside the scope of the thesis.

10.2.2. "VIDIOGRAPHIC" Implementation of Objectives

Taking these stated aims point by point to see how they were implemented in VIDIOGRAPHIC:

(i) the Display Subsystem is implemented with a Projection CRT using Schmidt Optics, based on the commercially available RCA Projection TV System.

The viewer sees the display on a screen nominally of 18" x 24" size, but since only the central scanned area is used, the effective display area is 12" x 14·4". Some of the remaining peripheral area may be used as a "light-button" alphanumeric Keyboard and "cue" - keyboard. The performance parameters of the display are given below in section 10.3.

(ii) The Graphics Input Subsystem is facilitated by the "light-emitting pen" which can directly input user-specified graphics by pointing to the appropriate location on the display screen. The input area being identical to the display screen, "registration problems" are minimized, that is the problem of locating graphic data correctly with respect to some displayed area is minimized. "Pointability" is provided simply by pointing the light-emitting pen at the desired location and enabling "on" a simple switch on the pen which in turn enables on some logic circuitry (the "i_{L2}" Level Detector) changing the light pen from "graphics input" to "pointability mode".

An alphanumeric Keyboard may be provided but there is provision in the scanned area peripheral area for a light-button Keyboard and "cue" Keyboard.

(iii) Display Refresh Storage is inherent in the system. So long as the Vidicon and the CRT are aligned in a 1:1 positional relationship and the H- and V-Correction Circuits are enabled, the display is self-maintaining - i.e. "Display Refresh Storage" is present. The refresh rate is the usual TV 25 frames/sec. (or 50 fields/sec), which provides a flicker-free display. Refresh is independent of the display information content, unlike with the usual magnetic core refresh storage (sec.2.5.2)

The storage is enabled by two processes:

(i) the CRT W-Phosphor phosphorescence. When a CRT display location is generated (within a "beam dwell time $T_d \approx 0{\cdot}1$us"), appreciable display location luminance is still evident up to 8-10ms after excitation. This inherent delay in generating luminance ensures that adequate charge is stored on the Vidicon photoconductor target.

(ii) Charge storage on the Vidicon phototarget, due to the CRT luminance. If the scanning electron beam is not present such a stored charge would remain for at least several seconds.

The actual transit time of information within the optical and electric loop is negligible compared with the above delays.

The refresh rate can be varied with trade-offs between refresh rates and the amount of information being displayed (or stored) (see below, section 10.3.3.3). In this respect it is similar to the "refresh rate/information capacity" tradeoff in random-access memories with limited read-out rates (section 2.5.2).

10.2.3 Additional Advantages of "VIDIOGRAPHIC"

There are two additional benefits in a system using a closed "dynamic loop", such as the Vidicon-CRT "electric-optical loop," to enable display refresh. These are:

(i) The display has excellent geometrical linearity of better than 0·2%, which is about one order better than currently available displays. Thus applications where "precision graphics" is required, are possible.

More importantly, for our original application of direct graphical solution of circuit-design-problems (particularly having non-linear elements), this display linearity and accuracy ensures that overall accuracy of the final solution is still high (much higher than the typical 5% overall accuracy which may be tolerated in practical cases of circuit design).

Thus the fact that high display linearity is present (as well as in the Vidicon camera) means that not only is user-confidence increased, but the areas of application of "VIDIOGRAPHIC" is extended to "precision graphics" and "graphical computing".

(ii) The relatively passive nature of the "light-emitting pen" (passive in the sense that no software support is needed), allows the user-graphics input, at any instant, to be independent of any system-timing or order of input. The reason for this is that the pen, unlike most other devices (except perhaps the suggested light-emitting pen for the Plasma Panel Display (see Appendix A.5.2(14)) is not based on pick-up of CRT, or "input pad", signals (which require timing signals or software support), but injects its own signals into the system, to be stored on the photo-target. This randomly inserted data is then detected at specified instants by the raster scan.

Hence the input (as well as "pointability") is "asynchronous", and for that reason does not tie up the CPU I/O Interface at instants of user-input, but only during the raster readout. Hence the CPU Interface interrupts are minimized.

10.2.4. The Realization of "VIDIOGRAPHIC".

The realization of "VIDIOGRAPHIC," with the above features, depend on the following requirements being met:

(i) the Display Subsystem must supply adequate luminance, via the Projection System, to present to the viewer a screen brightness of some 10 ft-L, that being adequate for viewing purposes. Similarly some of this luminance need be directly imaged in a 1:1 geometrical relationship onto the Vidicon photoconductor.

The most efficient means of achieving this division of screen display luminance into two functional parts is by Schmidt Reflective Mirror Optics. The necessary system description and calculations were given in Chapter 6, sections 6.3 - 6.5 , together with the viewing screen requirements and characteristics.

For full viewing brightness (and to align the input pen correctly), some movement of the user's head may be necessary (see Section 6.4.3.2).

(ii) The realization of graphics input and "point-ability", involves the inputting of luminous energy onto the Vidicon photoconductor at new locations, their detection by the appropriate Current Level Detector, and the generation of luminance at the corresponding CRT display locations. This requires:

(a) the presence of a "light generating pen". This is described in section 6.7.

(b) the provision of a light source for the "light pen", with appropriate spectral and intensity characteristics compatable with the Vidicon and CRT requirements (as regards their time response). The solution is to tap some of the high intensity CRT luminance near the display peripheral areas via optic fibres, as described in section 6.6.7. To enable the display "erase" function, the CRT light source is eminently suitable, capable of being switched off at "electronic" speeds - see section 6.6.5.

(c) the general transient properties of CRT phosphor luminance as regards luminance buildup when new data is inserted, need be investigated (see section 4.1), to see whether newly inserted display data is detected at the Vidicon phototarget on the first CRT display cycle. This also applies to CPU specified data.

(d) Similarly the transient properties of the Vidicon photoconductor, which are usually stated to be "slow" in buildup of stored charge, need be investigated to determine whether new luminous incident information generates adequate Vidicon output signal to be detected and hence recirculated into the display. This has been done in section 4.3 and Appendix 10.

The Vidicon response to the particular CRT phosphor luminance spectrum is required, as this differs from the spectrum of the light source for which manufacturers' data is usually given. The effects of this difference and the required modification has been given in Appendix A.8.2.

(e) The signal output of the Vidicon (as distinct from the charge buildup mechanism of photo-conduction) requires examination due to it being usually accepted that incomplete signal erasure on scanning occurs, with unwanted signals at subsequent frames. Particularly for the "erase" functions, these remanent signals need be minimized. Chapter 5 describes the nature of the beam signal read-out problem and examines in some detail the expected output signal degradation.

The presence of Signal Current Level Detectors ensure that any such signal variations is not a problem.

(iii) For Display Refresh Storage to be feasible, two requirements are necessary:

(a) adequate CRT luminance to be generated and imaged onto, and detected at, the Vidicon photoconductor. The requirement for this is very similar as for the newly inserted user-graphics data, in that information is written-in at each frame time, but at locations previously excited; hence no build-up effects need be considered.

The CRT generated luminance and its reduction due to the Vidicon lens and photocurrent buildup are treated in Chapter 4. Vidicon beam readout effects (and defects!) are treated in Chapter 5.

(iv) The other major requirement is that 1:1 geometric or positional relationship (except for a reduction in size) between locations on the CRT screen and those imaged on the Vidicon photoconductor, be present. Distortion normally prevents this from being met. The CRT and Vidicon each need be as distortion-free as possible. This requires the following:

(a) Reasonable quality CRTs and Vidicons and focussing coil and beam deflection-assemblies are required. This is to minimize or eliminate gross misalignment between the tube optical axis and the various sub-components such as deflection coils, electron focus coil-assemblies etc.

(b) The minimization or elimination of inherent pincushion or barrel distortion is required. In Chapter 9, sections 9.3 - 9.4, expressions were derived for barrel or pincushion distortions in terms of available H- and V - scanning current waveforms; from these, the necessary corrections were obtained, along with circuits to realize these. These corrections were based on a correction voltage proportional to a term of the form "$I_x^2 + KI_y^2$", where "I_x" and "I_y" are the H-and V-scanning current waveforms. This term is common for the Vidicon, the CRT, and for both pin-cushion and barrel distortion and for focussing corrections.

(c) The remanent distortion requiring to be eliminated needs firstly to be measured to a high degree of accuracy and precision (better than 0·1%) using Moire Pattern Methods (see Appendix 11). The resulting Distortion Information thus obtained is expressed in the form of "Distortion Maps" with appropriate distortion contours drawn, which are "time compressed" and located in the appropriate area of the CRT scanned area. For V- Correction, only one vertical correction line is required for the CRT and one correction line for the Vidicon.

The form and implementation for this Graphic Information Storage is given in Chapter 7, sections 7.4. - 7.5.

(d) In Chapter 8 are described the suggested means of decoding this Correction Information from the Graphical Storage and generating the correction voltages and currents, to result in a linear CRT display and linear Vidicon scanning.

(iv) Video amplifiers and video signal Level Detecting Circuits, are required, but have not being mentioned in any detail as the techniques for realizing them are well known and provide no difficulties.

Thus all of the necessary requirements for determining the feasability and realization of "VIDIOGRAPHIC" have been given and proved.

10.2.5 Physical Implementation of "VIDIOGRAPHIC"

10.2.5.1 Required Subsystems

The major hardware requirements for "VIDIOGRAPHIC" are:

(i) A commercial Projection TV-reciever with a 5" Projection CRT with a 3" x 4" scanned area, and a Rear-projection Screen (with a Fresnel Lens) of size 18" x 24".
The RCA Projection TV system fits the above requirements. The CRT phosphor is to be "W" phosphor or else a "P-4" phosphor with persistance characteristics similar to "W" phosphor.

(ii) A 1" Vidicon Camera (or only a Vidicon tube with Deflecting and Focussing Subsystems) with a Class II photoconductor, with photocurrent time constants given by expression 4.16. RCA Vidicons 7262A, 8507A, 8573A are quite adequate from this viewpoint.

(iii) The control logic and timing is implemented from RTL and TTL Logic (318, 319), while the analog or hybrid circuits (Summers, Differential Amps etc.) are implemented with commercial I/Cs. Power supplies of some +4V (for the logic) and +15V and -15V for the analog I/C circuits are also required.

10.2.5.2 Operating Characteristics

For optimum operating values, from the viewpoint of adequate signal levels being generated, and "spurious -

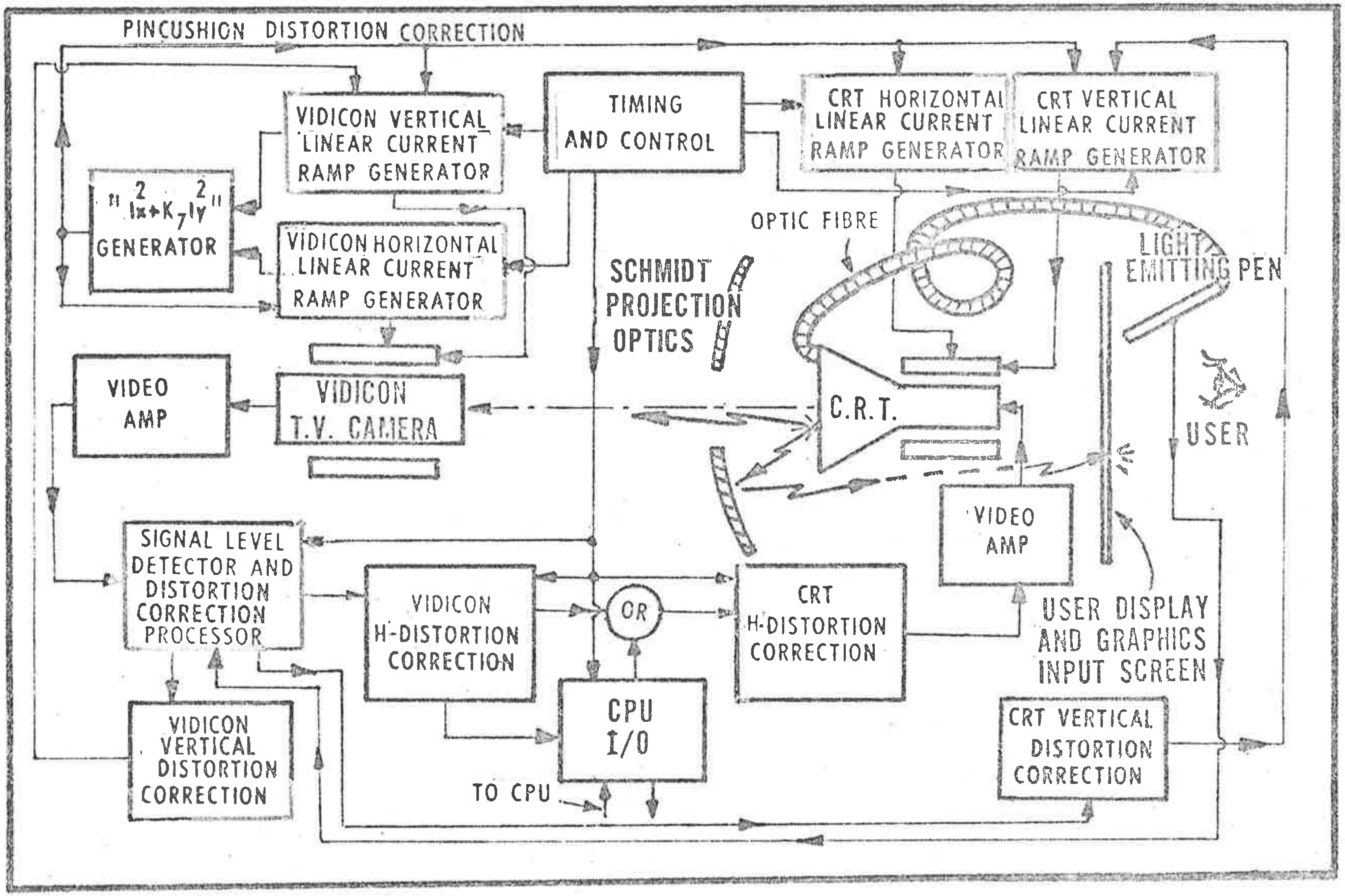

Figure 128. General Block Diagram of the "VIDIOGRAPHIC" System.

signal free operation," the Vidicon is set to operate on a steady state signal output current level of $\geqslant 0 \cdot 45$uA (the maximum output signal tolerated is usually quoted as $0 \cdot 55$uA (see Fig.66(a))), and the "i_{L1}" Detector is set at $0 \cdot 24$uA (Appendix A.7.7). This requires an electron beam of the order of 1uA (see Fig.74). Signal plate voltage "V_s" is of the order of 30V.

The resultant current signals as a result of "pointability", are due to a luminance of approximately twice the normal steady-state display luminance (section 4.3.6) and are thus approximately double the steady-state output current of $0 \cdot 45$uA. This larger than the recommended max. output signal occurs for relatively short time instants and does not affect or impair the photoconductor performance (320).

To obtain the steady state value of Vidicon output current of $0 \cdot 45$ uA, and for adequate viewer screen luminance of about 10ft-L, the CRT screen luminance must be of the order of "$B_{AV} \geqslant 350$ ft-L", and the Vidicon Camera Lens setting is to be at the "F-number" setting of "2.8" (section 6.3.6). The "F-number" also satisfies the depth-of-field requirements, as the CRT screen is non-planar (Appendix A8.3.4).

At the CRT screen peripheral areas, where the light pen illuminating source is located, the CRT luminance is set at the maximum of about "$B_{AV\ max} = 1500$ft-L" (section 6.6.6.3).

From the "Overall CRT Luminance Transfer Curve", as in Fig. A.9.1(b), the video input at the CRT control grid is of the order of 30V for the required display signals and about 60V for the peripheral area luminance.

The complete system block diagram for VIDIOGRAPHIC is shown in Fig.128.

10.3 "VIDIOGRAPHIC" PERFORMANCE

10.3.1 Introduction

An objective evaluation of the potential performance and capabilities of "VIDIOGRAPHIC" can be made by comparing its performance figures with the performance parameters required of an IGC as enumerated in sections 2.2.- 2.4

The parameters will be treated separately for the Display Subsystem and the Graphics Input Subsystem, as is normally the case for IGCs, although in our case they should be treated together as the "light" pen is no more than an extension of the Display; the parameters of the Graphics Input Subsystem are thus nearly identical to the parameters of the Display.

10.3.2. Display Parameters

10.3.2.1 Resolution

The spot size on a 3" x 4" scanned area of a 625-line system, when projected on a 18" x 24" screen is 0·03" x 0·03". This is somewhat larger than typical CRT spot sizes which are in the range of 0·015"-0·02".

10.3.2.2. Addressability

The feasability study was based on a 200 x 200 point grid display being feasible. The addressability is thus 1 in 200, or approximately 8-bits coordinate addressability for each "x" and "y" coordinate. This is appreciably lower than current displays of 10-bits coordinate addressability for each "x" and "y" coordinate (1024 x 1024 point grid display). For our application of a "computing graphic pad" the 200 x 200 addressability is, however, very adequate.

Tradeoffs between the speed of scanning and the number of scan lines per frame is possible, so long as a

CRT phosphor decay characteristic to compensate for flicker is made. A greater number of display locations would thus result with a corresponding increase in addressability. An increase in the number of Distortion Lines in the Distortion Correction Information Map will result, with a corresponding increase in complexity of Correction Circuits. These tradeoffs must be taken into account.

10.3.2.3. Brightness

The Viewer-screen luminance can be varied over a large range. The CRT can supply a peak luminance of "$B_{AV} \approx 1500$ ft-L," whereas for a viewer screen brightness of some 10ft-L, a "$B_{AV} \geq 350$ft-L" is all that is required. Hence up to 40ft-L viewer screen luminance is available. This is usually too bright for a user observing a screen some 20"- 24" away.

For a higher luminance the Vidicon Lens must be appropriately "stopped down" to a new "F-number".

The expression for the F-number can be easily shown to be given by

$$\text{F-number} = 2 \cdot 8 \sqrt{\frac{B_{AV}}{10}}$$

as for a required F-number of F = 2·8, a "B_{AV}" of about 10 ft-L results on the screen.

10.3.2.4 Contrast

Contrast is required to be high for Vidicon considerations (otherwise spurious signals present in frames times just after "erasure" may be generated). The CRT control grid need thus be biased at, or near, cutoff (see Fig.A.9.1(b)). Contrast greater than 30-40:1 is easily obtained. This is more than adequate, and compares more than favourably with existing displays (e.g. a DVST has a contrast of the order of 6:1).

The presence of stray or direct light near the display will degrade contrast only as far as the viewer is concerned, but does not affect the contrast of the incident illumination on the Vidicon photoconductor.

10.3.2.5 Geometrical Linearity

The geometrical linearity is excellent, being better than 0·2% of the active display height. This is a full order higher than in existing "good quality" displays. It arises from the inherent linearity required to enable maintenance of a steady display.

10.3.2.6 Repeatability

Similarly repeatability is excellent, being of the same order as linearity.
Jitter is eliminated as each display location is relocated each frame time back in its nominal location.

10.3.2.7 Display Response Time

Each location in a display frame is accessed every 40ms. On the average the access time to any given point at any instant is half the frame time, or 20ms. This then is the average access time for user-input graphics data. For the CRT, since no interlaced fields are used (ie. both fields superimposed), then for CPU inserted data, the worst-case access time is 20ms, with 10ms being an average value. Thus the worst case Response Time for a user-indicated display location for processing is, "Worst Case User Input Time + Worst Case CPU-inserted CRT Response Time + CPU Processing Time"

= 60ms + CPU Processing Time

For points requiring CPU processing which are not previously displayed, two frame times are required to insert this data to the CPU (section 6.7.1(5)). Hence the

" Display Response Time = 100ms + CPU Processing Time."

10.3.2.8 Size and Layout of Display Screen

The size of the display is the "active display area" of some 12" x 14·4", with additional peripheral areas for light-button alphanumeric keyboards or "cue"-Keyboard, bringing the screen size area to 18" x 24". This is of the same order or slightly larger than existing displays (16" x 16" being the largest).

The layout is as in most IGCs. In a commercial TV Projection Unit, the Screen is usually vertical and at eye level. It can be tilted slightly off the vertical as required by tilting the plane reflecting mirror (see Fig. 83(b)) by half the angle of the screen angle off vertical.

10.3.2.9 Readability

Character readability depends on the methods of generating the characters (section 2.5), the display resolution and addressability, and on any defocussing effects on the display screen.

In "VIDIOGRAPHIC", the display spot size, being about 0·03" x 0·03", with every alternate line blank (as 2 raster lines are associated with each display location), would result in a character formed on a distinct "dot structure" (as say in Fig.25). For a 5 x 7 character matrix, each character would be 0·3" x 0·4" in size, which is easily legible due to its size.

Allowing for 1 display line separation (effectively 3 TV scan lines), about 25 lines of characters can be inserted and displayed, with about 25-30 characters/line. A display capacity of some 650 characters would result.

Hand drawn characters are possible.

10.3.2.10 Half-tones and Colour

No half-tone capability is possible, although perhaps with signal output constant (say with high quality Vidicons, and beam landing error corrections), an intermediate signal level (and hence an intermediate brightness level) may be possible.

Higher luminance levels (e.g. corresponding to the "i_{L2}" Current Level Detector Signal) may also be displayed.

Separate colours, e.g. blue, red and yellow (but not intermediate tones) could perhaps be feasible but the persistance and luminance of the phosphors for colour, required by the Vidicon, have not been investigated.

10.3.2.11 Hard Copy Capability

This certainly is feasible by inserting a one-way "beam splitter" between the Projection Schmidt Optics and the viewer screen, to extract luminous energy and image it onto a "dry-copier" image target. The resulting reduction in viewer screen-luminance can be compensated for by increasing CRT screen luminance (which is available-see "brightness" above).

This scheme is much simpler than the current techniques in IGCs requiring separate CRTs in addition to the viewer CRT, to obtain the object image for the copier.

10.3.2.12 Optional Features.

(a) Blink

TABLE 4

PERFORMANCE PARAMETERS OF VIDIOGRAPHIC

PARAMETER	DISPLAY CHARACTERISTICS		GRAPHIC INPUT CHARACTERISTICS	
	TYPICAL	VIDIOGRAPHIC	TYPICAL	VIDIOGRAPHIC
RESOLUTION OR SPOT SIZE	0·015"-0·020" Diameter	0·03" Diameter	0·01"	0·03" Diameter
ADDRESSABILITY	1024x1024	200x200	1024 x 1024	200x200
BRIGHTNESS	10-20ft-L	10 ft-L Typical (40ft-LMax)		
CONTRAST	6 - 10	30-40 Typical		
GEOMETRICAL LINEARITY	1 - 2%	0·2%	0·1 - 1%	0·2%
REPEATABILITY	0·1-0·2%	< 0·1%	0·1-0·5%	< 0·1%
DISPLAY RESPONSE TIME	10-100 uS.	40ms MAX 20ms TYP. (+ CPU Processing Time)	1ms Typical	40-60ms
DISPLAY SIZE	10x10"	12"x 14·4" (18"x24" TOT)	10" x 10"	12" x 14·4" (18"x24" TOT)
HALFTONES AND COLOUR	RARE	COLOUR POSSIBLE		
HARD COPY CAPABILITY	DIFFICULT & COSTLY.	POSSIBLE- VERY ECONOMIC.	COMMON WITH INPUT GRAPHICS PADS.	NO

As an attention-getting device, "blink" can be implemented within the light-button keyboard and "cue"-board area. However within the active display area, blink implies an alternating absense of luminance and as a result non-refresh conditions would exist ; consequently blink cannot be implemented in the active display area.
At best, "flicker" rather than "blink" is possible with the luminance varying between the normal steady state display location luminance (say 10ft-L) and some higher value (up to 40ft-L).

(b) Variable Brightness.

The comments regarding "blink" and "halftones" (see section 10.3.2.10 above) apply here.

(c) Vector Line Forms

"Broken," "dotted," "thick vector" etc forms of vector representation on the display are all possible.

(d) Variable Character Size

Variable character sizes are possible.

(e) Optical Superposition

A "beam adder" (a semi-silvered mirror) inserted between the Schmidt Optics and the viewer screen, can be used to superimpose an externally generated fixed display (e.g. map - grids, grid axis etc) onto the viewing screen. Its luminance must be such that the fraction of luminous flux back-projected into the Schmidt Optics does not generate spurious signals (this is easily complied with).

The above parameters and performance figures are tabulated and compared with typical IGC parameters in Table 4.

10.3.3. System User-Input and User-Display Interaction Parameters.

10.3.3.1 Introduction

The User-graphics Input and User-display Interaction is by a hand-held "light-emitting" pen, whose spectrum and luminance is derived from the CRT screen. The input area is the display screen itself. The mechanics of user-data insertion into the CRT-Vidicon loop is identical to the write-in/erase cycle of the circulating display information in the CRT - Vidicon loop.
For these reasons, the performance parameters of the Graphics Input Subsystem are nearly identical to the parameters of the Display Subsystem. Near-complete Display/Input compatability is achieved.

These Input Subsystem parameters are enumerated briefly below.

10.3.3.2 Resolution

The light pen output beam diameter is 0·045" (section 6.6.7.3), as distinct from a display location diameter of 0·03". This is to overcome the difficulty in precisely aligning a 0·03" diameter spot with a displayed 0·03" diameter spot. As two raster lines (a total of 0·06" in width) are associated with each location, with a horizontal width of 0·07" (14·4" ÷ 200), such a larger input spot size is necessary, particularly as a user has not the same constancy of input as the fixed, imaged CRT display locations.

10.3.3.3 Addressability

This is identical to the display addressability, being 1 in 200, or 8 bits for each "x" and "y" coordinate. This is lower than most commercially available input devices.

10.3.3.4 Geometrical Linearity

This is identical to the display linearity, being better than 0·2%. It is of the same order as the digitally specified input pads such as the "Grafacon" (see Table A.5).

10.3.3.5 Repeatability

No problems of repeatability exist.

10.3.3.6 Input Response Time

This is identical to that mentioned for the Display Response Time, being, at worst case, equal to 40ms for graphics input or erase, and 80ms (two frame times), for indicating processing at display locations not previously displayed.

10.3.3.7 Input Area Size

Again this is identieal to the display area size, with an area 12" x 14·4" for interactive graphics input, and peripheral areas for light-button alphanumeric keyboard and "cue"-board.

10.3.3.8 Hard-Copy Capability

The pen being light emitting, no objects can be inserted between the pen and the screen. Hence inputting, say by tracing from a "hard copy", is precluded.

10.3.3.9 General Input Subsystem Considerations

In addition factors such as "ease of use", "economy in use" and "capital outlay", "input display compatability" which were enumerated in section 2.4.2, must be considered. Taking these requirements in section 2.4.2, point by point:

(i) "Naturalness of use"

The light pen is handled as any other pen device, having similar physical dimensions. It has 2 "status lights", one "red" and one "green", which switch on, indicating to the user whether the pen is correctly located and aligned with respect to the screen (as the pen tip must be at normal screen incidence), and whether data inputting, or display data indicating, is being performed. A simple switch on the pen determines the latter.

Table 2, facing p. 281, gives the meaning of the "status light" combinations.

(ii) The Pen and Input Subsystem is inherently compatible with the Display from all viewpoints.

(iii) No problem of interfacing with the CPU or Display Subsystem exists. Indeed a major advantage is that no CPU I/O interupts are generated during graphics input or display location erasure. The CPU is accessed only when CPU processing of display features or single display locations is necessary.

(iv) No additional software is necessary for the Input Subsystem. Display locations once inserted in the system (without CPU I/O interupts) are treated identically as though they are "display refresh" locations for CPU processing.

(v) Geometric accuracy in data positioning of input is certainly much higher then in most existing analog input devices, but primarily depends on the positioning accuracy of the user.

(iv) Capital outlay for the Input Subsystem is negligible (less then $50!) as only the cost of optic fibres, the pen casing, and two simple lens is involved. (The illuminating light source is present in the CRT). This compares extremely favourably with the cost of existing devices with a starting price of $2500 and up (see Table in Appendix 5).

10.3.4 The Display Refresh Storage

Two distinct Information Storage processes are present in "VIDIOGRAPHIC":

(i) the Display Refresh Storage Process.

(ii) the Distortion Correction Information Storage which makes display refresh possible.

10.3.4.1 Display Refresh Storage

The Display Refresh Storage is unlike any other in the commonly implemented refresh storage methods in present IGCs.

For example, in Magnetic Core Storage Refresh, "write-in" of display graphics information is made once when the graphics information is specified; display refresh information is obtained from sequential "non-destructive readout" of this stored information. Only when new updated graphics information is specified are magnetic cores erased and new information written-in.

In Delay-line or Cyclic Storage Refresh, "storage" is provided by recirculating the graphics information through a delaying medium, such that at each frame time (or display refresh interval), the same display location is presented for display- refresh purposes. No true "storage" is involved.

In "VIDIOGRAPHIC", on the other hand, the display-refresh information is "written-in" and "destructively read-out" each frame time! This destructive readout is necessary to enable User-display Interaction, particularly display location erasure.

Writing-in itself is part of the storage process. The graphics information being stored during any cycle is that due to the graphics information of the previous display cycle. A CRT screen display location is excited and its luminance is present for the complete frame, in varying degrees of intensity, due to phosphorescence. This resulting luminance "display information" is "written-in" by being imaged onto the Vidicon photoconductor target, resulting in a charge being generated and stored at the corresponding Vidicon scanned area location. This generating and storing process of the charge itself occurs during the whole of the frame time. Writing-in and storage of display information is thus done concurrently.

One frame time later, when the CRT emitted luminance is negligible (0·16% of its value at the beginning of the cycle), and when the photocurrents, generating the charge being stored, are also negligible, the Vidicon scanning beam accesses that location, restoring the charge and bringing the surface potential of that location back to its "stabilized potential "ΔV_{ST}"", which is near OV (the cathode potential). This charge restoration generates the Video signal, which then is output from the Vidicon and circulates, with negligible delays by the "electric loop" into the CRT, via the "i_{L1}" Level Detector (and if required, via the "i_{L2}" Level Detector), to again generate on the CRT screen, the same display location. The delays within the electric loop, are the "i_{L1}" delays, the transit time between the Vidicon and CRT, and any corrective pulse delays necessary to relocate correctly the display location. At most these total delays are in the order of several 100ns.

If no scanning beam would read-out the stored charge on the Vidicon phototarget, charge storage would be present for several seconds at least.

The storage or "delay" in the Display Refresh Storage is thus due to:

(i) the generation of CRT luminance,
(ii) the generation of stored charge on the photoconductor,
(iii) and in the storage of charge, due to the semi-conductive/insulating nature of the photoconductor having negligible stored charge leakage.

The similarity of the "VIDIOGRAPHIC" Display Refresh Storage to a Cyclic Store is thus not in the nature of the storage process itself, but in that stored information at any given location always is accessed at exactly the same instant in every refresh cycle, independently of whatever amount of graphics information is present. This of course is due to the raster scan.

The capacity of this "Refresh Storage" is up to 200 x 200 = 4.10^4 locations. Since each location is associated with 2 8-bit coordinate information for each "x" and "y" coordinate, then because graphics User-input data can be input randomly, the storage capacity may be considered to be equivalent to $6 \cdot 4.10^5$ bits.

However, since formatting is inherent due to the raster scan, then for reading out or display purposes, the order of readout is predetermined; then from this viewpoint the storage capacity is of the order of 4.10^4 bits.

10.3.4.2 Distortion Correction Information Storage

The Distortion Correction Information Storage is "true" fixed-storage in a graphic form ("hard copy" graphics storage). The process of reading-in is still essentially the same as above. The Distortion Correction Lines scribed on a black film, are "back-illuminated" by a constant CRT screen luminance at the locations where this Distortion Information is located (see Fig.105). The resulting visible Distortion Correction Lines are imaged onto the Vidicon phototarget, with the CRT luminance, charge storage process, and scanning beam readout being as above.

As the Distortion Information is located in the relatively peripheral areas of the CRT scanning area, the possibility of non-constant signal output currents etc exists. The CRT screen luminance can be increased to ensure adequate output signal.

The amount of Distortion Information is specifically for a 200 x 200 point grid; in the best case, with distortion being monotonically increasing or decreasing, only 1 bit is necessary to specify the correction at each location (to specify whether the correction is to be incremented or not by a "Distortion Correction Increment"). This is a valid arguement for the Vertical Coordinate Correction for both the CRT and the Vidicon, and also the Vidicon H-correction. However for the CRT H-correction, where correction is continuously varying at different rates, up to 4-bits per H-coordinate may be associated with each correction.

Thus the capacity of the Distortion Correction Information Storage is at least,

$$(N_H \times N_V).\left(\frac{1}{\text{H-correction}} + \frac{1}{\text{V-correction}}\right) \text{ bits (for the Vidicon)}$$

$$+(N_H \times N_V).\left(\frac{4}{\text{H-correction}} + \frac{1}{\text{V-correction}}\right) \text{ bits (for the CRT)}.$$

ie. a total of some $2{\cdot}8.10^5$ bits(as $N_H \times N_V = 200 \times 200 = 4.10^4$).

10.4 COSTING OF "VIDIOGRAPHIC"

Costing of the "VIDIOGRAPHIC" System can only be tentative at best, as the system has not yet been built. However most of individual subcircuits have been built and tested (Chapter 11), and thus an estimate of their cost is possible. The number of each of such circuits is known for each subsystem from Chapter 8-9. The required logic can also be costed, as can also the cost the various major subsystem such as the RCA TV Projection Unit or the Vidicon TV Camera.

Labour, packaging, testing, Moire Pattern testing etc are not costed, nor is the original research work. The following tentative costing is based only on hardware component cost.

(The price given for the TV Projection Unit is tentative and is based on a price of £90 (sterling) (year 1948) for a Phillips unit (273)).

The detailed costing is based on the following approximate costs for the subcircuits:

COMPONENT	COST (Dollars)	
R-S F/F, J-K F/F	Each	\$ 1
AND gates, OR gate	Each	\$ 0·5
"÷ 8" Counter, " ÷ 8" Decoder	Each	\$ 3
Shift Register Stage (on average)	Each	\$ 5
Voltage Controlled Monostable	Each	\$ 2
Voltage Controlled Astable	Each	\$ 2
Leading Edge Indicator	Each	\$ 1
Pulse Integrator	Each	\$ 2

High Impedance Buffer (I/C)	Each	$ 6
Constant Stabilized Level Circuit	Each	$ 2
Discharge Circuit (FET)	Each	$ 3
Summer (I/C)	Each	$ 12
Analog Squarer/Buffer (I/C)	Each	$ 20
Current Amplifier	Each	$ 10

The "VIDIOGRAPHIC" system is costed as follows:

SUBSYSTEM	COST
RCA PROJECTION TV UNIT (includes Schmidt Optics, Projection CRT, Deflection Units, Video Amplifiers etc).	$ 400
VIDICON TV CAMERA (includes Vidicon, Deflection unit, Focussing Unit, Video Amplifiers, Power Supplies and Vidicon Lens).	$ 350
LIGHT PEN (400 CROFON Fibres, 6ft in length, polishing, bonding agents, lenses, pen casing).	$ 30
H-DEFLECTION CIRCUIT FOR VIDICON	$ 30
V-DEFLECTION CIRCUIT FOR VIDICON	$ 20
H-DEFLECTION CIRCUIT FOR CRT	$ 40
SUBTOTAL	$ 870

SUBSYSTEM	COST
V-DEFLECTION CIRCUIT FOR CRT	$ 30
CRT V-CORRECTION CIRCUIT (5 F/Fs, 2 AND-gates, 2 Summers, Pulse Integrator, Discharge Circuit etc).	$ 40
VIDICON V-CORRECTION CIRCUIT (Similar as for CRT Correction Circuit).	$ 40
VIDICON H-CORRECTION CIRCUIT (20 AND-gates, 14 F/Fs, 1"÷8" Counter, 7 Pulse Integrators, 7 Discharge Circuits, 7 Buffers, 7 Constant Level Circuits, 7 Voltage Controlled Monostables, 5 Shift Register Stages etc).	$ 160
CRT H-CORRECTION CIRCUIT (3"÷8" Counters and Decoders, 23 Pulse Integrators, 23 Constant Level Circuits, 23 Discharge Circuits, 8 3-bit Registers, 8 Voltage Controlled Monostables/Astables, 25 F/Fs, 50 AND-gates, 15 OR-gates 5 Shift Register Stages).	$ 280
PINCUSHION, BARREL DISTORTION DEFOCUSSING CORRECTION CIRCUITS (Fig.127) (4 Multipliers, 7 Summers, 4 Current Amps).	$ 220
TIMING AND LOGIC (Timing Source, 200 AND OR gates, 100 F Fs).	$ 250
SUBTOTAL CARRIED OVER	$ 870
TOTAL	$ 1890

Thus the hardware costs can be kept to around $2000. This of course excludes packaging, testing, and production costs, and exclusive of Vector and Alphanumeric Generators, and CPU I/O Interface costs.

A total cost figure of some $3-4000 for the full system (ie including Character and Vector Generators) seems probable. This compares very favourably with the cost of existing IGCs starting at around $10000 (for an ARDS-100A, with a DVST and hence with a very limited User-Display Interaction), while Graphics Input Devices start at around $2000.

It can thus be seen that "VIDIOGRAPHIC" certainly meets the original stated aim of low cost in capital outlay.

10.5 POSSIBLE FUTURE DEVELOPMENT OF "VIDIOGRAPHIC"

It may seem jumping the gun slightly to talk about "future developments" of "VIDIOGRAPHIC" when the system itself has not been built yet. However obvious areas of improvement in the system exist, the main being the relatively low addressability of the display. This is because the original system feasability was based on it being realized from the most economic available commercial equipment, specifically that based on the 625-line TV equipment. Partly because of this the resultant addressability of the system was a display located on a 200 x 200 point grid.

(i) Clearly the first task for future development is increasing the addressability.

Commercially available systems, have been developed with 1200 or even 1800 scan lines per display height (321). Even higher scan line counts have been implemented in military applications. Such schemes require high resolution

CRTs, and happily, the 5" Projection CRT screen is ideal from this respect (323).
Thus 512 x 512 or even higher addressable display grids seem very feasible.
Larger Vidicons ($1\frac{1}{2}$") may be necessary to provide this high resolution (322).

The major approach to obtain these high scan line counts has been to reduce the frame scanning frequency to a frame rate of 15-20Hz, thus not requiring any wholesale changes in deflection coil design. For a flicker-free display, under these conditions, phosphors different to P-4 need be used (see Fig.18).
The lower scanning rate ensures that the "beam dwell time" in the Vidicon is still adequate to ensure complete charge discharge, with negligible unwanted current signals in subsequent frame times.

Alternatively some schemes use electrostatic deflection (which is inherently faster than electromagnetic deflection) with a corresponding redesign of focussing coils etc. Scan rates per frame are 25Hz as before, but element and line scan intervals are much shorter.

For Projection CRTs the former scheme must be used as high current beams are impractical with electrostatic deflection due to defocussing effects; such beams are necessary for high luminance.

For higher addressability, the remanent distortion tolerated must be correspondingly lower (expression 7.7), and thus the Distortion Correction and hence the Distortion Correction Information must be specified more precisely. A separate Vidicon may be required to scan adequately such higher precision Distortion Information (section 7.5.8).

(ii) Another major area for future development has been mentioned in section 10.3.2.10; that is the possibility of colour displays, with separate colours, such as "red", "blue", "yellow" being permitted only.

Phosphors such as P-1 (green-yellow), P-18 (white) and P-27 (red-orange) have very similar persistance characteristics (324) and are thus compatable with each other as far as Display Refresh requirements go. However Vidicon photoconductor response to these different spectrums would need careful investigation.

(iii) A major subsystem of "VIDIOGRAPHIC" is the Projection Optics which result in an optical path (the "optical loop segment") being present, by which CRT screen displays are projected on the viewing screen. This "optical path" can be "broken into", or else information can be extracted therefrom, by "beam splitters" or "beam adders" (for their action see Fig.82).

(a) With a beam adder, "optical superposition" of complex graphics data can be made onto the active display area. The superimposed graphics can be coordinate axis, drawing plans, etc. Perhaps a simple device such as an "epidiascope" (an "opaque" projector), could be used as the projector for superposition, projecting user-specified drawings, transfer curves, device characteristics etc. onto the viewing screen, which then can be "traced" over by the user light pen and be inserted into the CRT-Vidicon loop as normal input data. This would get over the problem of lack of data input from "hard-copy".

(b) With a beam splitter, adequate luminous energy could be extracted for imaging onto a simple "hard-copy generator" such as a photographic plate or sensitive image plate of a dry-copier, thus enabling hard-copy output. Such a scheme would overcome the costly and cumbersome existing methods of "hard-copiers" which often require the use of secondary small CRTs or DVSTs in parallel with the primary display CRT.

The above are but a few of the promising areas of improvements which can be researched after the basic system has been implemented.

10.6 GENERAL COMMENTS AND CONCLUSIONS

An Interactive Graphics Console "VIDIOGRAPHIC", based on novel principles, has been proposed and its feasibility examined in detail. The conclusions are that its practicability has been established and that its meets, very readily, the stated requirements of an IGC in providing a Display Subsystem and a Graphics Input and Display Interaction Subsystem. It can be implemented for a cost of around $3-4000.

Thus a solution to the original problem stated by Sutherland and quoted in the Preface, that the foremost problem in Man-Computer Graphics is the need for a "low cost display device, suitable for on-line graphical use", has been given.

Primarily this Thesis has concerned itself with developing the principles of this new IGC and showing in detail its feasibility and the suggested implementation by calculations and proposed circuits.
Its physical realization has not been attempted in full due to two main reasons:

(1) a full working system is beyond the physical means of one person, during the time allocated for a Thesis of this nature.

(2) the lack of funds.

This work then must be left to others.

However, the studies reported within this Thesis show that a very promising solution to the problem of a low cost Interactive Graphics Console is present in "VIDIOGRAPHIC".

To conclude, the advantages of "VIDIOGRAPHIC" will be again briefly mentioned.

Despite the disadvantages of the relatively coarse resolution and the need of formatting from the relatively random vector specification within the CPU to the raster-scan formatting for display purposes, the following features are what make "VIDIOGRAPHIC" so attractive:

(i) The use of existing hardware for the Subsystems ensure that the total cost is in the vicinity of only $ 3-4000.

(ii) The Principles on which "VIDIOGRAPHIC" is based ensure complete compatability between the Display Subsystem, the Graphics Input and Display Interaction Subsystem, and the Display Refresh Storage.

(iii) During User-graphics Input and User-interaction with displayed features, CPU I/O interrupts are minimal.

(iv) The high geometrical linearity of the display and the hybrid hardware implementation, suggest that "precision graphics" and "graphical computing" are possible in VIDIOGRAPHIC.

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PART 3

EXPERIMENTAL WORK

CHAPTER 11

EXPERIMENTAL WORK AND SELECTED CIRCUITS

11.1 INTRODUCTION

11.1.1 General Remarks

The task reported in this thesis was to investigate the feasability of an economic IGC, of necessity based on new principles, and to realize the IGC physically. The feasability of this has been shown in the previous chapters and the appendices following. The physical realization however takes more time and unfortunately requires funds, neither of which were available in any quantity after the feasability study was completed. A fixed amount of time is associated with Ph.D studies leaving two alternative approaches open:

(i) either the complete "VIDIOGRAPHIC" system is investigated and described fully,

or (ii) some aspect of it is explored exhaustively and described in detail.

Since "VIDIOGRAPHIC" is a completely new system, clearly the former approach was the one to be considered, there being little point in a detailed description and physical realization of a part of a new untried system.

Very limited funds made the requirements of an economic IGC the major objective; hence only limited equipment was able to have been purchased while other equipment had to be borrowed. Thus economics and availability of equipment, rather than suitability, were the deciding factors in the choice, purchase, and construction of hardware.

As in the feasability study, experimental work can be carried out in two distinct areas:

(i) experimental work to generate a visible display for the user and to generate adequate signal to maintain the display. This involves the measurement of CRT luminance and persistance measurement of display element dimensions, and of photocurrent buildup and decay etc.

(ii) the realization of distortion correction circuits for the H- and V- deflection circuits for both the CRT and the Vidicon camera to result in a steady display.

For reasons made clear below, most of the experimental work was concentrated on (ii) above.

Much of the system feasability was validated by referring to existing data, to reported results in the technical literature, and occassionally to existing commercial subsystems; this is particularly true for experimental work in (i) above. For example the verification of photocurrent rise and decay time constants was from figures available in manufacturers' data. Since the prime aim is to propose and validate "VIDIOGRAPHIC", it should not matter how these "valid" results are arrived at.

Under the conditions of limited funds and limited time, it would be doubly superflous to carry out or repeat experiments, the results of which are available in the literature. Moreover these available results provide independent checks for any derived results.

11.1.2 Available Hardware and Test Equipment

Whatever equipment was purchased or hardware built was governed by the very limited funds available. Consequently only one subsystem was purchased, namely a transistorized Vidicon camera (a SONY CVC-100 TV Camera (326)), the choice being solely based on the fact that it was the cheapest on the market ($310(A), Nov.1967).

The other major subsystem, the TV scan-mode CRT was a PYE TV Studio Monitor (Type 2788CG Monitor (325)), of 1955 vintage, on loan from W.R.E, Salisbury, S.A, by kind permission of the Director. The reason for this choice was availability at no cost and, being a studio-quality monitor, its frequency response and display linearity were better than in currently available TV receivers or TV camera monitors. Its disadvantages however were valve construction, and, being on loan, the possibility and even necessity of rebuilding certain subsystems such as deflection circuits to incorporate display linearity correction circuits, were greatly limited.

The third major subsystem required, the Schmidt TV-Projection System, was not available for two reasons:

(i) Projection TV was out of vogue by the time TV was introduced in Australia- hence no sets of this type exist in Australia (although they are still available from disposal stores in the USA).

(ii) When the first tentative concepts of "VIDIOGRAPHIC" were formulated, "lens optics" using beam adders and splitters (section 6.2.3) were envisaged. For this, only a standard-sized CRT screen was required (another reason for obtaining the 14" PYE Studio monitor). When the Schmidt Optical System was found to be more suited, the remaining time available was inadequate to find and obtain a complete RCA domestic TV Projection receiver.

Of the test equipment available, the usual lab. oscilloscopes, oscillators, counters and other measuring instruments were available. However photometric equipment was unavailable even from the Physics Dept. at the University. Cost, and the limited use of it after this particular application, precluded the purchase of such equipment. Measurements of CRT luminance, persistance, CRT spot sizes etc were thus not carried out. Manufacturers' data and published data had to be relied on.

The same considerations applied to any hardware which had to be built. For any logic which was required, Fairchild RTL I/Cs (318) had to be used, it being readily available within the Electrical Engineering Dept., while for any linear circuits such as the voltage-controlled monostables or astables etc, discrete element circuits had to be designed, as whatever I/C circuits available, performing the same functions (316), were considered too expensive. Similarly, although high linearity raster-scanned displays are commercially available (eg. 290), and even linear deflection subassemblies and pincushion correction subassemblies (311) too, again, due to cost considerations, discrete component circuits performing these functions had to be designed. The resultant performance of these circuits are as good or better than the commercially available ones; cost certainly is more favourable.

Summarizing then, the available hardware and equipment was:

(i) a purchased cheap transistorized TV camera working on a 625-line, 50Hz mode.

(ii) on loan, a 14" valve TV monitor working on a 625-line, 50Hz mode.

(iii) the usual range of lab. oscilloscopes, oscillators and measuring instruments.

(iv) a limited range of I-C logic function circuits (Fairchild RTL), a limited range of transistors, and a very limited range of linear I-Cs (mainly Op.-amps).

11.1.3 Policy of Experimental Work

The original policy for "VIDIOGRAPHIC" was to use existing off-the-shelf available subsystems, such as TV receivers, Vidicon cameras etc, and integrate them, with the least modification, into a workable IGC; this was to result in a very economic system. However the lack of funds added a new restriction, resulting in the purchase of the cheapest available equipment and, in the case of the equipment on loan, with the necessity of working with not a wholly suitable subsystem. The result was that some modifications to the equipment were required to be made; hopefully these were to be kept to a minimum. Certainly with the equipment on loan minimum modification had to be the case, under the original conditions of the loan.

In the early stages of experimental work this policy was strictly adhered to. However the stage was arrived at (particularly in the cheap TV camera) where modifications were insufficient, and certain sections had to be redesigned. Thus valuable months were lost. Subsequently the whole H- and V- deflection system of the Vidicon camera, as well as the timing, had to be redesigned. Not surprisingly much of the reported experimental work deals with this aspect of Vidicon camera deflection circuit design. This was made the more necessary as TV cameras being primarily commercially manufactured systems and subject to propriatry rights, the technical literature on camera circuits is poorly documented. Also the camera, having being purchased exclusively for that purpose, (unlike the CRT on loan), developmental work on it could be carried out. Being transistorized, modifications to it are easier to make than on the valve-implemented TV-mode CRT.

Had time and funds allowed, the CRT H- and V-deflection subsystems would also have been rebuilt using transistors. The task is not too different, as both Vidicons and CRT use magnetic deflection for the electron beam,resulting in very similar circuits in both subsystems, the prime difference being scanning current amplitudes. Magnetic deflection requires current sweeps producing the beam-deflecting magnetic field, which makes transistors, rather than valves, the ideal devices to implement these circuits.

Also, as mentioned previously, much of the experimental work was performed in determining an accurate method of measuring CRT display and Vidicon camera distortion; this resulted in the work on Moire Fringes, mentioned in section 7.3.3, and in the attached reprint of a paper on the subject in Appendix 11.

To summarize then, the experimental work performed to validate the feasability study presented in Chapters 3-10, can be divided into three main subsections:

(i) Photometric and electro-optical measurements to determine CRT phosphor-emitted brightness and persistance, and photoconductivity rise and decay time constants etc.

(ii) Work in measuring CRT display and TV camera geometrical distortion using Moire Fringes.

(iii) Hardware implementation of highly linear deflection circuits (mainly for the Vidicon camera) and also of the circuits mentioned in Chapter 8 in implementing the H- and V-distortion correction circuits, such as pulse integrators, voltage-controlled monostables and astables and so on.

The following sections describe this experimental work and report the results.

11.2 EXPERIMENTAL VALIDATION OF PHOTOMETRIC QUANTITIES

11.2.1 CRT Luminance

The luminance and persistance characteristics of the CRT W-phosphor under electron beam excitation is usually supplied by the CRT manufacturers in the form of curves shown in Figs.64, and occassionally in the form shown in Fig. A.9.1(b) in Appendix 9. These latter curves give, for any given phosphor and CRT, the value of control grid signal voltage required for any required output screen luminance. From the expression 4.4 and persistance curve as in Fig. 64(a) (or Fig. A.9.2), the actual form and value of the screen luminance at any instant can be found. The resultant Vidicon photoconductor illuminance can thus be found using expression 4.11.

Since all of the above data is available from the manufacturers in one form or another, experimental work in this area is superflous.

To measure phosphor luminance buildup (section 4.1.3) is another matter; luminance buildup data is only provided for long persistance phosphors (247) ("long" meaning several seconds or longer), used for radar applications, and by implication, buildup is considered to be of significance only in such types of phosphors, and not in TV-application phosphors. To measure CRT luminance buildup, a photometer with special characteristics is required; the cost of such a photometer is outside the limited funds available. Even the simplest of photometers (excluding photographic light-meters) were unavailable at the Physics Dept. of the University. Some of the required parameters of the photometer would be:

(i) a very narrow angle of view (1°-2° at most), so that significant luminance is available in the angle of view from CRT screen elements excited "simultaneously" (say within 100 μs); direct contact probes with fibre optics suggest themselves.

(ii) the speed of response of the light detector within the photometer need be negligible with respect to the frame time of 40ms, since the significant variation in luminance is expected to be apparent every successive frame time, indicating the build-up.

(iii) In addition the photometer would need to have a sufficiently accurate scale, accurate to about 1% or better (though not necessarily a linear scale).

(iv) The spectral response of the photodetector need not be accurately known, as only the relative apparent luminance between successive frame times need be known.

Such photometers are commercially available (344) but in our circumstances are prohibitively expensive (> $1000).

The approximate expression derived for luminance buildup (expression A.9.12) show that there is less than 10% contribution due to buildup, while Fig.68 indicates that such a 10% (or even 20%!) reduction in luminance has negligible effect on the capability of a Vidicon output signal being detected by the appropriate signal level detector.

For reason of costs of the measuring instruments, and the fact that a TV projection tube, required in the final system, was unavailable, measurement of CRT screen spot size and checks for the presence of defocussing upon deflection, were not made.

Such an instrument, essentially a microscope, but somewhat modified, would primarily determine the variations in spot sizes if any, and hence changes in CRT spot luminance, luminance being inversely proportional to spot size for any given beam current. Also the possibility of stray Vidicon output signals could also be explained by distorted CRT spots (see Fig.122(c), (d)). The effectiveness of the defocussing correction circuits (section 9.3.4) could also be measured.

11.2.2 Vidicon Photocurrent and Electron Beam Landing Validation.

As for the "verification" of the CRT phosphor performance, similarly for the "verification" of the Vidicon photoconductor performance, reliance had to be placed on published results and manufacturers' data. The figures used in Table A.10.1, verifying the accuracy of the expressions 4.15, 4.16 for the photocurrent rise time-constant and fall time-constant, are all derived from manufacturers' data. The percentage variation between calculated and manufacturers' results in most cases is within 20% of each other. The range of illuminances for which the time constants were evaluated, vary from some 100ft-C to about 1ft-C.

Actual experimental setups to measure photo-currents etc are difficult to achieve. In Vidicons, the output signals are due to the photocurrents being integrated over a frame time and thence discharged by the incident electron beam. To separate out signal effects due to the photocurrent and due to incomplete beam discharge, the stored-charge discharge mechanism must be replaced by an impedance-less "electron-beam". Also if the continuous photocurrent is to be monitored (ie. to verify the photocurrent curves as in Figs. 67(a),(b)), a "continuous" circuit with the photoconductor must be somehow provided.

Both experiments require a sample of the photoconductor under the same camera lens imaging conditions as in the normal Vidicon, but with a second contact on the scanning side of the photoconductor, of the same form as the signal plate contact on the glass faceplate side. This enables either continuous monitoring of the current flowing across the photoconductor sample (i.e the photocurrent) or else may provide the impedance-less discharge path after charge buildup of a frame-time interval. Simple lab. facilities are inadequate for providing such a contact, as contact potential must be allowed for, contamination of the photoconductor on contact deposition, and due to exposure to the atmosphere, must be eliminated and so on. Also photoconductor samples are difficult to get from manufacturers. Measurements on such samples have been made (252,336) and results from them, in addition to data from manufacturers, have been used to verify the expressions derived within this thesis.

Similarly in investigating beam acceptance at photoconductor impact, specially constructed "Vidicon" tubes are used, with an insulator rather than a photoconductor as the target, whose surface potential can be varied to simulate the surface potential variation due to photoconductively caused stored surface charge (252,253). Again these experimental setups are beyond our scope; but the reported results in (252, 253) have been used to obtain average or typical beam acceptance figures in section 5.2.

Recently an unusual application of a Vidicon has been reported (343), certain aspects of which are of considerable interest to our application. The Vidicon camera in this application forms a part of a working model of a character generator with a large set of characters (a set of 1024 Japanese characters). Briefly, a subset of 256 characters, in a 16 x 16 matrix, is optically projected onto a Vidicon faceplate; to select the appropriate character, the scanning beam is grossly positioned to the required character and a local linear raster scan is made over that character, generating a video signal representation of that character at the camera output which is then displayed on a storage CRT. Some 330 characters/second can be readout, with 3ms. associated with each character; of this, 1·5ms is required to "pre-scan" the area associated with that particular selected character to erase any remanent signal from prior-projected characters (from the other 3, 16 x 16 character matrices). The character mask containing the set of the 256 characters is illuminated with a Xenon flash lamp (the flash being of 5μs duration!), and the other 1·5ms of the 3ms cycle is required for the readout raster scan. The non-standard scan for each character area has a repetition rate of 0·67KHz in one direction and 20KHz in the other (vertical) direction; thus 30 scan lines per character are used. For such scanning rates, a beam dwell time of some 1·5us is associated with each display element, which is some 10-15 times longer than in normal TV scanning rates. From Fig.73 it can be seen that near-complete charge erasure is achieved under such long beam dwell times.

Of interest here is the example of a Vidicon illuminated by a high intensity flash (Xenon flash tube with a peak luminance typically of the order of 10^7-10^9ft-L (279)) of duration of some 5µs only, and resulting in a reasonable amplitude output signal. (In the case of "VIDIOGRAPHIC" the CRT illumination is some 10^4ft-L with a significant illumination duration of some 1-2ms). With the value of F-number of the Vidicon lens (F=5·6) and the semi-reduction magnification (M=0·5) and the presence of a semi-silvered mirror (T_S=0·4) quoted for that application (343), and taking an nominal value for the Xenon lamp illumination of 10^3ft-L(peak), the illuminance reaching the Vidicon photoconductor, using expression 4·9, can be calculated to be of the order of $1\cdot5.10^5$ft-C. Also the Vidicon used was an RCA 8572 (class I photoconductor). Using typical parameters for a 8572 as in Table A.10.1, for a back plate voltage "V_S" of some 35V, and using expression 4.15 to evaluate the photocurrent time constant, results in a time constant value of $\approx$ 0·7ms. This compares very favourably with the reported value of the time constant thus: "generally the photocurrent decay time constant is very short, of the order of one millisecond". Considering that exact values of Xenon lamp luminance are not given, the agreement is nevertheless very good.

It is thus considered that this application gives excellent experimental validation of the expressions derived for the photocurrent time constants at high illuminations and a convincing demonstration of the feasability of "VIDIOGRAPHIC" from the viewpoint of adequate signal being generated by W-phosphor type illumination within a frame time interval of 40ms.

11.2.3 Schmidt Projection Optics and Light Pen

As mentioned previously a Schmidt TV Projection System was unavailable to conduct experimental work. Again the figures used in the expressions within the feasability study were based on the comparitively well-documented literature on TV Projection Systems.

Concerning the projection of the CRT luminance to form a suitably bright display for the user, no problems exist, as systems such as the RCA TV Projection System were specifically designed for that purpose. Also no problems exist in producing adequate illuminance for the Vidicon photoconductive target; the existing blacked out central portion of the spherical reflecting mirror can be removed (sometimes it already is (see Fig.63(b))), to result in the direct line of sight axis between the CRT screen and the Vidicon photoconductor.

The inputting of user-originated graphics data would need to be demonstrated experimentally. This depends on the following factors:

(i) <u>The Principle of Optical (Ray) Reversability.</u>

Since in the Schmidt Optical System, light rays converge to form real images (at the viewing screen) from real objects (at the CRT screen), and since the media (transparent rear-projection screen and intervening space) are optically isotropic, optical light ray reversability holds (see section 6.5.2).

(ii) <u>The nature of the CRT Phosphor Screen being a Lambert Reflector</u>.

That a CRT screen is a Lambert radiator is clearly demonstrated by the TV image being visible without change in brightness from all angles of direct observation. That it is also an efficient Lambert reflector for incident light is physically evidenced by the formation of secondary, tertiary etc. "halos", or rings, around any central luminous spot on the CRT screen, due to light from such a central spot being internally reflected by the glass faceplate, and hence incident back onto the CRT screen to be diffusely (Lambert) reflected (see section 6.5.3). Thus light from a light-emitting pen projected in the reverse direction to the CRT screen-emitted light direction will, on incidence at the CRT screen, be reflected back; part of this will be reflected back to the viewer screen, and more importantly, a part will be reflected in the direction of the Vidicon photoconductive target, thus inserting user-originated graphics into the CRT-Vidicon loop.

(iii) Finally, a Light-emitting Pen of spectral characteristics and persistance similar to those of the W-Phosphor is required.

The theory and practical performance of optic fibres is well known and documented. The design of the light pen and figures used therein have been directly based on manufacturers' specification sheets and on the documented performance of optic fibres. Lack of photometric equipment and the inability to "tamper" with the CRT screen to use it as a light source for the light pen, precluded building a phototype pen.

No major difficulty is thus foreseen in physically realizing the Light Pen or the Schmidt Projection System in the manner required for "VIDIOGRAPHIC".

Whilst little direct experimental work has been carried out in this area specifically for "VIDIOGRAPHIC", adequate experimental results obtained by others, and manufacturers' data, of direct relevence, exists which can be used to validate the mathematical expressions used and the proposals suggested to implement "VIDIOGRAPHIC" successfully.

11.3 EXPERIMENTAL WORK ON DISPLAY LINEARITY MEASUREMENT

11.3.1 General Remarks

Prior to obtaining an adequately linear CRT and Vidicon to result in a stable display, the distortion information and hence the distortion correction information need be obtained. This has led to the theoretical work and the experimental work to validate it, on Moire Fringe Distortion Determination. This has been previously introduced in section 7.3.3 and is more comprehensively reported in Appendix 11, particularly in the reprint of the paper published on this work. Within this reprint is not only a self-contained description of the theory, but the illustrations and examples shown of measured CRT display and Vidicon scanned area distortions specifically refer to the CRT and Vidicon camera under consideration. Thus to repeat describing the method and results obtained here would be superflous.

In addition, sections 7.4.3, 7.5.5, 7.5.7, 7.5.8, and A.11.4.2 describe the method for encoding this resultant distortion information graphically for subsequent decoding by the Distortion Correction Circuits. From this it is seen that for the specific application of "VIDIOGRAPHIC", Moire Fringe Distortion Measurement methods not only enable distortion of the CRT and the Vidicon camera to be measured, but depending on the Moire Fringe method used to measure this distortion, the resultant distortion information, when plotted graphically is, with little modification, of the exact form required to be drawn in the appropriate Graphics Distortion Information Area on the CRT screen to be subsequently decoded by the appropriate Distortion Correction Circuit.

11.3.2 Experimental Setup for "VIDIOGRAPHIC"

Several additional remarks concerning the measurement setup for "VIDIOGRAPHIC" must be made.

In the Appendix of the reprint (pp. 582-583 of the reprint) it is stated that to minimize parallax errors, which lead to values of display distortion being different to the actual distortion values, the "reference transparency" on which the reference lines are drawn, need be placed in contact with the CRT screen on which the electronically generated lines are displayed, or at least be placed in such a way as to minimize the distance between the plane of the transparency and the "plane" of the screen (the screen may be, and invariably is, curved and not a plane).

This leads to two effects:

(i) To minimize the separation between the CRT screen and the reference transparency, the latter was mounted inside the implosion protection faceplate in front of the CRT screen, by being sandwiched between this protective faceplate and another perspex sheet (having being previously been carefully positioned). The resultant separation between the transparency and the CRT screen was less than 0·5". For this particular CRT under examination this required the withdrawal of the CRT from its mountings and from the deflection and focussing coils, each time a new transparency was inserted. In most CRTs, non-rigid mountings for coils are used; mainly these rest on the tube neck. In our case, they rested on a cardboard tube which supposedly had a "tight" fit over the CRT tube neck; however some 0·25" play was observed. The withdrawal and insertion of the CRT moved the focus and deflection coils somewhat, which necessitated readjustment each time; the effect of this was that reproductability of results was affected.

In the RCA Projection TV-System, no implosion shield is present; thus a separate mounting for placing the Moire Fringe reference transparency is required. However the CRT need not be removed each time a new transparency is inserted, and thus problems of reproductability do not exist.

(ii) The second point also concerns the presence of parallax errors. The reference transparency consists of straight parallel lines which lie on a plane; however the lines generated on the CRT screen, nominally parallel, lie on a screen which is invariably curved (except obviously in flat-faced CRTS), particularly so in the case of the RCA projection tube (to satisfy certain optical requirements of Schmidt Optics). The screen is essentially spherical with the centre of curvature at the centre of electron beam deflection. Thus whilst the reference transparency may be in contact with CRT screen at the centre of the screen, the spacing between the two diverges going away from the centre, leading to errors in distortion measurements due to parallax.

In the reprint, an expression is derived (expression 49) giving this added apparent distortion due to parallax. From expression 49, this additional "distortion" is

$$\frac{-\Delta S(x,y)}{S + \Delta S(x,y)}$$

where "$\Delta S(x,y)$" is the separation between the plane of the transparency and the CRT screen at the point where distortion is measured, "S" is the distance from the centre of the screen (where $\Delta S(x,y) = 0$) to the point where the resultant Moire Fringes are being observed (see Fig.16 in the reprint).

Clearly the distance of observation from the centre of the CRT screen determines the apparent total distortion of the CRT display. For the purpose of VIDIOGRAPHIC, of interest is the effective distortion of the CRT display as imaged onto the Vidicon photoconductor target, and thus distortion measurements must be made at that point where the Vidicon target is expected to be with respect to the CRT screen. Since a photographic camera is used to take the "hard-copy" result of the resultant Moire Fringes, its lens is located at the expected location of the Vidicon camera lens in VIDIOGRAPHIC. For the 14" PYE Monitor, this distance "S" is some 22", while for the RCA 5" - Projection CRT, this distance is some 9" (see Fig.83(b)).

The recorded Moire Fringes, giving the effective distortion as "seen" by the Vidicon camera, are then a result of the CRT displayed lines on a curved screen being projected in the line-of-sight (or line-of-"Vidicon sight") onto the plane linear reference transparency, which is the condition required for linearity measurement.

11.3.3 Vertical Bar Generator

To conclude, the circuit diagram for the "Vertical Bar" generator to test CRT linearity is included; it is shown in Fig. 129. No "Horizontal Bar" generator is necessary, since "horizontal lines" are already provided

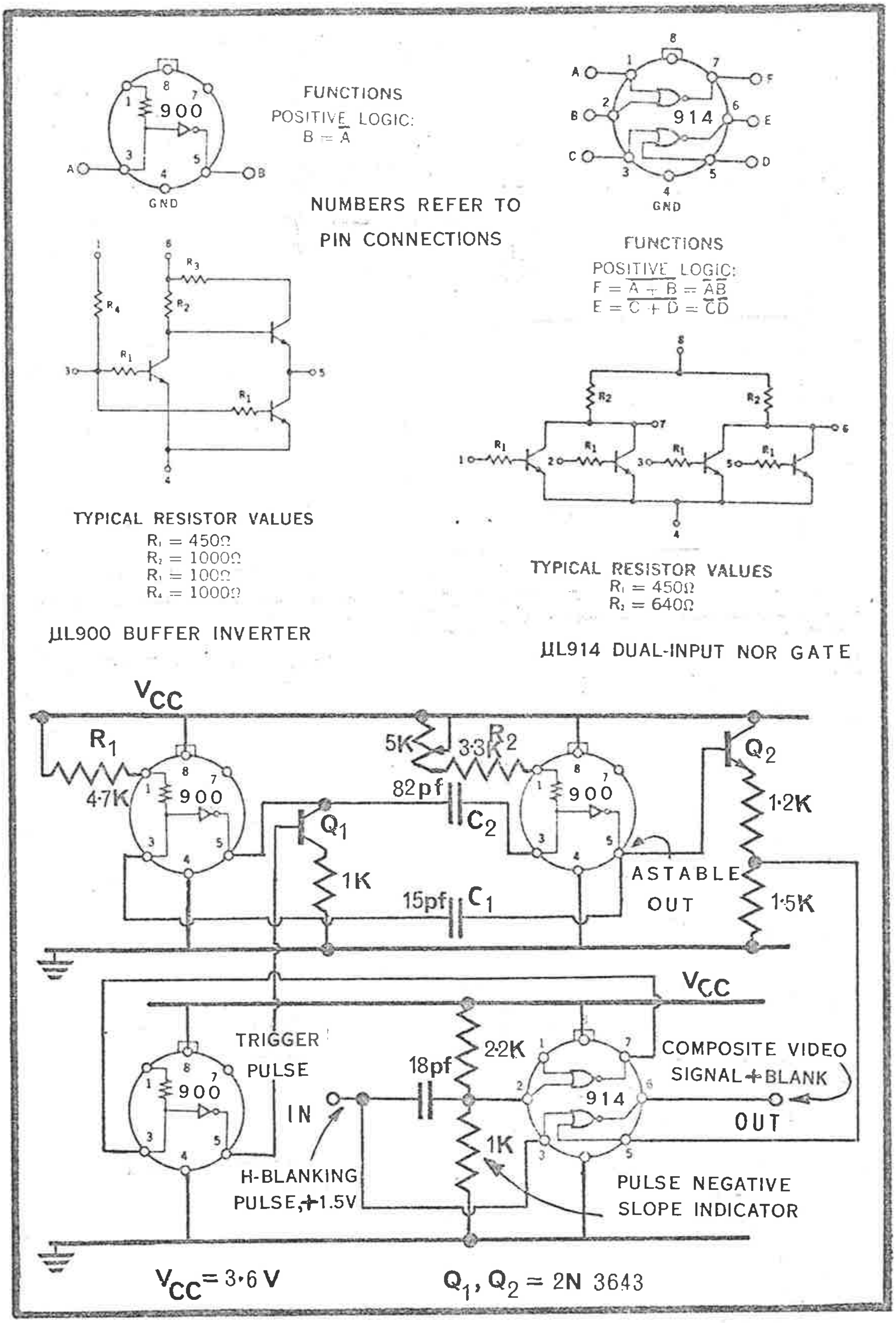

Figure 129. "Vertical" Bar Generator for Moire Fringe Measurements

by the "horizontal" raster-scan lines. To obtain Vidicon scanned area linearity, vertical bars are accurately drawn on a flat board which is then imaged onto the Vidicon photoconductor.

Briefly the generator consists of a resettable astable multivibrator (made from two μL900 buffer inverters), the reset or synchronizing pulse being derived from the H-line blanking pulse (which itself is derived from a crystal-controlled clock (section 11.6)). The output pulses, of a given nominal frequency corresponding to the required vertical bar separation, are synchronized to start from the same pulse edge, every H-line. The pulse is derived by the half of the μL914 dual-input NOR gate whose input is so biased by the resistor network and the coupling capacitor, that it forms a "pulse negative slope detector" (section 11.5.7); the resultant pulse, corresponding to the end of the H-blank pulse (and thus the beginning of the active portion of the H-line) is fed through an inverting μL900 buffer and the trigger transistor "Q_1". The duty cycle of the two halves of the astable are delibaretly made unequal (at least greater than 4:1) by appropriate selection of timing component values, so that the trigger pulse resets the astable in a given half period, unambiguously. Also the narrow output pulses form more sharply defined vertical bars when displayed (particularly if dynamic defocussing is still present).

The output frequency, as in simple astables, is given by

$$f \approx \frac{1}{(R_1C_1 + R_2C_2)\ln 2}$$

where "R_1","R_2" take into account the base spreading and base input resistors of the buffer inventer (R_1 and R_4 respectively in Fig.129(a)). For the values shown, the

output frequency range is about 2 - 4MHz.
Transistor "Q_2" acts as a buffer to prevent loading the output collector of the astable, and the resistance divider at its emitter gives the correct input amplitude for the other half of the μL914, which, with the original H-blank pulse, results in the correct polarity blanked video output signal feeding directly into the video input of the CRT to result in the "vertical bar" display.

11.4 HORIZONTAL AND VERTICAL SCANNING CIRCUITS.

11.4.1 General

The requirements of "VIDIOGRAPHIC" demand that the resultant CRT display be "geometrically stable" otherwise the display will, after several frames, exhibit "instability" by moving out of the viewer's sight. By a "geometrically stable" display is meant one where in successive frames, a given displayed spot is always located at the same display area coordinates, or at least is located within the elemental area associated nominally with that displayed spot. This requires that the electron beam deflection in both the CRT and the Vidicon be:

(i) linear , to better than 0·1% say. This may be achieved with a nominally linear scanning waveform generator (of say 0·2%- 0·3% scanning waveform linearity), with the required degree of display linearity obtained by adding correction waveforms derived from H- or V- Distortion Correction Circuits described in Chapter 8.

(ii) repeatable . The electron beam deflection may be linear but in addition, in successive scanning cycles, the scanning waveforms must be identical in amplitude, shape and duration.
For this, the requirements are:

(a) a stable timing source to initiate and terminate scanning cycles.

(b) Stabilizing networks to minimize or eliminate scanning waveform amplitude variations under temperature and power supply variations.

(c) the relative locations of components, such as deflection and focus coils, with respect to CRT tube neck or the Vidicon must be kept constant, otherwise deflection conditions are varied. This is of relevence particularly if the CRT need be taken out of its mountings during the insertion of the reference transparency for Moire Fringe Distortion Measurements (see section 11.3.2).

Precision jigs and mountings to locate and maintain coils positional accuracy are available (302).

Such relatively demanding requirements are not met in commercially available CRT displays or Vidicon cameras, yet as mentioned previously, one of the aims of "VIDIOGRAPHIC"was the use of commercial equipment in implementing it. Consequently in the available equipment to implement"VIDIOGRAPHIC", modifications, including some very major ones, had to be made. What started off as modifications was abandoned several months later and major redesign of equipment was initiated. The reason for this is briefly mentioned below.

In section 11.1.2, the available CRT display and Vidicon camera were briefly described; they are more fully described in Appendix 12, where system and circuit diagrams are given. On examing these, the difficulty in meeting the above requirements (i) and (ii), by modifying the existing circuits will become apparent.

Of the various requirements enumerated above for a "geometrically stable" display the prime requirement is stable timing. Timing signals define the start and termination of the scanning waveforms, blanking signals etc. and indicate the display element coordinates for both the CRT and the Vidicon. In most of the economic Closed-Circuit-TV systems, the camera/CRT display work in a master/slave mode as regards timing. The timing signals, indicating the start and end of the Horizontal and Vertical scans, are included in the composite video-sync. signal fed to the CRT display; thus the display is always in synchronism with the Vidicon camera. The short or long-term stability of the camera timing source is poor, often, as is the case in our CVC-100 camera, being derived from a freely running tank-circuit oscillator at the H-scanning frequency (15·625 KHz); the vertical timing signals are obtained from the mains 50Hz frequency. For the oscillator in the CVC-100 camera, the short-term stability (several minutes) was about $\pm 0 \cdot 5\%$. The result is poor repeatability in the location of the H-display lines in successive frames. Such a system is termed "random interlaced" (as against "2:1 interlacing" in Broadcast-TV systems).

The other method used, the solution ultimately adopted, is to use a stable external timing source, which controls directly the H- and V- scanning of both the camera and the CRT display. A crystal-controlled clock is used with a frequency of $\frac{"2"}{\Delta t}$ Hz where $\Delta t = 0 \cdot 162 \mu s$, which corresponds to the time interval associated with each display element H- coordinate in the 200 x 200 display grid. By suitable digital division, the H-line and V-frame timing pulses can be obtained to initiate the scanning cycles. The states of the frequency division counters directly indicate the H- and V- coordinates and other timing signals such as the start and termination of blanking signals. (see section 11.6 and Fig. 136).

In the TV camera, the H-scanning tank circuit oscillator does not allow external triggering for synchronization purposes, yet the subsequent scanning circuit stages require as their input the essentially sinusoidal outputs from that oscillator. Thus some time was spent in replacing the tank circuit oscillator and matching the waveforms to the required ones.
For the CRT, the external timing input modification was simple enough; the H- and V- timing pulses were fed separately into their corresponding scanning circuits as shown in Fig.A.12.2.

The above modification solved the problem of stable timing, still keeping the policy of minimum alteration to existing off-the-shelf equipment. However the problem of linear H- and V-scanning waveforms still remained.

To generate a sawtooth scanning current in a scanning coil of inductance L, the simplest solution, from the basic relation

$$v = L\frac{di}{dt} ,$$

is to keep the voltage "v" across "L" constant.

In the camera, this constant voltage, for the H- current sweep, was provided by the collector-to-emitter voltage of a saturated transistor ($V_{CE\ sat}$) during the sweep period (the transistor "Q_3" in Fig. A.12.4); nominally this voltage is constant for varying current, at some value 0·2 - 0·3V, but in practice, it is non-linear, particularly at low current values. The current sweep consequently was non-linear by some 6 - 8%, particularly at the beginning of each H- scan line where the sweep current was lowest.

The V- scanning current waveform was derived from the exponential discharge of a capacitor, the scanning waveform forming the initial segment of the discharge (capacitor C_{14} and resistors R_{24}, R_{25} in Fig. A.12.4). Again the resulting waveform is only an approximation to the linear case and again scanning waveform distortion of the order of 3 - 5% was present.

Bearing in mind that not only the scanning waveform need be linearized, but also pincushion and barrel distortion correction waveforms and remanent "analytically-indescribable" correction waveforms derived from Moire Fringe Measurements, need be inserted into the scanning waveform to result in the display linearity to be better than 0·1%, it became apparent that the existing scanning waveform generators were totally unsuitable. Some attempts at inserting correcting waveforms were made; being relatively unsucessful, these are not reported here. As a consequence it was decided to completely redesign the Vidicon H- and V-Scanning Circuits; the only components retained were the scanning coils mounted around the length of the Vidicon tube.

For reasons previously mentioned, the CRT H- and V- Scanning Circuits were not designed, although their design is very similar to the Vidicon scanning circuits, requiring in the main, additional current amplifiers.

11.4.2 Scanning Circuits Requirements and Design.

11.4.2.1 Scanning Circuit Requirements

The requirements for the H- and V- scanning circuits, for both the Vidicon camera, and TV display, are identical. They are:

(1) Synchronizing ability

The period of the scanning waveform must be capable of being initiated and terminated by external timing signals (derived from a crystal-controlled clock). The duration of the H-scan period is 64us, with the active (display generation) scan interval being 54µs, and the H-blanking period being 10µs. The V-scan period is 20ms, with the active scan interval being 18·8ms while the V-blank interval is 1·2ms.

(ii) Scanning waveform linearity is to be better than 0·3%.
(This is not to be confused with the overall resultant display linearity).
The figure of 0·3% is due to the limitation in resolving linearity measurement of the measuring instrument (see below - section 11.4.2.3.).

(iii) Capability to accept correction waveforms.
The output scanning current, fed into the H-and V- deflection coils, consists of the linear scanning waveform with inserted correction waveforms, generated outside the scanning circuits, to correct for pincushion or barrel distortion, and to correct for any remanent display distortion. These correction waveforms are generated by separate Pincushion or Barrel Distortion Correction Circuits (Chapter 9).

(iv) Independent Centering Control
This facility not only helps to position the undeflected beam at the centre of the display area, but can be used as a "fine" position control to align the CRT display optic axis with respect to the Vidicon scanned-area optic axis.

(v) Amplitude Control
This facility not only helps to adjust the amplitude of the scanning waveform and hence the dimensions of the display and scanned areas, but can be used as a "fine" scanned-area dimension

control to result in the required exact 1:1 magnification ratio between the CRT display and the Vidicon scanned area.

(v1) Temperature and Supply Voltage-Line Stabilization to ensure repeatability.

(vii) The H-scanning current is to feed a H-scanning coil whose self inductance is 1·16mH (series resistance is 4.1Ω) while the V- scanning current is to feed a V-coil whose self-inductance is 55·6mH (series resistance is 117Ω). These are the Vidicon camera coils. For comparison, self-inductance of the V-coils in the CRT are 5·2 mH (resistance being 8·6Ω) and for the H-coils, self inductance is 9·8 mH (resistance is 12·3Ω).

11.4.2.2 Design Considerations

The above requirements determine to a large degree the possible design approaches. Thus the requirement of external synchronizing ability leads to the use of pulse integrators to generate the V-scanning staircase waveform or the H-scanning sawtooth; the output is a voltage and not a current waveform.

The requirement of externally generated correction waveforms to be added to the linear scanning waveforms suggests the use of Op-amp. summers; thus summing of voltage waveforms is used.

The centering control (effectively performed by a variable DC current flowing through the scanning coils) can be effected by a variable DC voltage fed to the Op-amp. summer.

The requirement of using a priori specified scanning coils with the given inductances, determines the amplitude of the required scanning current in the coils, and thus whether the output current from the op-amp can be fed directly to the scanning coil or not. This last factor determines the required output stage of the scanning circuits and is the main reason for the difference between the V- and the H- scanning circuits. The reason is as follows:

In the Vidicon, it is shown (expression 11(f) in Appendix A.6.4) that beam deflection "d" is, to a first approximation, proportional to the deflecting magnetic field "B" generated by the scanning current flowing through the scanning coil.

Thus

$$d_x \propto B_x \text{ and } d_y \propto B_y$$

where "d_x" is the horizontal deflection due to the field in the H-scanning coil, "B_x",

"d_y" is the vertical deflection due to the field in the V-scanning coil, "B_y".

The magnetic field energy "W_M" in a given volume "V" due to a field "B" is given by the well known expression,

$$W_M = \frac{1}{2} \cdot \frac{B^2}{\mu} \cdot V$$

where "μ" is the permeability of the medium.

In a coil of inductance "L", such as the scanning coil surrounding the Vidicon, the magnetic energy is given by another well known expression,

$$W_M = \frac{1}{2} Li^2$$

where "i" is the scanning current.

From the above two expressions it is seen that

$$B = K.i\sqrt{L}$$

where "K" is a constant,

and further the beam deflection is given by,

$$d = K_1 .\ i\sqrt{L}$$

For maximum deflection, taking note of the 4:3 aspect ratio of scanned areas,

$$d_x = \frac{4}{3} d_y$$

Since the V- and H-scanning coils are of approximately the same length and diameter, their enclosing volume is nearly identical. Under those conditions, at maximum deflection

$$i_x \sqrt{L_x} \approx \frac{4}{3} \; i_y \sqrt{L_y}$$

where "L_x", "L_y" are the inductances of the H-and V-scanning coils respectively.

Inserting the values for "L_x" and "L_y" (see section 11.4.2.1 (vii) above)

$$\frac{i_x}{i_y} \approx \frac{4}{3} \sqrt{\frac{L_y}{L_x}} \approx \frac{4}{3} \sqrt{\frac{55 \cdot 6}{1 \cdot 16}} = 9.2$$

In actual fact $i_{xmax} \approx 125mA$ and $i_{ymax} \approx 15mA$. Consequently for the V-scanning circuit, the output current from the op-amp can be used to feed the scanning coils directly, while for the H-scanning circuit, a current amplifier with transformer coupling to the scanning coils had to be used, as the op-amps available at reasonable cost were inadequate in providing this required peak current. However op-amps with this output current capability are commercially available (316); others, with output currents up to 500 - 600mA, suitable to drive CRT H-and V-deflection coils, are also available.

11.4.2.3. Scanning Current Linearity Measurement

Accurate measurement of the scanning waveform provides some difficulties; for example when observing the sawtooth current on a CRO, any resultant distortion observed includes the display distortion of the CRO itself.

The CRO used (DUMONT 765) was a dual-input, dual-trace unit with a summing mode for the two inputs provided. Each input has a "normal" or "invert" mode and thus summing or differencing of the two input signals are possible and the result displayed. When displaying any given signal by using either of the two inputs in either of their modes, four different errors are introduced,each associated with one of the 4 different combinations. Without an external calibrated standard, and using the different possible combinations of summing or differencing, it is trivial to show that these error signals are individually indeterminate (the determinant of the matrix giving the equations linking the errors of each possible combination is equal to zero). However it is known that the summers and the input networks result in an error of no more that ±0·3%.
In addition, a reference 50Hz sawtooth waveform is available from the CRT, also of some ±0·3% linearity.

There are two types of distortion measurement to be made. One which determines the absolute linearity of the scanning sawtooth waveform say, and the other which determines the relative, or introduced distortion, between the sawtooth in one part of the circuit with the amplified sawtooth, say, in some other part of the circuit.

To determine the "absolute" linearity, the H-sawtooth or V-staircase is compared with the CRO reference sawtooth (by differencing the two) and the difference is displayed and measured. All four combinations of measurements are taken (i.e. input probes are interchanged and so are input polarities) and the average difference is used to obtain the distortion. Thus Scanning Waveform Non-linearity is then given by

$$\frac{\text{average difference signal} \times 100\%}{\text{scanning waveform amplitude}}$$

In most cases this was within the ± 0·3% error limit of the CRO.

When comparing two similar waveforms to determine distortion introduced by the intermediate circuit stages, one of the waveforms is fed to both CRO inputs and the difference signal or error signal is noted; call this " $f(\epsilon_1)$"; ideally this should be zero. The two waveforms are then compared for the difference signal; call this " $f(\epsilon_2)$". The nett intruduced distortion "$f(\epsilon)$" is the difference between " $f(\epsilon_2)$" and " $f(\epsilon_1)$" i.e

Net distortion, $f(\epsilon) = f(\epsilon_2) - f(\epsilon_1)$.

In appearance on a CRO, ideal or zero linearity would be evidenced by a horizontal line if the two input signals are appropriately scaled; otherwise, for distortion present, or error signals in the CRO input circuits or summing-amp being present, the result is a "bowed" line of length corresponding to the scanning interval.

The above method has limits in accuracy, but with the available equipment, was the most suitable method available.

11.4.3 Vidicon V-scanning Waveform Generator

11.4.3.1 Requirements

The functional block diagram of the Vidicon Vertical Scanning Waveform Generator and the required timing signals and resultant waveforms have been given in Figs. 106,107. The current staircase waveform has steps of 64µs duration, with each step being generated in nominally 10µs (the "step buildup") and for the remaining 54us, corresponding to the active or display interval of a H-scanning line, the step is "level" or horizontal.

The 2:1 interlace required for the Vidicon is provided by the timing signals (see Fig. 107 and section 8.1.2.1). In addition:

(i) the active scanning interval is of 18·8ms duration while 1·2ms is allowed for retrace and V-blanking. The number of 64us steps within 18·8ms is thus 294.

(ii) The scanning current amplitude is to be about 15mA ± 15%. Thus each step height is to be 0·051mA ± 0·0076mA, the step height variation to be provided by an external control.

(iii) Centering ability of ± 15% of the scanning amplitude is to be provided. Thus an externally variable DC current of ± 2·25mA is to be provided in the coils.

(iv) Scanning waveform linearity is to be better than 0·3%.

11.4.3.2 Implementation

The V-scanning waveform generator consists of two main functional subsections:

(i) the pulse integrator whose inputs are timing signals to generate a voltage staircase of nominal step height, and additional correction signals from the Vertical Distortion Correction Circuits (section 8.1.2.1) to generate a "corrected" staircase to result in linear scanning.

(ii) an output driver stage consisting of an I/C Op-amp in a special configuration, whose output current directly drives the V-scanning coil. In addition, the Op-amp. acts as a summer for:

(1) corrected "linear" staircase voltage.
(2) for additional small voltage waveforms to correct for pincushion or barrel distortion.
(3) a variable DC Voltage to provide the variable DC centering current.

(a) The Pulse Integrator.

Referring to Fig. 130, showing the circuit, the pulse integrator is formed from the transistors Q_3, Q_6, feeding in common the capacitor C_1; the transistors in that configuration supply voltage-controlled constant-current pulses to increase the voltage across C_1 in a staircase fashion. Two transistors are used, one (Q_3) to generate the nominal step height, the other (Q_6) to generate the small variable correction obtained from the V-Distortion Correction Circuits. Q_3, Q_6 and the capacitor C_1 correspond in Fig.107 to the "$Summer_1$" and the "Pulse Integrator".

The input to Q_3 is a 10µs duration pulse derived from a R-S F/F (marked F/F_2 in Fig.107), triggered by crystal-clock derived pulses. (Timing is described in section 11. 6). The input to Q_6 is a variable duration pulse derived from another R-S F/F (marked F/F_3 in Fig.107). This pulse immediately follows the 10µs pulse into Q_3; thus Q_3 and Q_6 do not have at any time simultaneous inputs. The intermediate stages between the inputs and Q_3, Q_6 being identical, only one need be described, that for the 10µs input, say.

The 10µs pulses of some 1·8V (from Fairchild µL 923 R-S F/F) is buffered by the emitter follower Q_1, and inverted by Q_2. The pulse amplitude is limited by the Zener diode D_{Z1} in series with the Si diode D_{S2}. The voltage "V_B" presented at the base of Q_3 due to an 10µS input pulse is thus

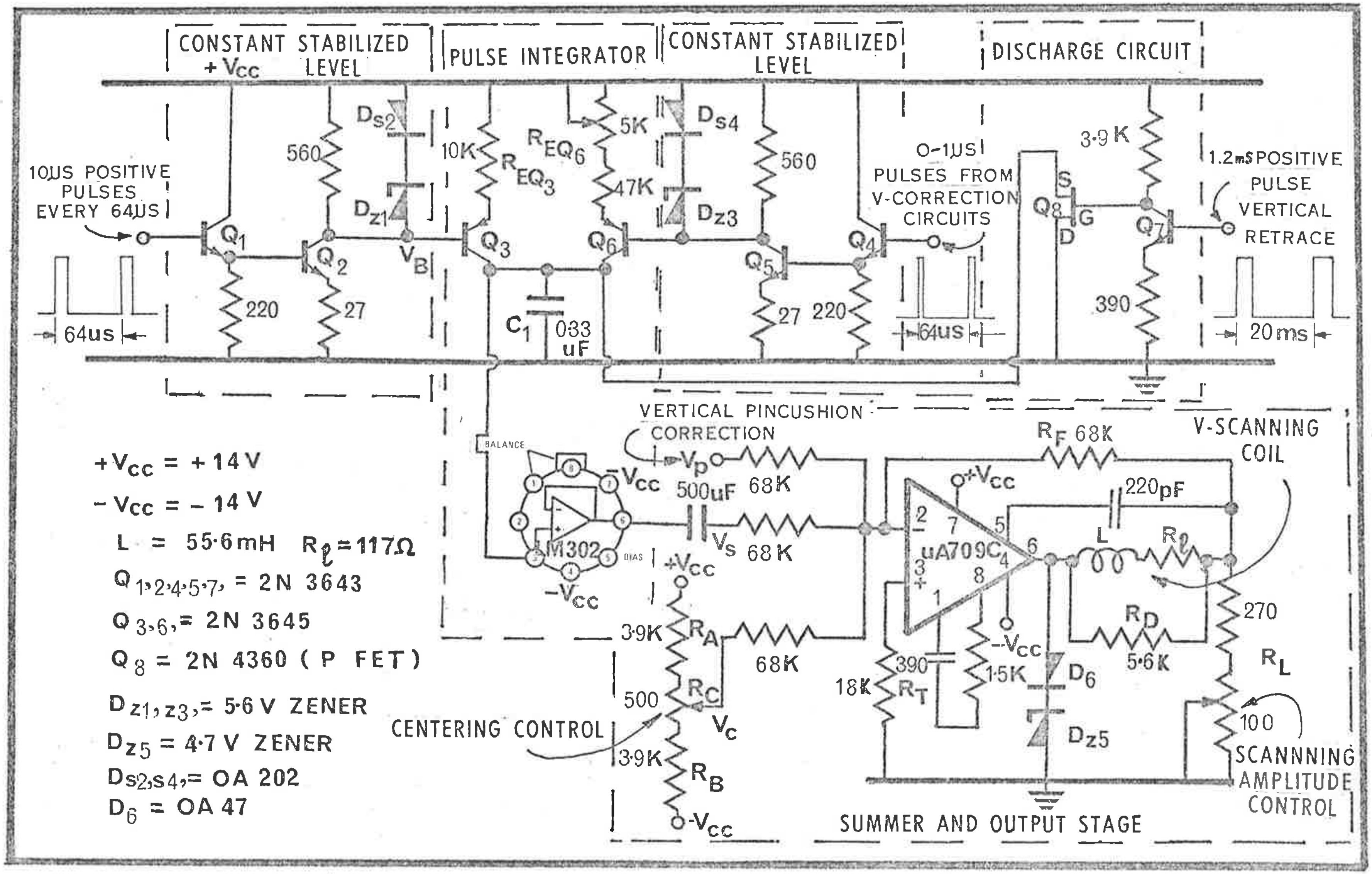

Figure 130. Vidicon Camera Vertical Scanning Waveform Generator.

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$$V_B = V_{CC} - \Delta V_{DZ1} - \Delta V_{DS2} \quad \ldots\ldots\ldots 11.1$$

where "ΔV_{DZ1}", "ΔV_{DS2}" are the voltage drops across each diode when conducting.
"$\Delta V_{DZ1} + \Delta V_{DS2}$" is essentially a constant value.

Otherwise when there is no pulse input (during the H-line scanning),

$$V_B = V_{CC} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 11.1(a)$$

The values of the emitter and collector resistors of Q_2 are so chosen that the thermal coefficiant of the Zener diode voltage, "$\frac{d\,\Delta V_{DZ1}}{d\,T^o}$" is ideally zero.

The emitter current of Q_3, during the pulse input interval "T_R" is

$$I_{EQ_3}(T_R) = \frac{V_{CC} - V_B(T_R) - V_{BEQ_3}}{R_{EQ_3}} \quad \ldots 11.2$$

Substituting for "V_B" above

$$I_{EQ_3}(T_R) = \frac{\Delta V_{DZ1} + \Delta V_{DS2} - V_{BEQ_3}}{R_{EQ_3}} \quad \ldots 11.3$$

an expression independent of "V_{CC}", the supply voltage.

Testing for temperature variation, results in

$$\frac{d\,I_{EQ_3}(T_R)}{d\,T^o} = \frac{1}{R_{EQ_3}}\left(\frac{d\,(\Delta V_{DZ1})}{d\,T^o} + \frac{d(\Delta V_{DS2})}{d\,T^o} - \frac{d\,V_{BEQ_3}}{d\,T^o}\right) \quad \ldots 11.4$$

As the current through "D_{Z1}" was chosen to make $\frac{d(\Delta V_{DZ1})}{dT^o} = 0$, while for a Si diode the temperature coefficiant is nearly identical to that in a Si transistor base-emitter junction, the above expression 11.4 is also independent of temperature.

The inverter Q_2 with the Zener diode/Silicon diode, effectively corresponds to the unit labelled "Constant stabilized Level Circuit" in Fig.107.

Since $\Delta V_{DS2} \approx V_{BEQ_3}$

then $$I_{EQ_3}(T_R) \approx \frac{\Delta V_{DZ1}}{R_{EQ_3}} \quad \ldots\ldots\ldots .11.5$$

The transistors Q_3, Q_6 are each connected in "common base", and the output impedance as seen at each collector is extremely high (several megohms); each transistor provides a current source, the output collector current being nearly independent of the load, in this case capacitive. Q_3, Q_6 are chosen to have a high current gain so that $I_C \approx I_E$ (For the transistors, $Q_3 = Q_6 = $ 2N3645, $h_{fe} > 150$).

Thus

$$I_{CQ_3}(T_R) \approx \frac{\Delta V_{DZ1}}{R_{EQ_3}} \quad \ldots\ldots\ldots .11.5(a)$$

During pulse input, $I_{CQ_3}(t)$ is constant at the above value. Hence the voltage across the capacitor C_1 is given by,

$$v = \frac{1}{C}\int i_c(t)dt = \frac{\Delta V_{DZ1}.t}{C_1.R_{EQ_3}} + V_o. \ldots\ldots .11.6$$

where "V_o" is the initial charge on the capacitor.

When pulse input is zero, "v" remains at its new value,

$$v = V_o + \frac{\Delta V_{DZ1}}{C_1 . R_{EQ_3}} . T_R \quad \ldots\ldots\ldots\ldots 11.7$$

Assuming that at the start of each new scanning cycle, $V_o = 0$ i.e. the capacitor is fully discharged (by the discharge circuit provided by the P-junction FET Q_8), the amplitude of the resultant scanning voltage staircase at the end of the V-scanning interval is,

$$V_{max} = \frac{\Delta V_{DZ1}}{C_1 . R_{EQ_3}} . n . T_R \quad \ldots\ldots\ldots\ldots 11.7(a)$$

where "n" is the number of staircase steps (=294)
"T_R" is the time interval of the current charge (nominally 10μs).
"ΔV_{DZ1}" is the value of the Zener voltage, (nominally at 5·6V).

"V_{max}" is chosen to be 5V, so that at "V_{max}", with a voltage supply V_{CC} = 14V (the recomended voltage supply rail in the Vidicon camera), sufficient V_{CE} exists (about 3V) to have $\frac{d V_{BE}}{d V_{CE}} = 0$, i.e. V_{BEQ_3} does not vary with "v".

The value of C_1, is chosen at 0·33uF (to provide sufficiently fast discharge (see below)). Substituting the above nominal values in expression 11.7(a) results in

$$R_{EQ_3} = \frac{\Delta V_{DZ1} . n . T_R}{v_{max} . C_1} = \frac{5 \cdot 6 . 294 . 10 . 10^{-6}}{5 . 0 \cdot 33 . 10^{-6}} = 10K\Omega$$

For the input stages Q_4, Q_5, and the other half of the Pulse Integrator Q_6, providing for the Vidicon Vertical Display Correction, the variable duration input pulse of 1μs maximum duration is to correspond to 2% of the staircase step height (see section 7.5.7). Hence, R_{EQ_6}, the emitter resistor of Q_6 is given by,

$$R_{EQ_6} = \frac{\Delta V_{DZ3} \cdot n.\ 10.10^{-6}}{0{\cdot}02\ V_{max}.C_1} \cdot \frac{1.10^{-6}}{10.10^{-6}} = \frac{R_{EQ_3}}{0{\cdot}2}$$

$$= 50K\Omega$$

A small trimmer resistor is thus required in R_{EQ_6}, to adjust its value such that a 1μs duration pulse will generate exactly 2% of the nominal step height.

Fig.131(a) shows the actual relationship between pulse duration and resultant step height, compared with the ideal value of step height based on nominal values. For a 5V staircase voltage output, with a 10μs pulse duration and 294 steps the nominal step height is 17mV.

The output of the integrator (at the common collectors of Q_3, Q_6) cannot be fed directly to the output stage (the op-amp) as the input impedance of the op-amp., although high, will provide a discharge path for the capacitor C_1, with the result that the staircase voltage waveform will exhibit a "droop" or non-linearity. If "R'" is the nett discharge impedance in parallel with C_1, the percent decrease of the voltage across C_1 is of the order of $\frac{\Delta T}{R'C_1}$, if $R'C_1 \gg \Delta T$; ΔT is the scanning duration of 18·8ms. For the percent decrease to be less than 0·1%, $R' > 6.10^7\Omega$. The output of the integrator is thus buffered by a unity-gain I/C voltage-follower (LM 302) with an input impedance of some $10^{10}\Omega$, satisfying the above requirement. Being essentially a non-inverting op-amp of unity gain, it exhibits negligible waveform distortion.

The capacitor C_1 is also connected to a simple discharge circuit, effectively a simple P-channel FET

(2N4360), which is switched on during the V-blank or V-retrace 1.2ms interval via the inverter Q_7; during the active scanning period of 18·8ms it is off. During the Q_8 "off" duration, the gate (G) of the FET being at V_{CC} (14V), while the source (S) is at some lower voltage "v", the possibility of leakage current "I_{GSS}" flowing and charging C_1, exists. However it is typically in the range of a nA and can be neglected. Similarly leakage currents "I_{ECS}" and "I_{ECS}" in the transistor Q_3, Q_6 can also be neglected, also being in the range of nA's.

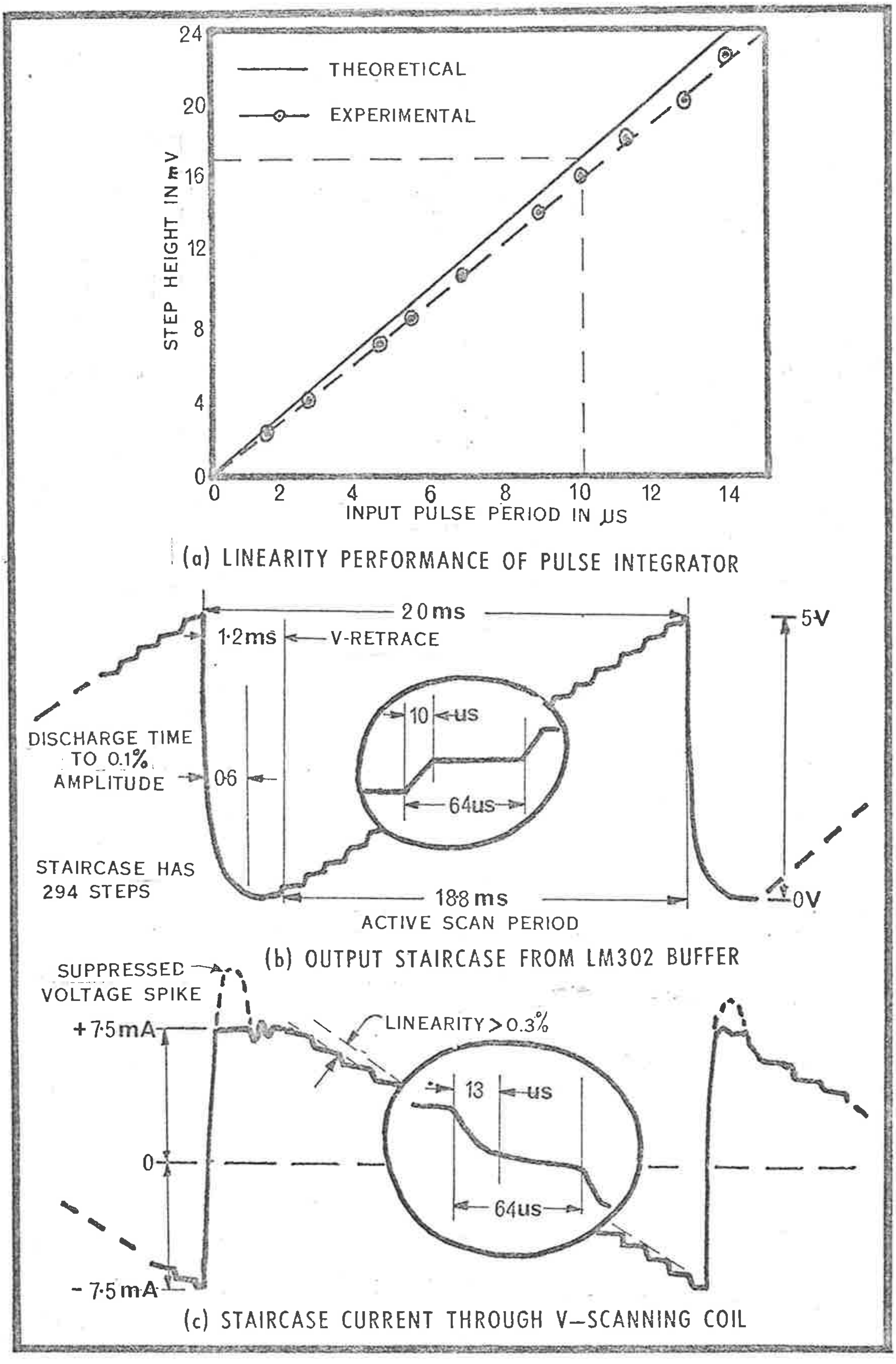
When the FET Q_8, is fully "on", during the retrace period, it appears as a resistance of some 300Ω between source (S) and drain (D), discharging the capacitor C_1, with resultant associated time-constant of some 0·1ms. Since within 9 time-constants an exponential discharge decreases to less than 0·01% of its initial value, the 1·2ms allowed for vertical retrace is more than adequate; capacitor C_1 thus discharges to a zero voltage value each scanning cycle. This is the "Discharge Circuit", labelled as such, in Fig. 107.

Linearity measurements show an overall linearity within the 0·3% error of the CRO. (This is without the variable correction input). Table 5 compares the nominal performance figures with the measured figures and shows the excellent performance of the Pulse Integrator. Fig.131(b) shows the output waveform.

(b) <u>The Output Driver Stage</u>

The output stage of the V-scanning circuit consists of a uA 709C I/C Op-amp, (corresponding to "Adder 2" in Fig. 107), connected in the configuration shown, which makes it a voltage-to-current converter. At its input, it acts as a summer for:

(i) the voltage staircase from the pulse integrator,



(a) LINEARITY PERFORMANCE OF PULSE INTEGRATOR

(b) OUTPUT STAIRCASE FROM LM302 BUFFER

(c) STAIRCASE CURRENT THROUGH V–SCANNING COIL

Figure 131. Performance and Waveforms of the V-Scanning

which includes the Vidicon Vertical Display Correction, "$V_S(t)$."

(ii) a voltage waveform for pincushion or barrel distortion "$V_p(t)$", generated elsewhere (see section 9.4.3).

(iii) a variable DC voltage from a potential divider to provide the required centering control, "V_C".

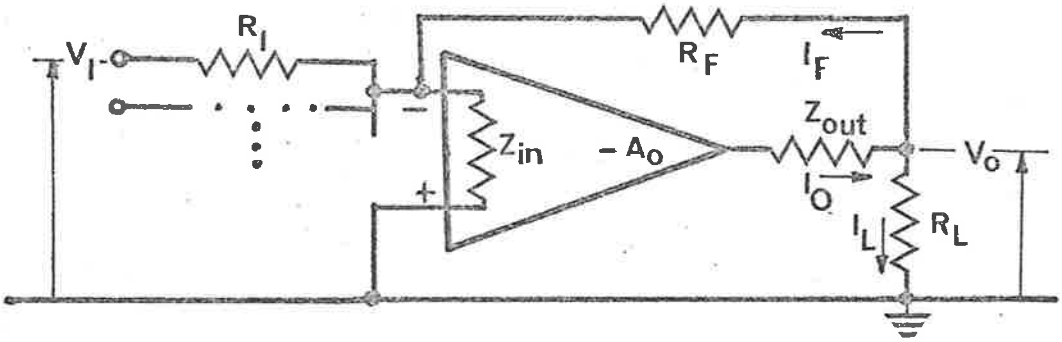
Thus

$$V_i(t) = V_S(t) + V_p(t) + V_C \quad \ldots\ldots\ldots 11.8$$

This summed input appears in the vertical deflection coil as a summed scanning current.

The V-deflection coils in the circuit, from an circuit-analysis viewpoint, can be considered as part of the output impedance of the op-amp (the approach taken below); alternatively, the resulting voltage-to-current conversion can be considered to be due to the "heavy" feedback resistor "R_L".

It is simple enough to show (see for example (345) that for an op-amp connected in the manner shown,



the output voltage "V_o" is given by

$$V_o = -V_I \cdot \frac{R_F}{R_I} \cdot \left(\frac{1}{1 + \mu} \right) \quad \ldots\ldots\ldots 11.9$$

where $V_o = I_L \cdot R_L$, with "I_L" being the load current, and $$\mu = \frac{\left(1 + \frac{Z_{out}}{R_F} + \frac{Z_{out}}{R_L}\right)\cdot\left(1 + \frac{R_F}{R_I} + \frac{R_F}{Z_{in}}\right)}{A_o - \frac{Z_{out}}{R_F}} \quad .11.10$$

where "Z_{in}" is the input impedance of the op-amp (ideally $Z_{in} \to \infty$)

"Z_{out}" is the output impedance of the op-amp (ideally $Z_{out} \to 0$).

"A_o" is the open-loop gain of the op-amp (ideally $A_o \to \infty$).

Also

$$I_o = I_L + I_F = I_L\left(1 + \frac{R_L}{R_F}\right) \quad . . . . .11.11$$

If $\mu \to 0$, or is negligible, then from expression 11.9, 11.11,

$$I_o = -\frac{R_F}{R_1} \cdot \left(1 + \frac{R_L}{R_F}\right) \cdot \frac{1}{R_L} \cdot V_I \quad . . . . . .11.12$$

i.e. the current waveform out of the op-amp follows the input voltage waveform "$V_I(t)$".

If an impedance is inserted between the op-amp output and the junction of "R_L" and "R_F", it effectively becomes a part of the op-amp's output impedance as far as analysis goes, subject to the above expressions.

For the uA 709C, typical vlaues are

$$A_o = 40.10^3$$
$$Z_{in} = 1\cdot 5.10^5 \Omega$$
$$Z_{out} = 150 \Omega$$

The scanning coil has L = 55·6 mH and R_C = 117Ω. R_1 and R_I, R_F are made 68KΩ each. At the highest frequency operating (of the order of $\frac{1}{2T_R}$ (where "T_R" is 10us, the step height buildup)), the scanning coil impedance is of the order of 20KΩ, making "Z_{out}" effectively 20KΩ. "R_L" is of the order of 300Ω (see below). Substituting these values

in expression 11.10 results in $\mu \approx 0 \cdot 01$; hence the current step buildup obeys the expression 11.12 very nearly.
For the overall staircase of duration 18·8ms (and hence of frequency $\approx$ 50Hz), where harmonics beyond the 10th need not be considered when considering linearity, the impedance of the coil at 500Hz results in $\mu \approx 0 \cdot 0003$. Thus, noting that $R_I = R_F$, the current "$I_o(t)$" through the scanning coil is given by,

$$I_o(t) = -\frac{V_i(t)}{R_L} \cdot \left(1 + \frac{R_L}{R_F} \right) \quad \ldots\ldots\ldots \quad 11.12(a)$$

For a $V_i(t) \approx 5V$ (the pincushion correction waveform amplitude being only some few percent of $V_i(t)$), and a required "$I_o(t)$" maximum amplitude of 15mA, R_L evaluates, from expression 11.12(a), to 330Ω. To provide a ± 15% amplitude variation, R_L is made 270Ω with a series potentiometer of 100Ω

Referring to the Fig. 130, the 4·7V Zener diode DZ_5 and the OA 47 Ge diode D_6, suppress a voltage spike appearing at the "true" output of the op-amp (terminal "6") during the V-retrace time (see Fig. 131(c)). The 390pF and 1·5KΩ series capacitor-resistor between terminals "1" and "8" and the 220pF capacitor between terminal "5" and R_L are the recommended input and output frequency compensating networks respectively.
R_T, of 18KΩ, at the non-inverting input is made equal to the parallel combination of the input resistors (R_1=R_2= R_3 = 68KΩ) and is for temperature compensation in the op-amp.

"R_D" across the V-scanning coils, chosen at 5·6KΩ, is a damping resistor for oscillations appearing across the coil just after the V-retrace, due to the frequency compensating capacitor of 220pF, the coil interwinding capacitance etc.

TABLE 5

PERFORMANCE OF V-SCANNING CURRENT GENERATOR

	NOMINAL	EXPERIMENTAL
VOLTAGE SWING ACROSS R_{EQ3}	5·6V	5·8V
STAIRCASE AMPLITUDE AT C_1	5V	4·72V
STAIRCASE AMPLITUDE OUT AT LM 302	5V	4·71V
LINEARITY	0	< 0·3%
DISCHARGE TO 0.1%	0·7ms	0·6ms
V_O VOLTAGE AT R_L (R_L = 330Ω)	5V	4·8V
V_6 VOLTAGE AT "6" OF OP-AMP	6·6V	6·4V
ΔV_{COIL} ($V_6 - V_O$)	1·8V	1·6V
COIL CURRENT	15mA	13·9mA
STAIRCASE STEP BUILDUP	10us	13us
AMPLITUDE VARIATION (R_L = 270Ω+100Ω)	±15%	-14%, +11%
CENTERING	±15%	±17%
LINEARTY	0	< 0·3%

TABLE 6

PERFORMANCE OF H-SCANNING CURRENT GENERATOR

	NOMINAL	EXPERIMENTAL
SAWTOOTH AMPLITUDE OUT OF LM 302	5V	4·8V
LINEARITY	0	< 0·3%
DISCHARGE TO 1%	3·6us	2·9us
VOLTAGE AT V_O	5V	4·9V
CURRENT	125mA	130mA
LINEAR (0.4%) CURRENT DURATION	54us	53us
AMPLITUDE VARIATION (R_L = 33Ω+10Ω)	±15%	-14%, +12%
CENTERING	±15%	-13%, +13·5%
LINEARITY	0	≈ 0·3→0·4%

The input staircase "$V_S(t)$" is capacitively coupled ($C_2 \approx 500uF$) to the op-amp.

The potential divider providing the DC centering current, feeds a variable DC voltage, as required, to the op-amp. For positive and negative supplies being equal in magnitude (+14V and -14V) and if $R_A = R_B$, then the input voltage variation is given by

$$\pm V_C = \pm \frac{V_{CC} \cdot R_C}{R_A + R_B + R_C} \quad \ldots\ldots\ldots\ldots \; 11.13$$

For the values chosen $R_A = R_B = 3{\cdot}9K\Omega, R_C = 500\Omega$, $\pm V_C \approx \pm 0{\cdot}85V$, which is approximately $\pm$ 15% of "$V_S(t)$" (equal to some 5V). Thus the centering provides $\pm$ 15% variation of $I_o(t)$, the scanning coil current amplitude.

Actual tests were carried out on a wound inductor of L = 55·6 mH in series with a resistor of 120Ω in series. This enabled waveforms to be measured "inside" the "V-scanning coil".
Table 5 summarizes the performance of the complete V-scanning current generator.

11.4.4 Vidicon H-Scanning Waveform Generator

11.4.3.1 Requirements

The specific requirements for the Vidicon H-scanning waveform generator are as follows:

(i) H-scanning being continuous, (unlike the V-scanning staircase waveform), a sawtooth current is required in the H-scanning coils. A block diagram showing the Vidicon H-scanning system is shown in Fig.113.

(ii) The H-scanning period is 64μs, of which 54μs is to be the active scanning interval, while the remaining 10μs is for the H-retrace.

(iii) The nominal scanning current amplitude is to be 125mA (peak-to-peak) with ±15% amplitude variation provided by external control.

(iv) Centering ability for the scanning is to be ± 15% of the scanned area width, and is to be provided by external control; thus a ± 19mA DC current variation is required in the scanning coil.

(v) Linearity of the scanning current is to be better than 0·3%.

(vi) the scanning coil current is to consist of the nominal linear sawtooth current and an externally generated pincushion or barrel distortion correction current waveform to result in linear H-scanning.

(vii) the H-scanning current is to feed a scanning coil whose inductance is 1·16mH and whose coil resistance is 4·1Ω. (For tests, however, an inductance of 1·16mH of negligible resistance in series, with a 22Ω resistor was used to enable current measurements to be made).

11.4.3.2 <u>Implementation</u>

As for the V-scanning generator, the H-scanning current generator consists of a pulse integrator, whose output is a voltage sawtooth of the same form as the required sawtooth current, and an output stage to convert this voltage waveform into the current sawtooth and to directly drive the H-scanning coils. There are several essential differences however:

(i) <u>In the Pulse Integrator</u>, the main difference is that a continuous sawtooth and not a staircase waveform is generated. The "pulse" feeding the pulse integrator is of some 54us duration, the active H-scanning duration.

The second difference is that no second input to the pulse integrator is required, corresponding to the 0→1μs variable correction pulse input in the V-scanning generator, as H-scanning correction is carried out by selectively delaying output video pulses.

Consequently the pulse integrator is much simpler than in the V-scanning generator.

(ii) In the Output Driver Stage, the essential difference is due to the amplitude of the scanning current being some 8-10 larger than in the V-scanning coils. Op-amps being incapable of supplying the H-scanning current amplitude (at least available and "reasonably" priced ones), a wholly different approach was required. The output stage is essentially a voltage-controlled current generator provided by transistors connected in a "common-base" configuration feeding the H-scanning coils via a 1:1 transformer, which eliminates an unwanted DC current, allows the polarity of the scanning current to be selected, and makes possible a very simple centering control.

This voltage current converter is fed from an op-amp summer to sum the scanning sawtooth voltage with externally generated H-pincushion or barrel correction waveforms; the op-amp is to have a fast "slew rate" (i.e. a fast, large-amplitude step response) since the large amplitude output scanning waveform occurs at H-scanning frequencies (i.e. 15·625KHz), whereas previously, the V-scanning frequencies were at frame frequencies of 50Hz.

(a) The Pulse Integrator

The pulse Integrator is nearly identical to that described in section 11.4.3.2(a), for the V-scanning generator. Referring to Fig.132, the input is a pulse of 56µs duration (from 8us to 64us within a 64µs H-scanning interval) fed from a R-S F/F (not shown), the timing pulses for which are obtained from the System Clock. The H-retrace pulse is of 8µs duration (from 0 to 8µs within the H-scanning interval) and feeds the discharge circuit Q_4, Q_5; complete discharge (to 0·1% of the initial amplitude) is within some 3·5→4µs.
The resultant active scanning period required in 54µs, but the additional 2µs above is to allow for damping of additional transients appearing at the output stage in the scanning sawtooth current.

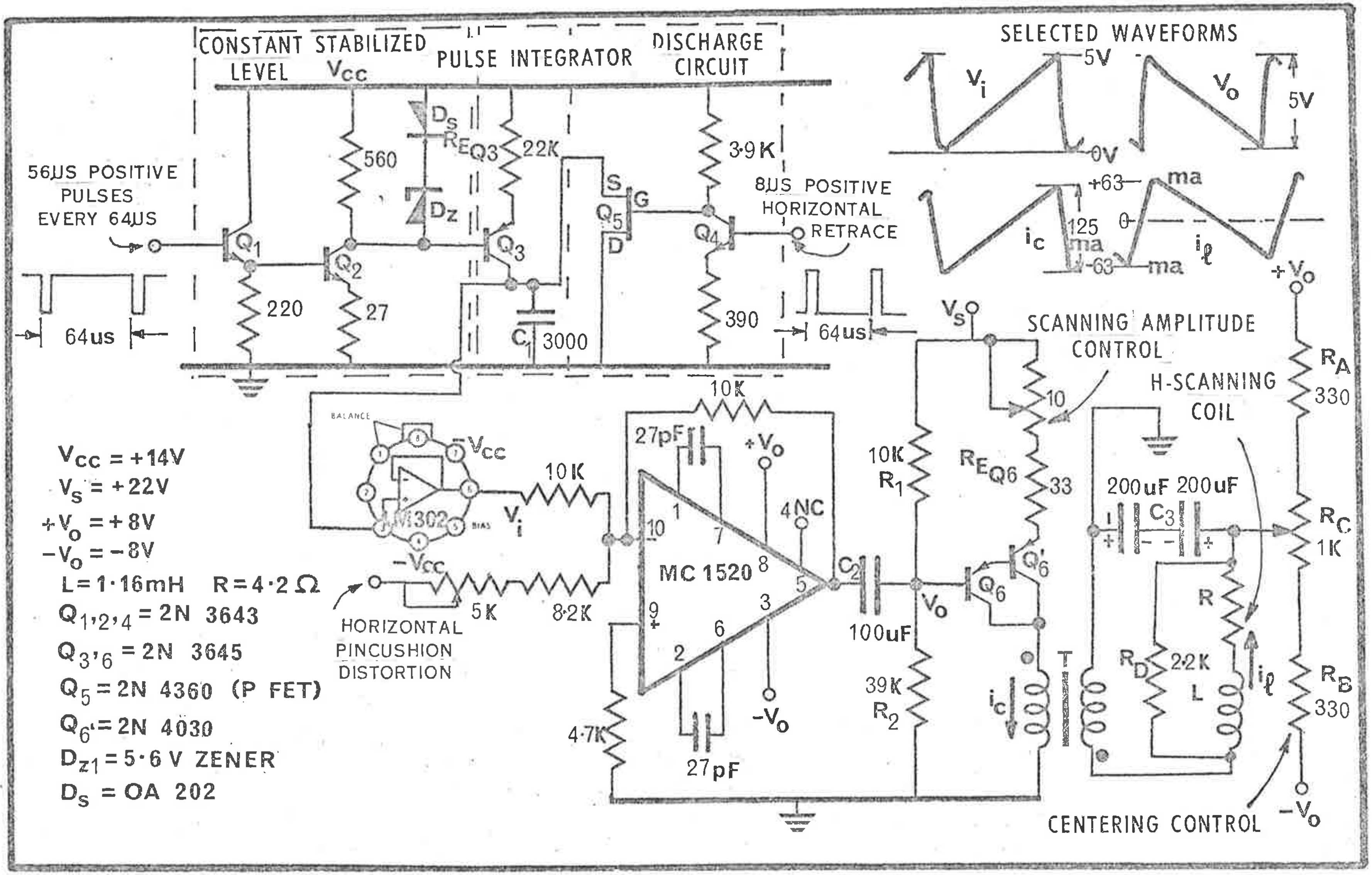
The input buffer Q_1 and the inverter Q_2 with its "constant stabilized output" is identical to that in the V-scanning generator.

The Amplitude Control Resistor R_{EQ_3} determining the sawtooth output amplitude from the integrator is evaluated using expression 11.7(a).

For ΔV_{DZ1} = 5·6V nominally,
C_1 = 3000pF,
ΔT = 56µs ,
V_{max} = 5V , the sawtooth output amplitude,

$$R_{EQ_3} = \frac{\Delta V_{DZ1} \cdot \Delta T}{C_1 \cdot V_{max}} = \frac{5{\cdot}6 . 56 . 10^{-6}}{3 . 10^{-9} . 5} = 20{\cdot}9K\Omega$$

"R_{EQ_3}" was chosen at 22K . The output sawtooth amplitude



Facing p.

Waveform Generator

was 4·6V (measured).

The output at C_1 is buffered by a LM302 unity gain, high-input impedance buffer as before.

(b) The Output Driver Stage.

A Motorola MC 1520 differential Op-amp was used in a single-ended summer configuration, to sum the sawtooth output from the pulse integrator with voltage waveforms externally generated providing the H-pincushion or barrel distortion correction (see section 9.4.3); the maximum amplitude of the latter is at most some 3-4% of the sawtooth amplitude. The 5KΩ potentiometer at this input provides the "fine" adjustment for correctly scaling the pincushion waveform amplitude with respect to the scanning sawtooth amplitude. The slew rate of the MC1520 is some 5-6V/us, which is an adequately fast response, as during H-retrace, the slope of the discharge corresponds to some 2-3V/us.

The summed "modified" voltage sawtooth is AC fed to a biased "common-base" connected transistor, Q_6-Q_6' similar to that used in the Pulse Integrator. In this connection, the output, at the collector, is essentially a near-perfect current source, controlled by the voltage at its base-input, due to its high output impedance (of the order of $10^7\Omega$). Since the effective impedance as seen by the collector, is due to the scanning coil of L = 1·16mH, then at a frequency corresponding to say the 10th harmonic of the scanning sawtooth, the load impedance is some 1KΩ ($10.2\pi.f_H.L$, where $f_H = 15{\cdot}625$KHz), which is insignificant with the output impedance of the transistor. Hence the output current is independent of the load.

The 10th harmonic is chosen, since when considering fidelity in reproducing a sawtooth, harmonics beyond the 10th play an insignificant part.

A Darlington connection is used for $Q_6 - Q_{6'}$, to minimize the base current drain (and hence its variation) as $Q_{6'}$ has a relatively low "h_{fe}" (≈ 30). For the particular application, the transistors are chosen for a high "h_{fe}", an high "f_T" (say $\geqslant$ 100MHz), a high V_{ECO} (> -50-60V). $Q_{6'}$ in particular is to have a high output current capability ($>$ 200mA) and a medium to high-power dissipation capability ($>$ 2 W); a heat sink is required to dissipate some 1·5W.

The resultant collector current is transformer-coupled to the H-scanning coils. For the input sawtooth "V_{max}" of some 5V amplitude, to appear across the emitter resistor, $R_{EQ6'}$, and generate a sawtooth emitter current and hence a sawtooth collector current, the compound transistor $Q_6 - Q_{6'}$ must be biased by the biasing resistors R_1, R_2, such that the DC voltage at the base satisfies

$$\frac{V_{max}}{2} < V_S - V_{EQ6'}$$
$$< (V_S - (V_B + V_{BEQ6} + V_{BEQ6'}) \quad . \quad . \quad . \quad 11.14$$

where "$V_{EQ6'}$" is the quiescent voltage of $Q_{6'}$ emitter,
"V_S" is the supply voltage,
"V_B" is the quiescent base voltage of Q_6,
"V_{BEQ6}", "$V_{BEQ6'}$" are the base-emitter voltage drops during conduction.

For a V_S = 22V (the choice of this value is explained below) and "$V_{BEQ6} \approx V_{BEQ6'} \approx 0{\cdot}7$ V and "$V_o \approx 5$V,

$$V_B < 18{\cdot}1 \text{ V}.$$

Choosing R_1 = 10KΩ and R_2 = 39KΩ makes $V_B \approx 17{\cdot}5$V nominally, which should be chosen close to its maximum value to minimize the power dissipation of the transistor Q_6!, and also to minimize the reduction of the effective inductance of the primary winding of the coupling transformer T, which occurs when a DC current flows through it (346); this DC current is of course

$$I_{DC} = \frac{V_S - V_{EQ6}}{R_{EQ6}}$$

The A-C emitter current, and hence the collector current (as the current gain of the Darlington connected transistor is of the order of 10^3) flowing through the primary of the transformer is given by,

$$i_{Ep-p} = i_{Cp-p} = \frac{V_{max}}{R_{EQ_6}} \quad \ldots\ldots\ldots\ldots \quad 11.15$$

and since a 1:1 near ideal transformer is used, the secondary coil current is equal to the primary coil current; hence

$$i_{coil} = \frac{V_{max}}{R_{EQ6}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 11.15($$

For a nominal coil current amplitude of 125mA and a nominal "V_{max}" of 5V,

$$R_{EQ6} = \frac{V_{max}}{i_{coil}} = \frac{5}{125.10^{-3}} = 40\Omega. \quad \ldots\ldots \quad 11.15($$

For a ±15% amplitude variation or thereabouts, "R_{EQ6}" was selected at 33Ω in series with a 10Ω potentiometer, providing the external controllable amplitude variation.

The 1:1 coupling transformer is necessary to eliminate the DC quiescent collector current and enables the correct scanning coil current polarity to be selected. It is required to be a near-ideal transformer for the frequencies and the inductive load in question. The magnetising inductance and primary coil winding inductance "L_p" are to be as high as possible with respect to the scanning coil inductance L_{coil} = 1·16mH. A 35mm. Ferroxcube transformer pot-core was used (346) with 420 turns of 34swg wire. Nominally $L_p = L_s = 1\cdot5$H (the primary and secondary coil inductance respectively), but with a DC current of some 80mA flowing through the primary coil, "L_p" was effectively reduced to 0·3 - 0·4H (346). The leakage inductance "L_L" is of the order of 1·2mH. Hence the inductive load reflected into the primary and seen by the collector of Q_6', for a 1:1 transformer, is

$$L_{Load} \approx L_{coil} + 2L_L$$
$$\approx 3\cdot6\text{mH}$$

when appropriate values are substituted.

In the presence of a finite primary coil resistance "R_p", and a reflected secondary coil resistance, "R_S" and scanning coil resistance "R_{coil}", and with an AC collector current "i_{p-p}", the voltage across the primary coil (see Fig.133(a)) is given by,

$$V_{Cpeak} = L_{Load} \cdot \frac{di}{dt} + R_{Load} \cdot \frac{i(t)}{2} + V_{DC} \quad ..11.16$$

$$= L_{Load} \cdot \frac{\dot{i}_{p-p}}{\Delta T_s} + R_{Load} \cdot \frac{\dot{i}_{p-p}}{2} + V_{DC} \quad ...11.16(a)$$

where $V_{DC} = \dfrac{V_S - V_{EQ_3}}{R_{EQ_3}} \cdot R_p$

and "L_{Load}" $\approx$ 3·6mH, the reflected inductance into primary coil plus "L_p",

"R_{LOAD}" = 40Ω, the reflected resistance into the primary coil plus "R_p",

"R_p" = 15Ω, the primary coil resistance,

"V_S" = 22V, the supply rail voltage,

"i_{p-p}" = 125mA, the AC scanning current amplitude,

"ΔT_S" = 54μs, the scanning current period,

"V_{EQ_3}" = 19 V, the Q_6 emitter quiescent voltage,

"R_{EQ_3}" = 40Ω, the Q_6 emitter resistance, Evaluating for the above values gives

$$V_{cpeak} \approx 12V.$$

Also at "V_{cpeak}"

$$V_S \geqslant V_{c\ peak} + V_{CE} + V_{max} \quad \ldots\ldots\ 11.17$$

$$\text{i.e. } V_S > 17 + V_{CE} \quad \ldots\ldots\ldots\ldots\ 11.17(a)$$

A "V_{CE}" greater than some 2-3V is required so that Q_6-$Q_{6'}$ does not saturate; $V_S = 22V$ was selected (to allow for peak currents of up to 145mA (125mA + 15%)).

Now across an ideal inductance (i.e. resistance-less) there is no mett avarage voltage during a periodic waveform; thus from the ideal voltage - time waveforms across the primary coil (neglecting finite rise times etc), and referring to Fig. 133(a),

$$V_R \cdot \Delta T_R = V_C \cdot \Delta T_S \quad \ldots\ldots\ldots\ 11.18$$

where

"ΔT_R" is the H-retrace time ($\approx$ 8-10µs)
"ΔT_S" is the H-scanning period ($\simeq$ 54µs)
"V_C" is the voltage across the primary coil during "ΔT_S".
"V_R" is the voltage across the primary coil during "ΔT_R".

Thus the voltage-time products during each part of the cycle are equal ($A_1 = A_2$ on Fig.133(a)) and this is true whether winding resistances are included or not.

Including the transformer winding resistances and "R_{coil}" and neglecting "V_{DC}" (as it is of the order of 1V) and neglecting the finite response of the transistors, and using expression 11.6(a), the time allowed for retrace "ΔT_R" is then given by,

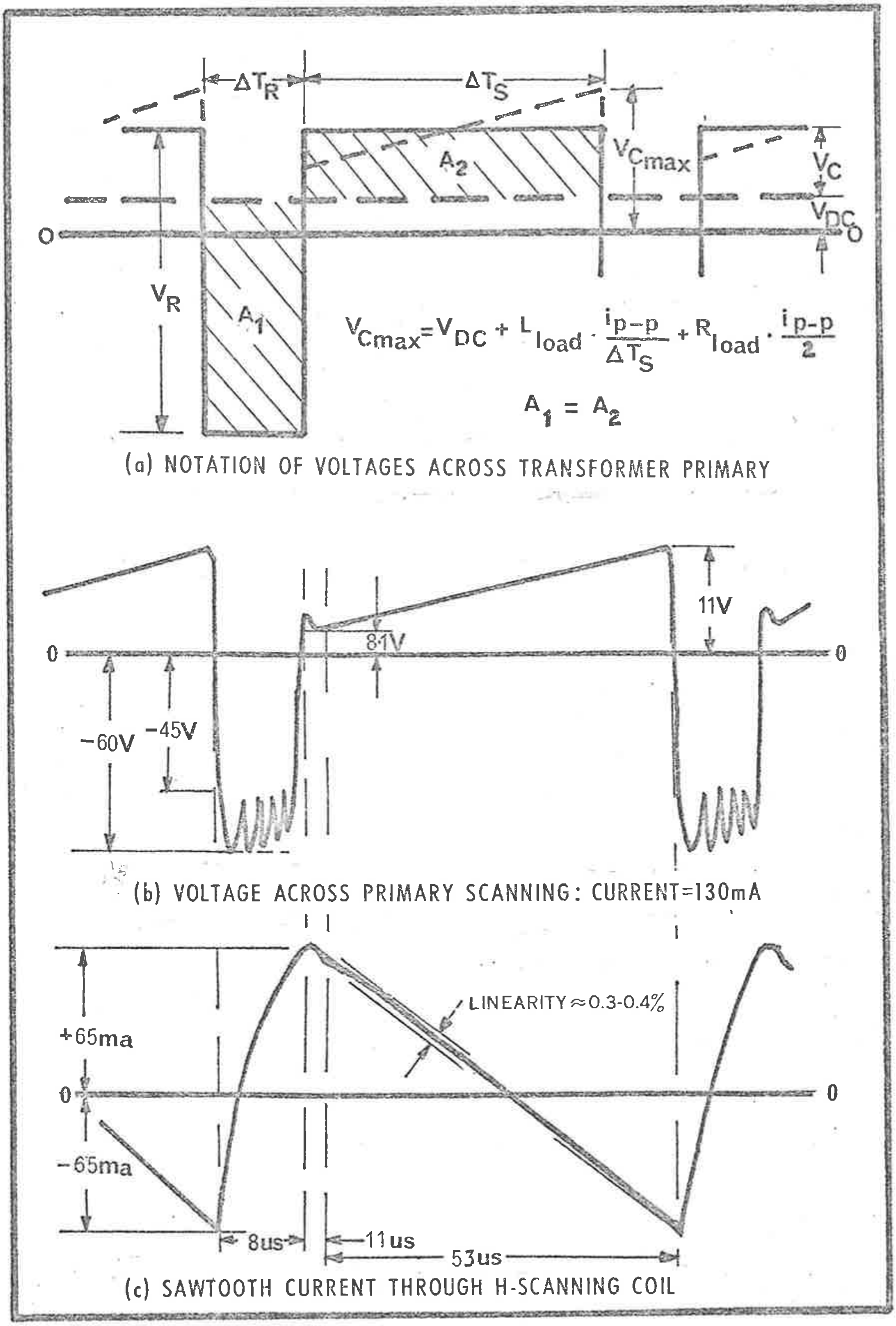


Figure 133. Performance and Waveforms of the H-Scanning Waveform Generator.

$$\Delta T_R = \frac{\Delta T_S}{V_R} \cdot V_C \quad \ldots\ldots\ldots\ldots .11.18(a)$$

$$= \frac{\Delta T_S}{V_R} \cdot L_{LOAD} \cdot \frac{i_{p-p}}{\Delta T_S} \quad \ldots\ldots\ldots .11.18(b)$$

"V_R" is approximately constant during "ΔT_R". During "ΔT_R", V_{EQ_3} is nearly equal to "V_S", Q_6 being near cutoff, while the voltage at the collector of Q_6 is "V_R".

As $V_S \approx V_{CEQ_6} + V_R$ 11.19

thence $V_R = V_S - V_{CEQ_6}$ . . . . .11.19(a)

Hence "V_R" is dependent on (and limited by) "V_{CEQ_6}"

To minimize the retrace time "ΔT_R" for a given scanning coil and current amplitude, "V_R" need be maximized; hence from the above expression "V_{CE}" should be maximized. The value of "V_{CEO}" thus set the minimum vlaue of "ΔT_R" possible; the available transistors (2N4030) satisfying the other requirements enumerated previously, have a "V_{CEO}" of around - 60V. With $V_S = 22V$, "$V_{Rmax.}$" is some -40V. Substituting this value in expression 11.18(b) and using the nominal values of "L_{LOAD}" and "i_{p-p}",

$$\Delta T_R = \frac{3 \cdot 6.10^{-3}.\ 125.10^{-3}}{40} \approx 11 \cdot 3\mu s$$

The voltage across the primary is shown in Fig. 133(b) (for a current amplitude of 130mA). Oscillations, due to the coil inductance and capacitance of the windings, and the switching negative current-voltage characteristics near "V_{CEO}" are evident during "ΔT_R", but the expected value of $V_R \approx -40V$ (experimentally $\approx$ -45) is clearly seen.

The simple scanning current "centering circuit" consisting of "R_A","R_B"and "R_C", inserts a DC current of some ±15% of the nominal current amplitude (i.e. a ± 19mA DC current). The capacitor "C_3" provides the low impedance AC return path for the sawtooth scanning current; hence no interference between the centering circuit and the sawtooth current occurs.

For $|+V_o| = |-V_o|$ and for $R_A = R_B$ it can be easily shown that

$$\pm i_c = \frac{\pm |V_o| . R_C}{R_{Coil}(R_A + R_B + R_C) + R_A(R_B + R_C)} \quad . \; 11.20$$

$$\approx \frac{\pm |V_o| . R_C}{R_A(R_B + R_C)}, \text{as } R_{Load} \ll R_A \quad . \; . \; 11.20(a)$$

For the values shown of $R_A = R_B = 330\Omega$,

$|+V_o| = |-V_o| = 8V$ and $R_C = 1000\Omega$,

$\pm i_c \approx \pm$ 18mA, the required variation.

A 2·2KΩ damping resistor, "R_D" is required across the coil, to damp the oscillations occuring during H-retrace and at the beginning of the scanning interval.

The output scanning current, measured at 130mA, is shown in Fig.133(c). It was measured by the voltage across an inserted resistance of 22Ω in series with a 1·16mH inductance representing the required H-scanning coil. The voltage across this series L-R was of the same form as the voltage across the primary coil (Fig.133(b)) but of reduced amplitude (a smaller effective L and R acting).

The overall scanning waveform linearity was some 0·3-0·4%. The performance of the H-scanning current generator is tabulated in Table 6.

11.5. FUNCTION CIRCUIT BLOCKS

11.5.1 General Remarks

Within this feasability study, particularly in Chapters 7,8,9, only block diagrams of the proposed hardware implementation were given, with many of the individual functions performed by blocks labelled "Pulse Integrator" (P.I.), "Voltage Controlled Monostable" (VCM) and so on. The circuits performing these functions are given below but are described only briefly since some have already been described in section 11.4 above, as they form part of the H- and V- Scanning Waveform Generators; while others, such as the Voltage Controlled Monostable and Voltage Controlled Astable (VCA) etc, are more fully described in Appendix 13, in short design notes submitted or accepted for publication.

The common feature of all of these circuits is simplicity, low cost and stability of output parameters, and independence or near-independence of temperature and voltage-supply variations. Since these circuits control scanning current amplitude, scanning current linearity and to some extent timing, and hence control the repeatability of display location coordinates, output parameter stability is of paramount importance. Minimizing or eliminating voltage rail variations or its effects is simple enough by using I/C voltage regulators, but variations in ambient temperature can cause significant variations in output parameters. Temperature stabilization is briefly treated in section 11.6.3; being individually tailored to each circuit, it is not shown in most of the circuits.

Several of the function blocks, such as the VCA, VCM and "Leading" or "Lagging Pulse Edge Indicators"

(LEI) are built around a Fairchild RTL μL914 Dual-Input NOR Gate, to ensure economy and signal level and voltage-rail compatability with the gating and control logic. These circuits are shown in Figs. 135(a) - (d). While very successful, the performance, particularly of the VCA, was limited at high speeds (1-2MHz) as RTL has certain inherent speed limitations (318). Discrete component versions were built, which improved the performance but TTL logic, having a speed improvement of at least 5-10 over RTL, could probably prove even better. At the time, cost precluded this line of further experimentation.

Squarers and multipliers, required to generate the pincushion or barrel distortion correction terms, and dynamic focussing correction (see section 9.3.5, 9.3.6, 9.4) are not described as it is felt that the approach suggested in section 9.5, which suggests that only two squarers and two multipliers (or effectively four multipliers (Fig.127)) are required for the complete CRT and Vidicon camera, warrants the use of commercially available I/C multipliers as these are becoming less expensive ($15- 20).

Function blocks such as "Adders" and "Summers" are implemented with commercially available I/C Op-amps; the techniques for using these are well known.

11.5.2 Constant Stabilized Level Output Circuit (CSL)

This circuit, shown separately in Fig.134(a) has been already described in section 11.4.3.2. The input may be either continuous or pulse input; the CSL output supplies to a Pulse Integrator a constant level inverted signal which is temperature and voltage supply-variation independent. This is due to the clamping effect of the Zener diode in series with a Si diode at its output. The output pulse amplitude is some 6V. Temperature independence is achieved simultaneously, as at this voltage the temperature coefficient of the Zener voltage is near zero.

11.5.3. Pulse Integrator (P.I.

This circuit, shown separately in Fig.134(b), has been described in section 11.4.3.2. Depending on whether its input from the CSL is a pulse input or a continuous input, either a staircase or a sawtooth of constant slope is generated at its output. The step height or the slope of the sawtooth is varied by varying the value of the emitter resistor "R_E" or the charging capacitor "C".

The LM 302 high-input impedance buffer is necessary to eliminate discharge of the capacitor "C" by successive circuit stages at the P.I. output.

P.I's, in addition to generating H- or V-scanning waveforms, are used to generate the control voltages for Voltage Controlled Monostables, whose output pulse duration define the Horizontal Distortion Regions in the Vidicon Camera (see Fig.110) and the CRT display (see Fig. 116) and to generate the "Correcting Ramp Voltages" in the CRT H-distortion Correction (Fig.117).

11.5.4 Discharge Circuit (D)

This circuit although always used in conjunction with a P.I., is shown separately in Fig.134(C); it has been described previously in section 11.4.3.2.

During the active scanning period, the FET is "off" and any leakage currents charging the capacitor "C" are of the order of a nA and hence can be neglected. The source-to-drain resistance during the discharge interval when the FET is "on" is of the order of 300Ω. The value of "C" is chosen to allow the discharge time constant "T_C" to be less than 10% of the time allowed for discharge (the H- or V- retrace interval). Since some $9.T_C$'s are

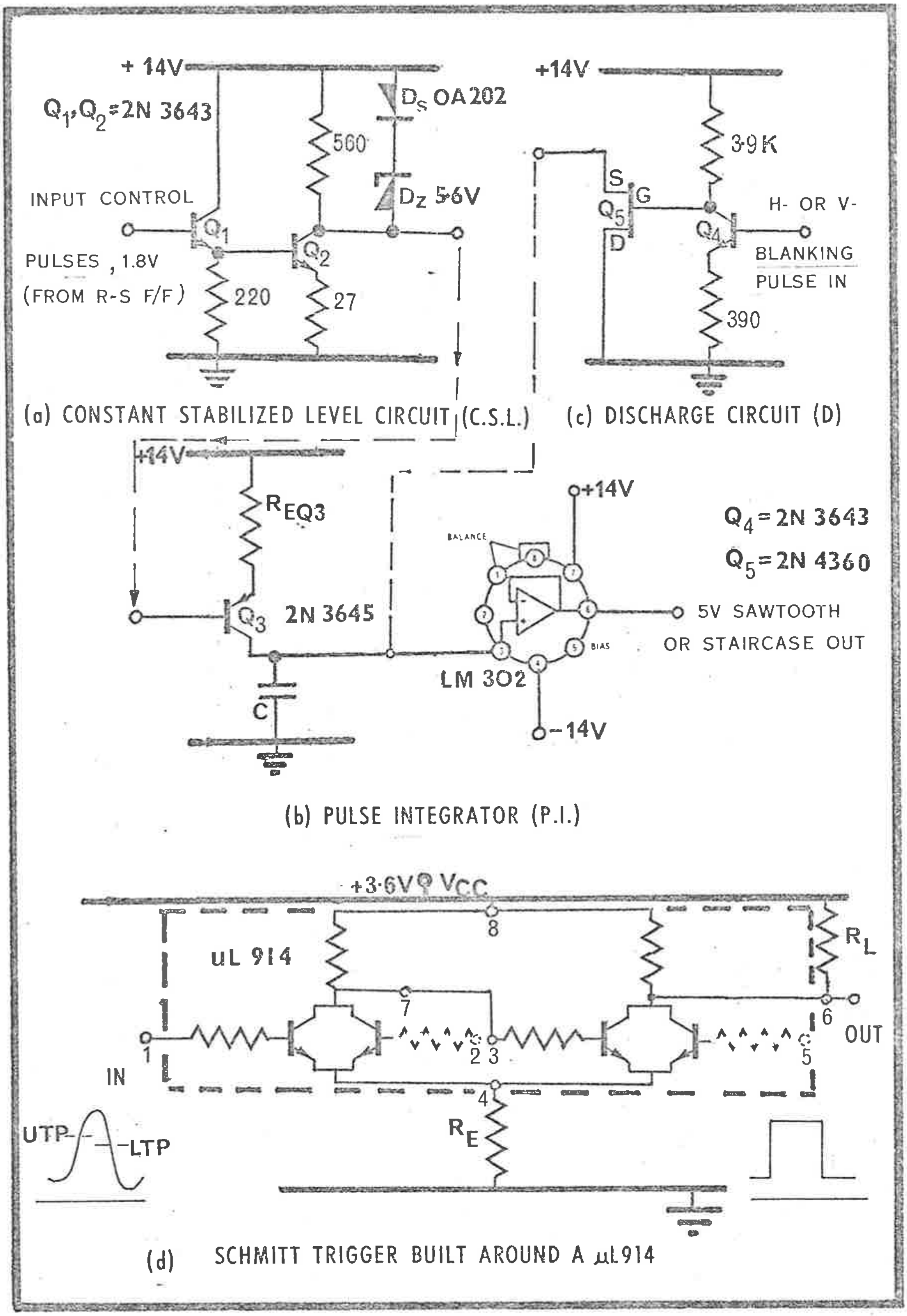


Figure 134. Circuits of Standard Function Blocks .

required to discharge a capacitor to 0·01% of its initial value, the capacitor prior to a new integration interval is always fully discharged.

11.5.5. Voltage Controlled Monostable (VCM)

The theory, description, and performance of a VCM using the RTL μL 914 Dual-Input NOR Gate as the building block is given in Appendix A.13.4.1, whilst a discrete component version is also fully described in Appendix A.13.5; both are reprints accepted for publication. The μL 914 version is shown in Fig. 135(a).
The VCM is voltage -rail and output-level compatable with the low level (3·6V) logic used throughout.

The performance curves of the VCM, particularly of the discrete component version (p. A.228), show a linear range (better than 1% linearity) of about 8:1 of the output pulse duration. In section 8.3.3.3, in discussing the accuracy required of the "control voltage/output pulse duration" relationship, it is stated that the order of accuracy required is typically of the order of 1-2%. Since the pulse durations define H-distortion regions for scanned areas with only remanent distortions (as pin-cushion and scanning waveform non-linearities have been, in the main, eliminated), the distortions are expected to change gradually, and over the height of the scanned area, a given distortion region (say the 0·25% - 0·5% Distortion Region) is not expected to have more than say a 3→5:1 width variation, as can be seen in Fig.104(b), which is not compensated for H-pincushion distortion. The above performance figures satisfactorily meet these requirments.

11.5.6 Voltage Controlled Astable (VCA)

The theory, description and performance of a VCA using the RTL μL914 as a building block is given in

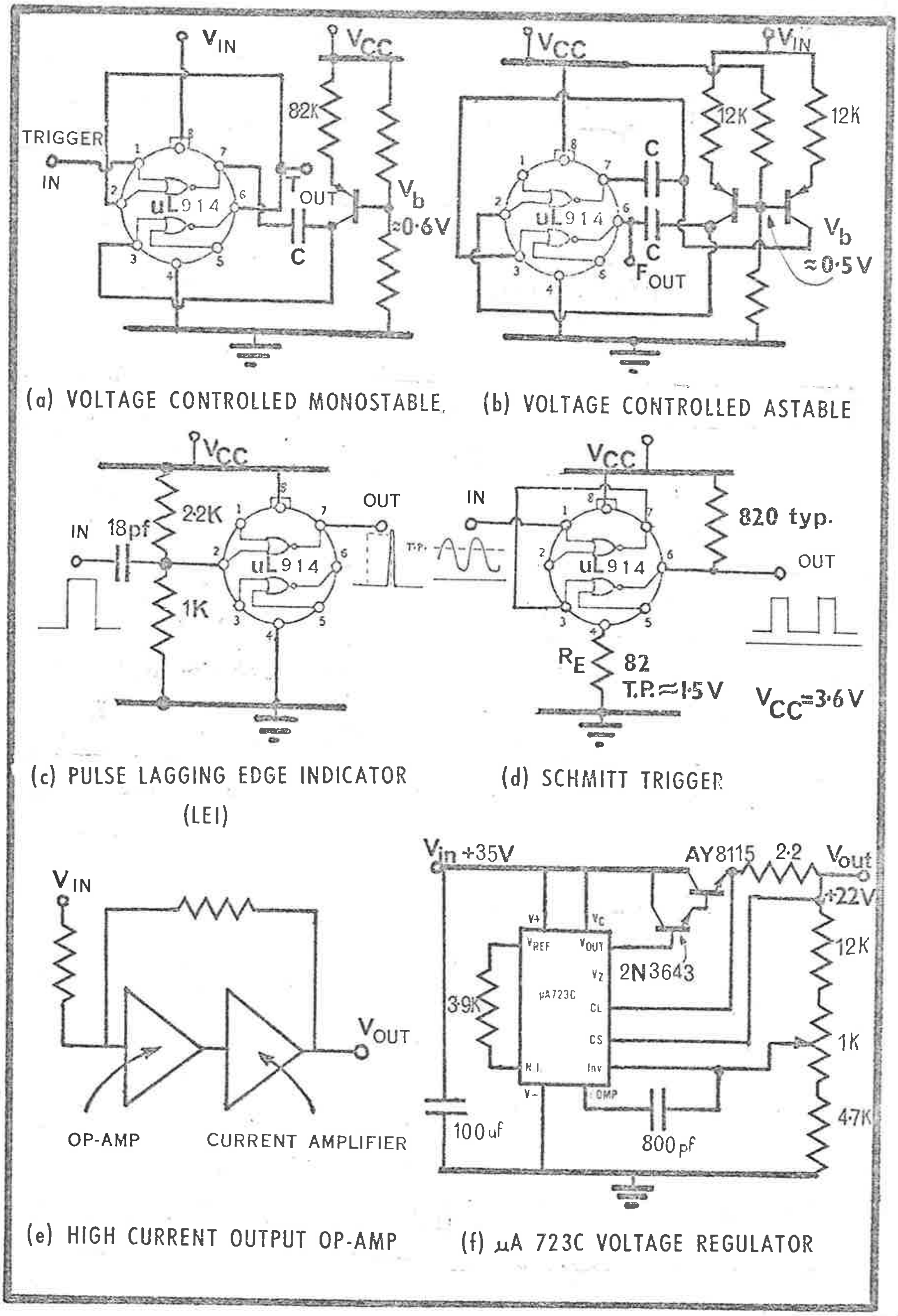


Figure 135. Required Circuit Functions Built Around the uL 914 and Other Circuits.

Appendix A.13.4.1; it is shown in Fig.135(b). The VCA is used in the repositioning or delaying of video input pulses for obtaining a linear CRT display, by deriving from the VCA, output frequency-variable shift pulses to feed a shift register (see Fig.119).

In section 8.4.3.2 the required frequency variation is shown to be of the order of 1·15:1. The performance curve of the VCA shown on p. A.215, show a linear (better than 1%) control voltage frequency relationship of over 2:1, indicating its suitability. Being a relaxation oscillator, the VCA can be reset by external trigger pulses (see the trigger pulse input in the Astable in the Vertical Bar Generator (Fig.129)). As discussed in section 8.4.3.8, such trigger or "reset" pulses are required in the VCA in the above application.

11.5.7 Leading and Lagging Pulse Edge Indicator (LEI)

This is alternatively called a "Positive (or Negative) Slope Pulse Edge Indicator". It is described more fully in Appendix A.13.4.2 and is shown in Fig.135(c).

The LEI is required to precisely locate the start and completion of pulse durations such as the derivations of a shift pulse from the leading edge of the VCA pulse output or to derive a trigger pulse for a VCM by detecting the lagging edge of the previous VCM output pulse (e.g. as in Fig.116).

The LEI is built around a μL914 and produces a 3-4V output pulse, of less than 50ns duration(the measurement being limited by the CRO used of 25MHz bandwidth), and a propagation delay between the detected pulse edge and the output, of the order of 20ns. This is precise enough for the purpose of indicating distortion regions, since a H-coordinate of a display location is of some 0·162μs duration.

11.5.8 Schmitt Trigger or "Current" Level Detector

A simple level detector, suitable to serve as the "i_{L1}" and "i_{L2}" Current Level Detectors at the Vidicon Camera Output to discriminate between required and unwanted signals, can be implemented by a simple Schmitt Trigger circuit build around a µL914 which is shown in detail in Fig.134(d); the Schematic is shown in Fig.135(d). The output of one of the two-input inverters is connected to the input of the other inverter, and two external resistors are added. "R_L" controls the voltage-level separation between the "Upper Trip Point" (UTP) and the "Lower Trip Point" (LTP) (i.e. the voltage levels at which the Schmitt Trigger is enabled "on" and "off" respectively). "R_E" determines the level of the UTP.

It is easily shown that:

$$UTP\ (\text{"on"})(\text{Volts}) \approx \frac{R_E}{R_L /\!/ R_{C2} + R_E} \cdot V_{CC} + V_{BEQ_1\ \text{cut in}} \quad \ldots\ldots 11.21$$

and

$$LTP\ (\text{"off"})(\text{Volts}) \approx \frac{R_E}{R_{C1} + R_E} \cdot V_{CC} + V_{BEQ_1\ \text{cut off}} \quad \ldots\ldots 11.22$$

As nominally $R_{C1} \approx R_{C2}$, and $V_{BE\ \text{cut in}} \approx V_{BE\ \text{cut off}}$

then UTP $\geqslant$ LTP.

"V_{CC}" is nominally 3·6V; "$V_{BE\ \text{cut in}}$" is of the order of 0·8V, and if R_E=0, "$V_{BE\ \text{cut in}}$" sets the minimum UTP.

The Schmitt Trigger above has been successively tested for frequencies up to 16MHz. Its output amplitude at around 3·6V need be attenuated by the simple potential divider, to directly drive other RTL Fairchild logic.

11.5.9 Current Amplifiers

In the sections dealing with Pincushion or Barrel Distortion Correction in the Vidicon and the CRT (see, for example, Fig.127), function blocks labelled "Current Amplifiers" are shown, primarily to drive focussing or deflection coils, with signals of up to 500mA amplitude being required.

A current amplifier capable of delivering up to several hundreds of mAs has been described in section 11.4.3.2, being the transistor Q_6, $Q_{6'}$ in Fig.132, connected in common-base configuration.

Alternatively, current amplifiers formed from either matched discrete PNP-NPN transistors, or obtainable in an IC form, and joined as a complimentary pair working in Class B operation, can be used. They can be used either directly as a series amplifier, or can be inserted within the feedback loop of the "R_F" resistor of an Op-amp (as the V-scanning coils in Fig.130) to effectively result in a "High Output Current Op-amp." This is shown in Fig.135(e).

11.5.10 Voltage Supplies

Several voltage supplies are required namely:

(i) "3·6V" for the RTL logic (AND-, OR-gates, R-S F/Fs etc).

(ii) "+ 14V" for the recommended Vidicon Camera circuits voltage supply rail (e.g the video amplifier), and for the positive supply of the op-amps, and the Centering Circuit of the V-scanning Waveform Generator.

(iii) "-14V" for the negative supply of the Op-amps and the centering circuit of the V-scanning Waveform Generator.

(iv) "+ 8V" and "-8V" for the MC 1520 H-scanning Waveform op-amp Summer and the corresponding Centering Circuit.

(v) "+22V" for the H-scanning Current Amplifier.

The voltage supplies need be well regulated and be temperature insensitive to ensure overall display repeatability.
I/C Voltage Regulators, (Fairchild uA 723C, costing around $4.50 each) were used extensively. The measured load regulation was better than 0.05% of the output voltage, while the quoted temperature coefficient of the output voltage is an insignificant 0·003% / °C ambient. Use of the µA 723C is well documented in the commercial literature (347); a typical circuit configuration is shown in Fig. 135(f).

A simple power supply provided the primary DC supply of "+35V" and "-35V", from the AC mains, which where then fed into the µA 723C and external series pass power transistors, to give the above voltages. The "-35V" supply also supplied the voltage rail to simple pulse amplifiers to generate adequate amplitude pulse signals to provide the H- and V- sync. pulses to directly time the H- and V- scanning circuits in the CRT during tests (see Fig. A. 12.2).

A separate 3·6V, 3 Amp supply for the RTL logic (variable externally by ±10% about 3·6V), was also designed from discrete components; of conventional design (full-wave rectifier bridge with a series-pass transistor voltage regulator and a pre-regulator), it was temperature stabilized by diodes, while load regulation was improved by "common earth wire" feedback, resulting in some 0·1% full load regulation.

11.6 TIMING, AND CONTROL

11.6.1 Requirements and Design

The Timing and Control System in "VIDIOGRAPHIC" has three main functions:

(i) To provide the control timing signals for the V- and H-scanning waveforms in the Vidicon Camera and CRT Display.

(ii) To provide certain control timing signals for the H- and V- Correction Circuits for the Vidicon Camera and CRT Display.

(iii) To provide the H- and V- coordinates (or x- and y- display coordinates) of the graphics information display locations for CPU I/O requirements, whether CPU-requested or user-specified.

11.6.1.1 Fundamental Timing Signals

The basic timing interval in VIDIOGRAPHIC is $\Delta t \approx 0{\cdot}162\mu s$, where "$\Delta t$" corresponds to the time required for the scanning electron beam in the Vidicon or the CRT to travel between two adjacent display locations; this value of "Δt" is for a 200 x 200 addressable grid display, implemented on a 625-line, 50Hz. TV-system. (For other standards or different number of display grid elements "Δt" will differ; its value is discussed in section 7.5.4). However, to enable H-correction to be implemented, "shift" pulses are required to feed H-correction Shift Registers (see section 8.3), which require a period of $\frac{\Delta t}{2} \approx 0{\cdot}081\mu s$; thus a more "basic" timing source is required, of a frequency of $\frac{2}{\Delta t} \approx 12{\cdot}346MHz$. A crystal-controlled oscillator at this frequency is required.

The other basic timing signals required are the H-scanning line frequency of nominally 15·625KHz (a H-line duration of 64us), and the V-field frequency of nominally

50Hz (a V-field duration of 20ms).

If the basic frequency of 12·346MHz is divided by 790 (÷2÷5÷79), then a frequency of 15·627 KHz results, nearly equal to the required H-line frequency (giving a H-line duration of 64·008us).
Further dividing this resulting H-line frequency by 312 (÷3÷8÷13) gives a V-frame frequency of 50·087Hz (corresponding to a frame interval of 19·965ms).
The above frequency division is achieved quite simply by feeding in a suitable waveform of the basic 12·346MHz frequency into a mod(790) digital ripple-counter (the "H-Counter") to obtain the H-line frequency and thence into a mod(312) counter(the "V-Counter"). A suitable input waveform to feed the counter may be obtained by feeding the essentially sinusoid crystal oscillator waveshape into a Schmitt Trigger whose output then is a square-wave of the same frequency.

The Counters or Frequency Dividers are, in our case, synthesized from R-S Flip-Flops (Fairchild I/C µL 923 RTL) which essentially are "÷ 2" elements; when connected serially and when certain of their outputs are fed back to previous F/F stages, ÷3, ÷5, ÷79 etc dividers are obtained. Connecting these in series in the above combinations, the H- and V- frequencies are obtained from the "$\frac{\Delta t}{2}$" crystal oscillator. The methods of synthesizing these variable length counters are well known and need not be described here.

Each of the F/Fs within each counter stage can at any instant be in one of two states ("true" or "false" or simply "1" or "0"), and for any number of pulses input into the H-Counter, say, from 0 to 790, a unique combination of F/Fs states exists, which may be read off a "state table", which is a 1:1 correspondence between the number of input pulses and the counter states, (again these techniques are well known). Each such "state number" can be decoded and associated with the number of input pulses fed into the counter after some initial counter state Since the interval of "Δt" (or two "$\frac{\Delta t}{2}$" pulse counts) is associated with the scanning beam travel between adjacent display locations, the position of the beam, and thus the position of a displayed point, can be given by the state of the H-Counter. Similarly the state of the V-Counter indicates the number of raster-lines scanned and hence the position of the beam is the vertical direction.

Thus the H- and V- Counters in addition to providing the H- and V- timing signals from the fundamental timing source can, by suitable decoding, directly generate the H- and V- (or "x" and "y") display coordinates .

11.6.1.2 Other Timing Signals

Figs.106, 108 and 115 show the required timing and control signals required to define the various time intervals within a H-line or V-frame during which correction signals or active display signals occur.

Specifically "T_{HS}", the H-Blanking Start Pulse (and H-line Start Pulse) and "T_{SS}", the V-Scan Start Pulse (see Fig.106) are derived by detecting the lagging edge of the "0" output from the final stage of the H-Counter and V-Counter, respectively, by a pulse Lagging Edge Indicator (LEI). "T_{HS}" corresponds to 0us of the 64µs H-line duration, and "T_{SS}" corresponds to 0ms of the 20ms V-field duration.

To obtain a timing control pulse within a H-line or V-field interval, for example, "T_{HE}", the "H-Blanking End Pulse", occuring 10µs after "T_{HS}", the following method is used:

As

$$10\mu s \approx 123 . \frac{\Delta t}{2} \approx 123 . 0{\cdot}081\mu s \approx 9{\cdot}963us,$$

then the 123-rd pulse after the pulse corresponding to

"T_{HS}" is required to indicate "T_{HE}". From the mod(790) H-Counter consisting of 11 F/F stages (in the ÷ 2 ÷ 5 ÷ 79 version), the state corresponding to a count of "123" is fed into an 11-input AND-gate and the lagging edge of this resultant pulse is detected by an LEI.

Similarly any other timing control signals within an H-line can be obtained by obtaining the appropriate pulse corresponding to the required time interval after "T_{HS}". Similarly from the V-Counter states, "T_{SE}", the V-blanking start pulse can be obtained, or any other signals such as the V-active display boundaries occuring at t = 3ms and t = 15ms.

These timing signals, such as "T_{HS}" and "T_{HE}" are fed into the "S" and "R" inputs of a R-S F/F, whose "1" output thus gives the H-blanking interval required for the V-staircase Pulse Integrator (see Fig.130).

Other timing signals, derived in a similar manner to the above, feed other R-S F/Fs to determine other timing intervals, which are then utilized in the manner described in the appropriate sections in chapter 8.

11.6.1.3 Display Location Coordinate Generation

Display location coordinates are only required during CPU Input/Output operations or when display data is specified numerically by the user. The active display area, in the H-direction, is located between t = 20·8µs and t = 53·2µs from t = T_{HS}, the start of each H-line; this corresponds to a $\frac{"\Delta t"}{2}$ pulse count of 257 and 657 respectively. Similarly for the V-coordinate, the active display area occurs between t = 3·0ms and t = 15·8ms, corresponding to a vertical pulse count of 47 and 247 respectively. Thus the H- and V- (or "x" and "y") coordinates of any display location lie within the H-counter pulse count of between 257 to 657 and within the V-counter pulse count of between 47 and 247.

Two digital decoders, one for the H-Counter, the other for the V-Counter, based on the state table of each respective counter, are required to associate each display location as represented by the above 11-bit representation for the H-coordinate, and the 9-bit representation for the V-coordinate, with the two 8-bit representations used in the CPU (8 bits as there are 200 locations per H and V-coordinate). A suggested decoder, would consist, say for the H-coordinate, of a simple mod(200) counter, enabled on by the 257th "$\frac{\Delta t}{2}$" pulse, to which is fed every alternate $\frac{\Delta t}{2}$ pulse; after the 257th pulse the counter is inhibited by the 657-th "$\frac{\Delta t}{2}$" pulse. The output of this decoding counter is the H-coordinate of any pulse in straight binary form, with the "zero" origin taken at the left-hand boundary of the active display area. A similar decoding counter is necessary for the V-coordinate. If these decoding counters are "up-down" counters, where each input pulse either increments or decrements the original stored number in the counter, then choice of display-area origin is achieved, with the coordinate of the upper left corner of the display (beginning of the H- and V-scan) corresponding to the initial number stored in the H- and V up-down decoding counters.

11.6.1.4 CPU I/O

When data from the CPU is to be displayed, the display data need be ordered first by magnitude of the Vertical coordinate and then, for each Vertical coordinate, the H-coordinates are ordered again by magnitude. Each time there is a match between the input data display coordinate and the appropriate H-and V- Decoding Counters, an input pulse is fed into the Vidicon-CRT electronic loop (see Fig.71). Similarly when some display data is selected by the user for further processing, and this is detected by the "i_{L2}" Current Level Detector (see section 4.3.6 and Fig.71), the H- and V- Decoding Counter states are input into the CPU at instants of "i_{L2}" detection.

11.6.1.5 General Remarks

No greater detail than this need be mentioned here, as the techniques for implementing such decoding counters and functions are not new and are covered in most textbooks. The point to remember is that the H- and V- Counters "keep track" of the scanning electron beam by the elapsed time interval from a given time instant, the position of the beam being known at that instant; this "instant" is taken at the beginning of the H-line or V-field, or else at the upper left hand corner of the active display area. Since scanning of the beam after correction is linear, this elapsed time interval is a measure of the distance from the initial beam position, and hence the counters "keep track" of the coordinates of the electron beam at any instant. The H- and V- Counters thus give the scanned area coordinates of any Vidicon output signal, and by the 1:1 geometrical relation between the Vidicon scanned area and CRT display, give the coordinates of any displayed location or any user-input signal. By matching the H- and V- Counter counts with CPU input coordinates, graphic data can be input onto the display from the CPU.

The presence of an output pulse from the "i_{L1}" Current Level Detector indicates the presence of a displayed location, and by using the "i_{L1}" pulse output to sample the H- and V- Counter counts (or their decoded equivalents), the display location coordinates can be read out in binary coordinates into the CPU.

The presence of an output pulse from the "i_{L2}" Current Level Detector indicates display locations selectively pointed-to by the user for further processing,

and using the "i_{L2}" pulse output to sample the H- and V- Counter counts, selected items can be read out into the CPU or erased.
The H- and V- Frequency Dividers thus not only provide timing and control signals, but also indicate directly or via some fixed decoders, the "x" and "y" coordinates of the displayed information.

11.6.2 Implementation

11.6.2.1 The H- and V- Counters

The Timing System crystal-controlled Oscillator is described briefly below; the actual basic pulse frequency used was 8·9714 ± 0·00002 MHz. The reason for this was that had time permitted, a somewhat less ambitious version of "VIDIOGRAPHIC" would have been built, with a 64 x 64 grid locations display; time and lack of funds of course precluded this. Also, of necessity, the choice of crystals and thus of Timing System Clock Frequency had to be restricted to those available in the Electrical Engineering Dept; a crystal was suitable if its frequency, when divided by an integer (i.e. when a digital ripple counter was used) gave a value closest to the nominal line frequency of 15·625 KHz. Dividing f= 8·29714 MHz by 532(÷ 4 ÷133 or ÷4 ÷7 ÷19), a H-line frequency of 15·596KHz results (a H-line duration of 64·119us). Further dividing by 312 (÷3÷8 ÷13) gives a V-field frequency of 49·987Hz (a V-field duration of 20·005ms). A "÷133" stage was used rather than a "÷ 7" in series with a "÷19"; the 132-nd pulse fed into this stage was detected and fed back into the "preset" input of each µL923 R-S F/F, which cleared all the 8 F/F stages of the "÷133" part of the H-Counter.

Fig.136(a) shows the H- and V- Counters implemented from µL 923 R-S F/Fs and uL 914 NOR gates providing the timing signals "T_{HE}", "T_{SS}" etc. As an example

"T_{HE}", the "H-blanking and Pulse" is shown being selected in the Fig. 136(b). "T_{HE}" is required to occur some 8us after "T_{HS}", the "H-blanking Start Pulse" (see section 11.4.3.2 above). 8μs corresponds to the 66-th pulse in the "÷ 4 ÷ 133" counter, or the 33rd pulse in the "÷2÷133" stages (actually 33 pulses = 7·96us). This 33rd pulse for the 9 F/Fs in the "÷ 2÷133" counter in binary form is "000100001". To extract this 33rd pulse, these 9 outputs would need be fed into an 9-input AND gate, but as uL 914 NOR gates are used, the complents to the above are fed into two and a half uL 914 whose output terminals are combined.

This follows from the identity

$$\underset{\text{(AND-function)}}{A.B.C.\cdots} = \underset{\text{(NOR-function)}}{\overline{\bar{A} + \bar{B} + \bar{C} + \cdots}}$$

The lagging edge of this 33rd output pulse is detected by a LEI; and this detected pulse gives the required "T_{HE}" pulse.

Other timing signals are obtained in a similar fashion.

Only the timing control signals defining the H- and V- blanking signals were required as these were adequate to define the H-scanning sawtooth and the V-staircase scanning waveform. Other timing signals were not extracted as time precluded the building of the H- or V- Correction Circuits etc.

<u>11.6.2.2. The Timing System Crystal Oscillator</u>

The basic timing source was a crystal controlled version of the Clapp Oscillator (330), with a 3·6V voltage supply-rail (the same as the RTL Logic voltage Supply used), with the crystal frequency at 8·29714 ± 0·00002 MHz. The oscillator is shown in Fig.137(a).

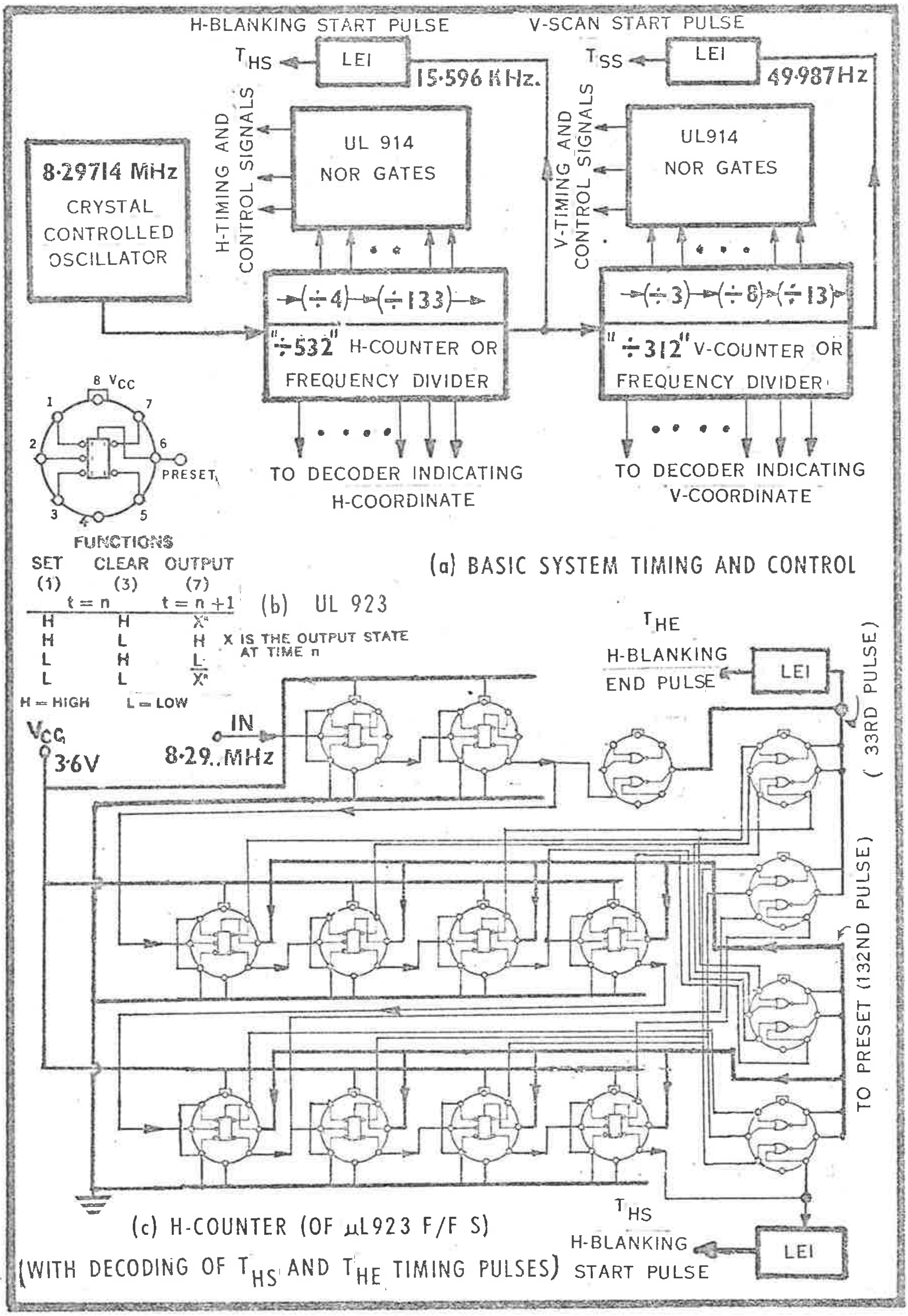


Figure 136. "VIDIOGRAPHIC" Timing and Control System.

Briefly the Clapp Oscillator is a Colpitts Oscillator with the tank circuit inductance replaced by a resonant LC series circuit; in the crystal version, the LC series circuit is of course the equivalent LC series circuit of the crystal. The feedback capacitances "C_1" "C_2" are selected to make their equivalent series capacitance very much larger than the equivalent crystal capacitance (which is typically a fraction of a picofarad).

The virtue of a Clapp Oscillator is its extreme stability for variations in supply voltage, and temperature etc. A discrete "L" and "C" component version was designed working at a nominal frequency of 5 MHz, (the other components shown in Fig.137(a) remaining approximately the same); it had the following characteristics:

(i) % frequency variation over 1 hour = ±0·007%

(ii) % frequency variation for a +1% variation in supply voltage = -0·002%

(iii) % frequency variation when the hot soldering tip was held near the transistor Q_1 for 30secs. = -0·08%

The crystal version showed a variation of ±200Hz in 8·29714MHz at room temperature,which is a negligible ± 0·00025% variation.

The output across the crystal is a slightly distorted sinusoid of some 1·6V, superimposed on 2·2V DC. The biased emitter follower "Q_2" acts as a buffer and also serves asa DC level adjuster for the uL 914 Schmitt Trigger (see section 11.5.8). The emitter of "Q_2" has a quiescent voltage of some 0·6V, which results in a zero output of the Schmitt Trigger, whose switching level is some 1·1V. The peak emitter swing is at some 1·4V due to the oscillator output sinusoid; it switches the Schmitt

Trigger on and produces a 3·6V at its output for a short duration. The resulting output square wave of 8·29714MHz sits on a DC pedestal of some 0·3V. The output is tapped from the potential divider, which reduces the possibility of switching the first F/F stage of the H-Counter by noise superimposed on this DC pedestal of 0·3V.

11.6.3 Temperature Compensation

Timing and control signals are derived from the crystal-controlled oscillator which, as seen above, is for our purposes independent of temperature and supply voltage variations. Hence timing control signals are similarly independent of temperature and supply voltage variations.

On the other hand, H- and V-coordinate Distortion Correction, whether carried out by the relocation of CRT display locations using a V.C.A, or by the determination of H-correction intervals using a V.C.M, is dependent on ambient temperature and voltage rail variations, as the expressions relating output frequency or output pulse duration contain temperature dependent terms and supply voltage terms.

The nett effect of temperature and voltage variations in such circuits not only depends on the type of circuit, but, to some extent, on the component values. This is particularly true in I/Cs where the various resistors etc are within the chip and of a material such that typically a resistor may increase by 0·2% of its nominal value for each C^{o} rise in temperature.

Supply voltage variation effects can be neglected due to the relatively stable Voltage Regulators used (see section 11.5.10). Temperature effects are the ones of significance, with a change of some 20°C in ambient temperature capable of causing several percent change in

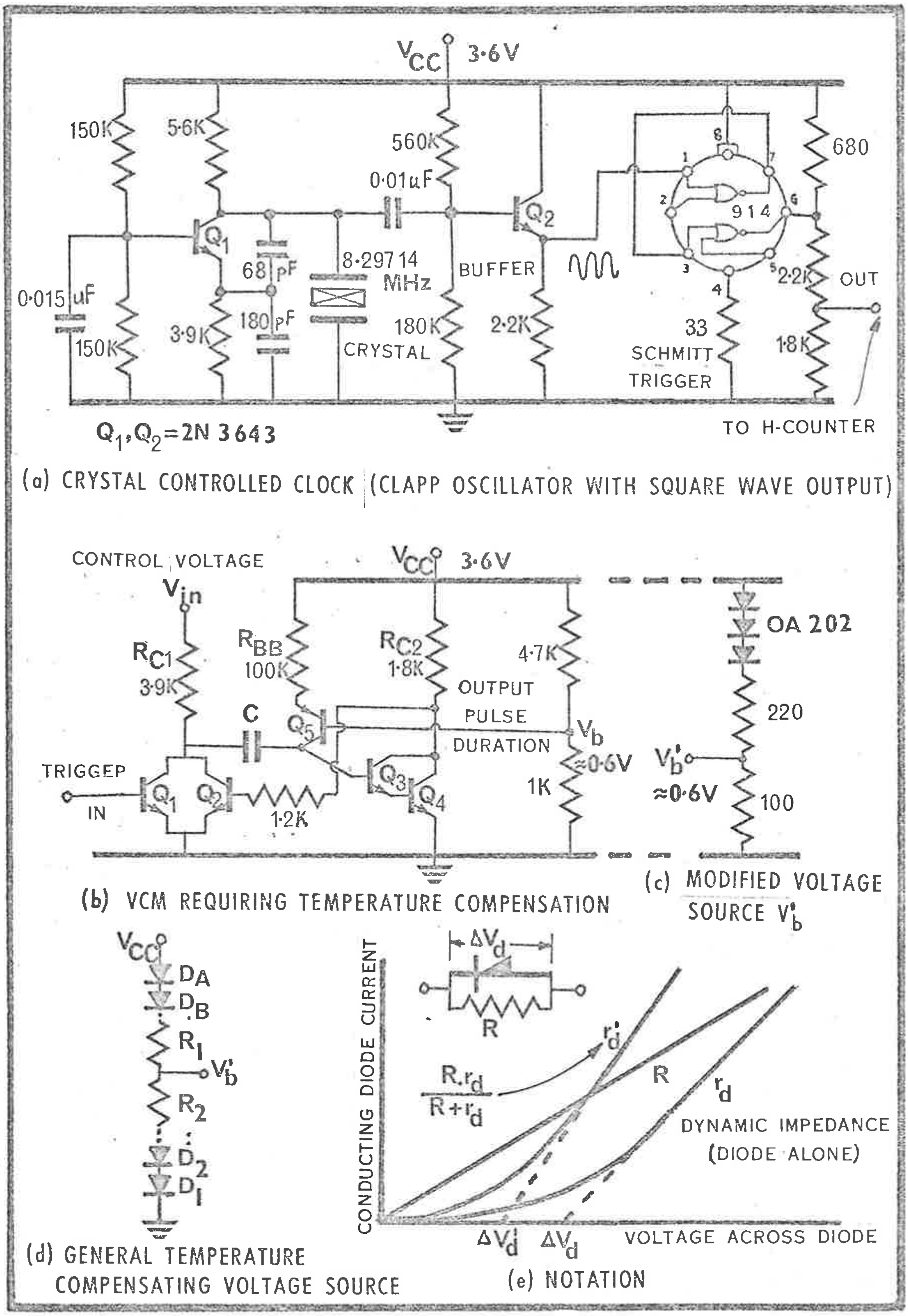


Figure 137. Stable Timing - Crystal Controlled Oscillat and Temperature Compensated Circuits.

VCA frequency or VCM output pulse duration. These effects need be minimized or eliminated by temperature compensation, which primarily is by the suitable placement within the circuit of Ge or Si diodes. The method given here, although specifically for a given circuit, applies in principle to other classes of circuits; each circuit must be treated individually for optimum results, due to the individual variations in component values, the use of different supply voltages, and also the significantly different temperature coefficiants of transistors, even in nominally identical ones.

As an example the VCM shown in Fig.137(b) will be temperature compensated ; it is reproduced from Appendix A.13.5 where its operation is fully described.

From expression (2) (p.A.222) the output pulse duration "T_D" is given by

$$T_D = \frac{R_{BB}C}{\alpha_{Q_3}} \cdot \frac{(V_{in} - V_{CE\ sat\ Q_1}) - (V_{BE\ sat} - V_{BE\ cut\ in})Q'_2}{V_{CC} - V_{BE\ Q_3} - V_B} \quad \ldots 11.23$$

Neglecting component value variation with temperature, and supply voltage variation, the significant voltage changes due to temperature are

(i) in "V_{BE}", the base-emitter voltage of transistors decreases by 2mV/°C, i.e. $\frac{dV_{BE}}{dT^o} = -2\text{mV}/^oC$.

(ii) to a lesser extent in V_{CE}, the collector emitter voltage, which increases by 0·2 → 0·5mV/°C,

i.e. $\frac{dV_{CE\ sat}}{dT^o} = 0{\cdot}2 \rightarrow 0{\cdot}5\text{mV}/^oC$.

Differentiating the above expression 11.23 with respect to "T^o", the temperature, results, after rearranging, in

$$\frac{dT_D}{T_D} = -\frac{\frac{dV_{CE\ sat\ Q_1}}{dT^o} \cdot \Delta T^o}{V_{in} - V_{CE\ sat\ Q_1} - (V_{BE\ cutin} - V_{BE\ sat})Q'_2}$$

$$+ \frac{\frac{dV_{BE\ Q_3}}{dT^o} \cdot \Delta T^o}{V_{CC} - V_{BEQ_3} - V_B} \quad \ldots\ldots\ldots .11.24$$

For a change in temperature "ΔT^o" of say 20°C, and substituting the above values for "$\frac{dV_{CE}}{dT^o}$" and "$\frac{dV_{BE}}{dT^o}$", and with $V_{CC} = 3{\cdot}6V$, $V_B \approx 0{\cdot}6V$ and "V_{in}" varying from 2V to say 8V,

$$\frac{dT_D}{T_D} \approx -0{\cdot}3\% - 2\% \approx -2{\cdot}3\% \quad \ldots\ldots\ldots .11.24(a)$$

in the worst case, which is a significant fraction of the output pulse duration.

An obvious method of reducing the above variation is to increase "V_{CC}", to say + 14V, which is an available voltage supply; this would reduce the above variation of the period to only some -0·6%. This value could be tolerated according to the accuracy requirements specified in section 11.5.5. For I/C implemented VCMs and VCAs, the voltage supply however is fixed and remains low, at some 3-5V. Thus "true" temperature compensation need be introduced, to minimize or fully eliminate the above temperature variation even with low level voltage supplies still present. An example of this was given in the Constant Stabilized Level Circuit (section 11.5.2) where the series Zener diode and Si diode compensated for the temperature variation in a base-emitter junction.

Temperature compensation described here is based on the introduction of Si (or Ge diodes) in certain parts of the circuit, to effectively give temperature-dependent voltage sources, which, when inserted in the expressions governing the output parameter, result in negligible temperature dependence.

For the above circuit, if the voltage source "V_B" is replaced by

$$V_B' = V_B - V'_{BE} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 11.25$$

then on substituting this into expression 11.23 above, results in a new value of the denominator becoming equal to "$V_{CC} - V_B$", independent of temperature variation. "V'_{BE}" is effected by using a diode or diodes. The actual numerical value of "V'_{BE}" is not important; of importance is the fact that the voltage drop across a conducting diode has a very similar temperature coefficiant as the base-emitter junction of a transistor of the same material (i.e. a Si or Ge transistor). The voltage drops across each element are also nearly identical.

Consider the network shown in Fig.137(d) consisting of a number of diodes and two resistors R_1 and R_2 to provide some voltage "V'_B" at the point shown. It is required that

$$\frac{dV'_B}{dT^\circ} \approx - \frac{dV_{BE\,Q_3}}{dT^\circ} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 11.26$$

The following relation holds:

$$V_{CC} = \Delta V_A + \Delta V_B + \ldots \Delta V_N + \Delta V_1 + \Delta V_2 + \ldots \Delta V_n + I(R_1 + R_2 + r_A + r_B + \ldots r_N + r_1 + r_2 + \ldots r_n \quad . \; . \; . \quad 11.27$$

where "ΔV_A", ..." ΔV_n" are the "modified" voltage drops across the diode (see Fig.137(e))

"I" is the current through the network,

and "r_A", ..."r_n" are the dynamic resistances of the conducting diodes (the slope of the I vs. V curve of a diode) and typically equal to some 5-10Ω.

Also

$$V_B' = \Delta V_1 + \Delta V_2 + \ldots \Delta V_n + I(R_2 + r_1 + \ldots r_n) \quad \ldots .11.28$$

And for Si diodes of the same type, and a B-E junction in a Si transistor,

$$\frac{\partial \Delta V_1}{dT^o} = \frac{\partial \Delta V_A}{dT^o} = \ldots \frac{\partial \Delta V_n}{dT^o} = -2mV/^oC \approx \frac{dV_{BE}}{dT^o}$$

Differentiating expression 11.27 with respect to "T^o" gives,

$$\frac{dV_{CC}}{dT^o} = 0 = \sum_A^N \frac{\partial \Delta V_i}{dT^o} + \sum_1^n \frac{\partial \Delta V_i}{dT^o} + \frac{dI}{dT^o}(R_1 + R_2 + \sum_{A,1}^{N,n} \ldots \quad \ldots .11.29$$

from which

$$\frac{dI}{dT^o} \approx - \frac{\sum_A^N \frac{\partial \Delta V_i}{dT^o} + \sum_1^n \frac{\partial \Delta V_i}{dT^o}}{R_1 + R_2} \quad \ldots .11.29(a$$

if it is assumed that $R_1 + R_2 \gg \sum_{A,1}^{N,n} r_i$.

Similarly differentiating expression 11.28,

$$\frac{dV_B'}{dT^o} \approx \sum_i^n \frac{\partial \Delta V_i}{dT^o} + \frac{dI}{dT^o} \cdot R_2 \quad \ldots .11.28(a$$

if $R_2 \gg \sum_1^n r_i$.

Substituting for "$\frac{dI}{dT^o}$" and rearranging gives,

$$\frac{dV'_B}{dT^o} \approx \frac{R_1}{R_1+R_2} \cdot \sum_i^n \frac{d\Delta V_i}{dT^o} - \frac{R_2}{R_1 + R_2} \cdot \sum_1^N \frac{d\Delta V_i}{dT^o} \quad \ldots 11.30$$

In the above circuit, this is to be equal to "$-\frac{dV_{BE}}{dt}$" (expression 11.26). Clearly if n = o, N = 2 and $R_1=R_2$, expression 11.26 would be satisfied. However "V'_B" is also required to be some 0·6V or thereabouts. Putting n=0 N=3 and making $R_1=2R_2$ satisfies this requirement and expression 11.26. The voltage at "V'_B" thus becomes

$$V'_B = \frac{R_2}{R_1+R_2} \cdot (V_{CC} - 3\,\Delta V_D) = \frac{1}{3}(3{\cdot}6 - 1{\cdot}8) \approx 0{\cdot}6V$$

as the voltage across a conducting Si diode $\approx$ 0·6V.

Also

$$\frac{dV'_B}{dT^o} = -\frac{1}{3} \sum_i^3 \frac{d\Delta V_i}{dT^o} \approx \frac{-d\Delta V_D}{dT^o} \approx \frac{-dV_{BE}}{dT^o}$$

as required.

"Fine adjustments" to the effective temperature coefficiant of a diode can be obtained by placing a resistor "R" in parallel with a diode. The nett temperature coefficiant then becomes

$$\frac{d\Delta V'_D}{dT^o} \approx \frac{R}{R + r_d} \cdot \frac{d\Delta V_D}{dT^o} \quad \ldots\ldots\ldots\ldots 11.31$$

Using such modified "diodes", the small variation due to "$\frac{dV_{CE}}{dT^o}$" can be compensated for partially.

For precise temperature compensation, the actual voltages changes due to temperature increases need be measured, so that the subsequent temperature compensation can also allow for component value variations; the above analysis has only allowed for "V_{BE}" temperature variations. With the above simple diode network, improvements of a factor of 5 - 10 over uncompensated circuits have been measured. For the above circuit, in the input voltage range "V_{in}" of 3→9V, a variation in output pulse duration of around ± 0·01% / °C has been obtained. This compares with an average of some 0·1%/°C for the uncompensated case. For a 20°C increase in temperature, the output pulse duration will change by some ± 0·2%.

These compensated circuit temperature variations fall well within the tolerable accuracy required in the VCA and VCM. Thus these simple diode compensating networks are more than adequate to ensure stable system operation.

11.7 CONCLUDING REMARKS

As mentioned previously, time and lack of funds precluded the building of a working model of "VIDIOGRAPHIC". However the major problems concerning the physical realization of "VIDIOGRAPHIC" have been either answered on paper by using available results in the literature, both commercial and technical, or else solved by designing and testing certain subsystems of "VIDIOGRAPHIC".

Manufacturers' data and recent unusual applications of Vidicons show that the oft-quoted "slow response" of Vidicons to "short" duration illumination is no problem, provided that the intensity and persistance of the illumination is adequate and suitable. "W"-phosphor in TV CRT projection tubes meets this requirement.

Commercially available Schmidt TV-Projection receivers with viewing screens provide the correct necessary optics system to enable the implementation of "VIDIOGRAPHIC".

The suggested methods for providing a "stable" display, the other essential requirement in "VIDIOGRAPHIC", although designed in the main only on paper, should provide no difficulty. The means of measuring precisely the CRT display and Vidicon scanned area distortion have been found, described, and implemented. From such Moire Fringe measurements, the display distortions expressed in a graphical form are of the correct form to be drawn on the CRT display screen areas to be used for correction; reading-in of this Correction Information is by TV scanning directly. The major H- and V- Distortion Correction Subsystems, to interpret this Distortion Information and to implement the Display Correction, are based on VCAs, VCMs, Pulse Integrators etc, which have been designed and tested, meeting the necessary specifications. Expressions to correct for pincushion or barrel distortions have been derived, to further result in a linear, stable display.

A Vidicon H- and V- scanning system has been designed and tested; it enables all the above correction inputs etc to be implemented. The CRT H- and V- deflection system required is essentially similar.

Finally the complete system is based on commercially available "off-the-shelf" components, which require some modifications. Existing techniques, indeed consumer product techniques, can implement these additional requirements, with the result that a basic, yet fully Interactive Graphics Console, capable of being interfaced to a small or large CPU can be built for a cost of around $2000(A.

As indicated in the Preface, the "biggest unsolved problem (in Man-Computer Graphics) is to build a low-cost display device suitable for on-line graphical use". The ever-increasing importance and need of Man-Computer Graphics, as described in Chapter 1, require a speedy solution to the above problem. Chapter 2, in describing the current techniques used to implement the hardware for an IGC and the requirements necessary of such an IGC, indicates the complexity of the problem and also point to the resultant high cost of current IGCs. The remainder of this Thesis puts forward the concept of "VIDIOGRAPHIC", and explores its feasability and implementation. It is hoped that it was shown that "VIDIOGRAPHIC" could contribute in some way to solve this urgent problem.

Much work needs to be done, particularly in the building of a working model. Resolution and display area size and addressability would need to be increased to at least a 512 x 512 grid. This work must be left to others. But this report, of necessity lengthy, covers and puts forward solutions to most of the problem areas envisaged; it is hoped others will take up this promising approach to the solution of the problem of realizing an economical Interactive Graphics Console.

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