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Vertical Resolution and Line Broadening

by

G. D. MONTEATH, B.Sc., F.Inst.P., A.M.I.E.E.

BRITISH BROADCASTING CORPORATION

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FOREWORD

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This series should be of interest and value to engineers engaged in the fields of broadcasting and of telecommunications generally.

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CONTENTS

PREVIOUS ISSUES IN THIS SERIES

No.	Title	Date
1.	*The Suppressed Frame System of Telerecording*	JUNE 1955
2.	*Absolute Measurements in Magnetic Recording*	SEPTEMBER 1955
3.	*The Visibility of Noise in Television*	OCTOBER 1955
4.	*The Design of a Ribbon Type Pressure-gradient Microphone for Broadcast Transmission*	DECEMBER 1955
5.	*Reproducing Equipment for Fine-groove Records*	FEBRUARY 1956
6.	*A V.H.F./U.H.F. Field-strength Recording Receiver using Post-detector Selectivity*	APRIL 1956
7.	*The Design of a High Quality Commentator's Microphone Insensitive to Ambient Noise*	JUNE 1956
8.	*An Automatic Integrator for Determining the Mean Spherical Response of Loudspeakers and Microphones*	AUGUST 1956
9.	*The Application of Phase-coherent Detection and Correlation Methods to Room Acoustics*	NOVEMBER 1956
10.	*An Automatic System for Synchronizing Sound on Quarter-inch Magnetic Tape with Action on 35-mm Cinematograph Film*	JANUARY 1957
11.	*Engineering Training in the BBC*	MARCH 1957
12.	*An Improved 'Roving Eye'*	APRIL 1957
13.	*The BBC Riverside Television Studios: The Architectural Aspects*	JULY 1957
14.	*The BBC Riverside Television Studios: Some Aspects of Technical Planning and Equipment*	OCTOBER 1957
15.	*New Equipment and Methods for the Evaluation of the Performance of Lenses for Television*	DECEMBER 1957
16.	*Analysis and Measurement of Programme Levels*	MARCH 1958
17.	*The Design of a Linear Phase-shift Low-pass Filter*	APRIL 1958
18.	*The BBC Colour Television Tests: An Appraisal of Results*	MAY 1958
19.	*A U.H.F. Television Link for Outside Broadcasts*	JUNE 1958
20.	*The BBC's Mark II Mobile Studio and Control Room for the Sound Broadcasting Service*	AUGUST 1958
21.	*Two New BBC Transparencies for Testing Television Camera Channels*	NOVEMBER 1958
22.	*The Engineering Facilities of the BBC Monitoring Service*	DECEMBER 1958
23.	*The Crystal Palace Band I Television Transmitting Aerial*	FEBRUARY 1959
24.	*The Measurement of Random Noise in the presence of a Television Signal*	MARCH 1959
25.	*A Quality-checking Receiver for V.H.F. F.M. Sound Broadcasting*	JUNE 1959
26.	*Transistor Amplifiers for Sound Broadcasting*	AUGUST 1959
27.	*The Equipment of the BBC Television Film Studios at Ealing*	JANUARY 1960
28.	*Programme Switching, Control, and Monitoring in Sound Broadcasting*	FEBRUARY 1960
29.	*A Summary of the Present Position of Stereophonic Broadcasting*	APRIL 1960
30.	*Film Processing and After-processing Treatment of* 16-*mm Films*	MAY 1960
31.	*The Power Gain of Multi-tiered V.H.F. Transmitting Aerials*	JULY 1960
32.	*A New Survey of the BBC Experimental Colour Transmissions*	OCTOBER 1960
33.	*Sensitometric Control in Film Making*	DECEMBER 1960
34.	*A Mobile Laboratory for UHF and VHF Television Surveys*	FEBRUARY 1961
35.	*Tables of Horizontal Radiation Patterns of Dipoles Mounted on Cylinders*	FEBRUARY 1961
36.	*Some Aspects of Optical Lens Performance*	APRIL 1961
37.	*An Instrument for Measuring Television Signal-to-noise Ratio*	JUNE 1961
38.	*Operational Research on Microphone and Studio Techniques in Stereophony*	SEPTEMBER 1961
39.	*Twenty-five Years of BBC Television*	OCTOBER 1961
40.	*The Broadcasting of Music in Television*	FEBRUARY 1962
41.	*The Design of a Group of Plug-in Television Studio Amplifiers*	APRIL 1962
42.	*Apparatus for Television and Sound Relay Stations*	JULY 1962
43.	*Propagational Factors in Short-wave Broadcasting*	AUGUST 1962
44.	*A Band V Signal-frequency Unit and a Correlation Detector for a VHF/UHF Field-strength Recording Receiver*	OCTOBER 1962

VERTICAL RESOLUTION AND LINE BROADENING

SUMMARY

This monograph is concerned with the effects of scanning in lines on a television picture, and with methods of broadening the scanning lines so as to reduce or eliminate these effects. The results of earlier work on the optimum number of lines for a given bandwidth are summarized, and a precise definition of the Kell factor is suggested. Scanning is treated theoretically as a sampling process, and the ideal form of the line profile is deduced. A similar result is shown to follow from consideration of polynomial interpolation. A number of methods of line broadening are discussed; two of these enable the profile to attain negative values, so that vertical aperture correction is possible. Subjective experiments are proposed.

1. Introduction

The fact that a scene to be reproduced by television is scanned in lines, and that the image is reproduced in lines, has a number of disadvantages.

The fact that the image is reproduced in lines on the screens of television receivers is considered objectionable by most people, so much so that some consider the forthcoming increase in the number of lines in Great Britain to be justified on this ground alone, even if imperfect resolutions in cameras, etc., should mean that the resolution of the image will not be improved.

The fact that an optical image of the scene (or motion-picture film) is scanned in lines also produces objectionable, though sometimes less obvious, effects, which have been explained by Mertz and Gray.[1] For example, moiré patterns may be produced when the scene includes fine horizontal stripes, and grain noise is accentuated when film is being reproduced. Moiré patterns are usually intolerable when an image laid down in lines is rescanned, as when pictures are converted from one television scanning standard to another, and when film telerecordings are rescanned for transmission. This effect, which is referred to as 'line beating', produces horizontal bands.

The line structure may be removed by spot wobble,[2] or by other means of elongating the spot perpendicularly to the scanning lines so as to broaden them. Opinions differ as to when it is advantageous to use line broadening, but it is always necessary to eliminate line beating in standards conversion and similar processes. In this case line broadening may be used when forming the image for rescanning, or when rescanning the image, or both.

A great deal of attention is always devoted to horizontal resolution, and response characteristics are often quoted to a fraction of a decibel, while vertical resolution tends to be neglected. It is unusual for this aspect of the performance of television equipment to be specified at all. This is presumably due to the complexity of the phenomena associated with vertical resolution, the difficulty of making measurements, and the even greater difficulty of making improvements. It is nevertheless thought that more attention should be directed to these problems.

The purpose of this monograph is to discuss vertical resolution in relation to the line structure, and in particular to consider the effect of broadening the scanning lines. Any method of line broadening entails a compromise between sharpness of portrayal of vertical detail and the reduction of unwanted effects associated with the scanning lines. The conflicting considerations underlying this compromise will be discussed, and methods of achieving it considered.

2. Terminology

It is convenient to define some of the terms to be used, but the definitions are intended only for the purpose of this monograph, not for general use.

Except where the contrary is stated the scanning lines will be assumed to be horizontal.

VERTICAL DETAIL
Variations in brightness with respect to vertical position (distance from the bottom of the picture); e.g. horizontal stripes in the scene constitute vertical detail.

VERTICAL RESOLUTION
Ability to portray vertical detail.

LINE BROADENING
Increasing the width of the scanning lines by elongating the scanning spot in a direction perpendicular to them. Spot wobble is one means of effecting line broadening.

LINE PROFILE
A function defining the distribution of brightness across one scanning line, the other lines being suppressed.

VERTICAL SPATIAL FREQUENCY
The spatial frequency of a pattern that is periodic in the vertical direction, measured in cycles* per unit length. The unit of length will be taken to be the picture height, so that vertical spatial frequency is measured in cycles per picture height (c/p.h.).

LINE FREQUENCY
The fundamental vertical spatial frequency of a raster. It is equal to the number of active scanning lines.

VERTICAL SPECTRUM
If the brightness along a vertical line in the picture is expressed as a function of vertical position, the Fourier transform of this function is termed the vertical spectrum. It is a function of vertical spatial frequency.

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* In measurements on lenses it is customary to express spatial frequencies in 'patterns per unit length'. This term is not used here because it seems confusing, obscuring the perfect analogy with 'cycles per unit time' for a function periodic in time. It dates from a time when some confusion existed between optical and electronic terminology.

VERTICAL FREQUENCY RESPONSE CHARACTERISTIC

The (complex) ratio of the vertical spectrum obtained after the picture has been modified by a linear process free from geometrical distortions to the corresponding spectrum before modification. It is analogous to the frequency response characteristic of a two-port network which modifies the horizontal spectrum.

NORMAL DETAIL*

Vertical detail in a television picture associated with components of the vertical spectrum that were present in the original scene.

EXTRANEOUS COMPONENTS*

Vertical detail in a television picture associated with spurious components in the vertical spectrum generated by the effect of scanning in lines.

3. Subjective Effect of the Line Structure on Picture Quality

This subject received much attention in the early days of American television, the object of this work being to provide material relevant to the choice of a television standard. Some papers relevant to the subject of this report will be mentioned below in chronological order.

Engstrom[3] simulated sequential television pictures by forming the line structure optically on film, using a defocused optical system with a rectangular aperture both for making a print and for projecting it. In effect the television systems simulated employed line broadening with a rectangular line profile both in the picture source and in the display. In the source the breadth of the lines must have been just sufficient to make them contiguous (this condition was imposed by the equipment used), but in the display it was somewhat less. Observers assessed the pictures by choosing the distances at which they preferred to view them. Although this work did not provide quantitative data having much value now, the techniques employed are still of interest.

Kell, Bedford, and Trainer[4] conducted experiments with a sequential television system. Observers viewed a test pattern of near-horizontal bars arranged in a tapered wedge.† They found that 100 scanning lines were required to resolve sixty-four black and white (presumably thirty-two of each) bars. This result was compared with conventional theory, which assumes that equal horizontal and vertical resolutions would be obtained by making the number of half-cycles (at the highest video frequency) per unit length along a scanning line equal to the number of lines per unit height. It was deduced that the band-width required by conventional theory should be reduced in the ratio $k : 1$, where k was equal to $0 \cdot 64$. It is this factor k, generalized to be applied to interlaced as well as sequential systems, that is now referred to as 'the Kell factor'.

Kell, Bedford, and Fredendall[5] examined theoretically the response of a television system to a horizontal transition between uniform black and white areas. Brightness of the display was plotted as a function of vertical position, and separate curves were plotted for different positions of the edge relative to the scanning lines. The mean curve was taken as indicative of the vertical resolution. Now the use of narrow scanning lines confers a kind of sharpness upon a horizontal edge that is spurious, in that the edge's position is inaccurately portrayed. But the errors in position tend to reduce the slope of a mean curve obtained in the manner indicated above. If the bandwidth were chosen to give a response with the same slope to a vertical edge, it would be less than that indicated by conventional theory. Kell, Bedford, and Fredendall did not compare their result with that obtained in the earlier paper.[4]

Baldwin[6] asked observers to assess the 'sharpness' of pictures. As a standard of comparison he used a defocused optical picture having equal resolutions in the horizontal and vertical directions. The observers assessed other types of picture by altering the focusing of the standard until the two pictures appeared to have equal sharpness. In the first experiment, the pictures assessed in this way were also obtained by defocusing a projector, but the lens aperture was made rectangular, so as to give unequal horizontal and vertical resolutions. Each point of the slide projected was represented by a uniformly illuminated rectangle on the screen. Baldwin found that for a given area of rectangle the picture appeared sharpest when the sides of the rectangle were approximately equal. For the larger areas of rectangle there was a slight preference for an excess of horizontal over vertical resolution (that is for a rectangle with the shorter sides horizontal).

Baldwin then assessed 240-line sequential television pictures with various video-frequency response characteristics. He did not specify the line profile in the picture source or display tube, or say whether deliberate line broadening was employed. Kell, Bedford, and Trainer's[4] constant k, which later became known as the 'Kell factor', was found to be $0 \cdot 7$. Baldwin also quotes values between $0 \cdot 53$ and $0 \cdot 85$ deduced by other workers.

Jesty[7] followed Engstrom[3] by asking observers to choose the distances at which they would prefer to view a picture. He began with isotropically blurred optical pictures. Assuming the sharpness of these to be characterized by the diameter of a circle of confusion, he found that observers tended to adjust their viewing distances in proportion to this diameter. They also showed a slight tendency to sit farther from a large picture than from a smaller one, even when the absolute diameter of the circle of confusion was the same.

Television pictures on the 405-line and 625-line standards were assessed in a similar manner, using various video-frequency bandwidths. By means of a curve-fitting procedure, making use of certain data from the optical experiment, Jesty deduced a certain bandwidth for each television standard. This he persistently referred to as 'the optimum bandwidth' for 405 (or 625) lines, but he seems to have meant 'that bandwidth for which 405 (or 625) is the optimum number of lines'. From this bandwidth he deduced that the 'Kell factor' for an interlaced system is $0 \cdot 42$.

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* These terms were introduced by Mertz and Gray.[1] See also Section 4.

† This information about the nature of the subjective tests was omitted from Reference 4 but published later in Reference 5.

Taking Baldwin's value of $0{\cdot}7$ for a sequential picture, Jesty deduced that the economy in bandwidth offered by interlacing was given by the factor $0{\cdot}7/(2\times0{\cdot}42)=0{\cdot}83$.

Jesty obtained a few results on the 405-line system with sinusoidal spot wobble applied to the display tube. He did not make quantitative deductions from them, but they suggest an increase of about 20 per cent in the Kell factor. He also used synchronous spot wobble (see Section 9.4).

The most useful quantitative data offered in the papers mentioned above are the values of the Kell factor for sequential and interlaced systems. Unfortunately it does not seem that much reliance can be placed on the values obtained. Different workers asked different questions of their observers and presumably measured different kinds of Kell factor. Thus Engstrom[3] and Jesty[7] asked their observers where they would like to sit, while Baldwin asked his to assess 'sharpness'. It seems likely that some objectionable features of the line structure may repel viewers from the screen without detracting to an equal extent from the 'sharpness'. Observations on geometrical test patterns, such as those of Kell, Bedford, and Trainer,[4] [5] or calculations on the response to an edge, such as those made by Kell, Bedford, and Fredendall,[5] appear irrelevant. Further difficulty is encountered when trying to use the various results obtained as a result of the arbitrary and various ways in which a bandwidth is assigned to a given filter characteristic.

All that can be deduced with certainty is that the Kell factor for a sequential system is appreciably less than unity, and that the Kell factor for an interlaced system is appreciably smaller still.

Although different workers conducted measurements in different ways, their deductions from the results suggest that their work was directed to the same end: to determine the optimum number of lines for a given bandwidth. It would seem desirable for further work to be devoted directly to that end. The Kell factor—apparently not yet precisely defined—should therefore be defined as follows:

> Suppose that a bandwidth is fixed and that the number of lines has been chosen to give the most pleasing picture. Then the Kell factor for that number of lines is the ratio of the number of half-cycles at the highest video frequency per unit length along a line to the number of lines per unit height.

It would be best to simplify the conditions by specifying the lowest reasonable signal-to-noise ratio, and by either maintaining a constant proportion of blanking time when varying the number of lines or changing the bandwidth slightly to correct for changes in the proportion of blanking time.

The bandwidth referred to above should be the total video bandwidth available—e.g. 3 Mc/s in present British channels. The response characteristics of filters used for subjective tests should therefore give a high attenuation (just how high remains to be decided) outside this band. Within the band the filter characteristic should be chosen in a subsidiary experiment to give the most pleasing result.

Observers should be asked some such question as 'Do you prefer this picture or that?' Assessments of 'sharpness' or some similar property seem to have less value for this purpose. The alternative is to use preferred viewing distance (Engstrom[3] and Jesty[7]) as the criterion. Although this criterion appears to have the advantage of expressing opinions of picture quality in quantitative form, this advantage may be illusory, for reasons advanced by contributors to the discussion on Jesty's paper.

4. Sampling

The effect of the line structure in scanning or reproducing a scene has been treated comprehensively in a classical paper by Mertz and Gray.[1] A similar method has been used by Graham and Reynolds[8] to study a method of simulating television pictures optically. The approach adopted here is the same in essence, but the mathematical argument has been replaced by discussion of an analogue in which the line structure is produced by sampling in time. This treatment may prove more enlightening to some television engineers, to whom sampling—particularly with time as the independent variable—is familiar. Nevertheless, the conclusions are essentially those of Mertz and Gray, deriving directly from their paper.

Fig. 1a shows the bare essentials of a television system, details such as amplifiers being omitted. The picture source A, which is taken to be a flying-spot film scanner, produces a signal which is fed to a display tube B. In so far as the horizontal line structure and the portrayal of vertical detail are concerned, the same picture would be produced by the system shown in Fig. 1b. Here the flying-spot scanner, which is now supposed to have perfect resolution, scans vertically rather than horizontally. The output is passed through a linear network D to a multiplier, in which it is sampled by multiplication by a train of infinitely narrow impulses. The resulting train of pulses is then fed through a linear network E to a display tube F. Like the flying-spot scanner the display tube is assumed to have perfect resolution, i.e. an infinitely small spot. In the original television system (Fig. 1a), the use of horizontal scanning is a characteristic which is given, and cannot be avoided. In Fig. 1b the given factor is the sampling process; one might, for example, suppose that the signal must be transmitted by some kind of pulse-modulation system. The sampling will produce horizontal lines corresponding to the lines obtained when scanning horizontally. These lines will, of course, be broken up by the vertical scanning lines in the arrangement of Fig. 1b, but we are not concerned with this aspect of the system.

The linear networks D and E respectively simulate imperfect vertical resolution (i.e. finite spot size measured vertically) in scanner A and display tube B.

The effect of sampling on waveforms and their spectra is very well known, but it is convenient to recapitulate some basic principles. Let the signal at the input to the multiplier be $F(t)$ and let the Fourier transform of this be

$$\phi(f)=\int_{-\infty}^{\infty}F(t)e^{-2\pi jft}\,dt \qquad (1)$$

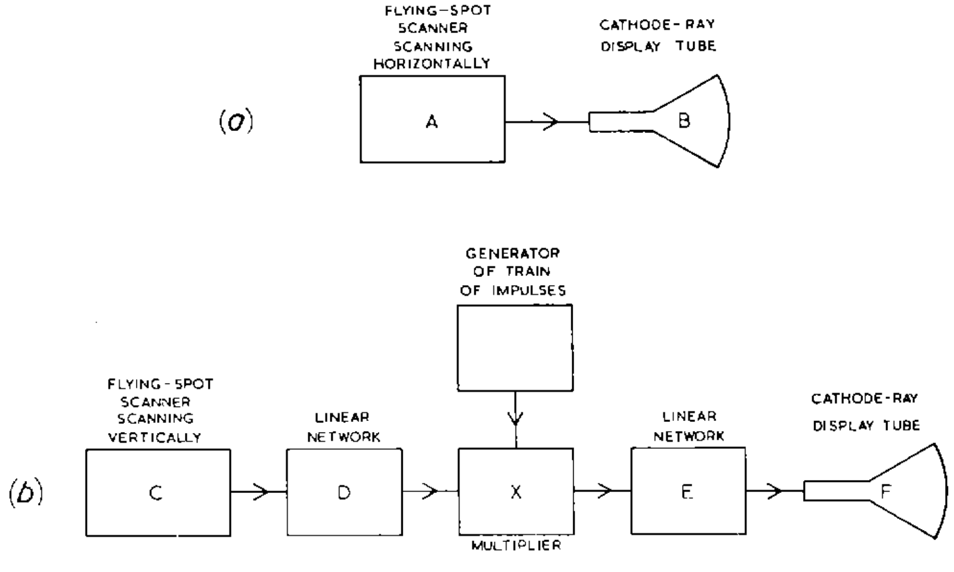

Fig. 1 — *Simulation of the horizontal scanning lines by sampling.*
(*a*) *Simple system with horizontal scanning.*
(*b*) *Horizontal lines simulated by sampling while scanning vertically.*

If the interval between sampling pulses is τ, and if one sampling pulse occurs at $t=0$, the spectrum of the output of the multiplier $\phi_1(f)$ is given by

$$\phi_1(f)=K\sum_{n=-\infty}^{\infty}\phi(f-n/\tau) \qquad (2)$$

where K is a constant. The sampling has the effect of adding to the spectrum a series of displaced versions of it spaced $1/\tau$ in frequency apart. This process is illustrated in Fig. 2. The width of the spectrum shown in Fig. 2a is a measure of the fine vertical detail of the film being scanned. The finer the detail, the greater the width of the spectrum before sampling, and the greater the degree of overlap between the displaced versions shown in Fig. 2b.

We shall now consider how to make the display on the cathode-ray tube F free from any horizontal line structure and from any other effects caused by the sampling process. This could be done by making each of the networks D and E band-pass filters restricting the video bandwidth to less than $1/2\tau$. For simplicity it will be supposed that each of these networks is an ideal phase-corrected band-pass filter having a rectangular characteristic with a cut-off frequency very slightly under $1/2\tau$; the result is illustrated in Fig. 3. The spectrum immediately before sampling, shown in Fig. 3a, is precisely the same as that shown in Fig. 2a apart from the bandwidth restriction. After sampling the displaced versions of the spectrum do not overlap and the resultant spectrum is as shown in Fig. 3b. Finally, the bandwidth restriction in network E removes all the displaced versions of the spectrum, leaving only the original, as shown in Fig. 3c. The sampling process has therefore no effect whatsoever on the signal.

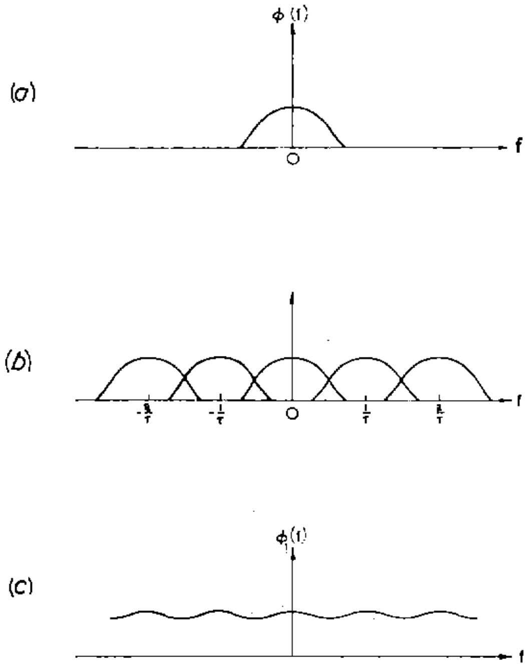

Fig. 2 — *Effect of sampling on spectrum.*
(*a*) *Original spectrum.*
(*b*) *Original and displaced versions of spectrum created by sampling.*
(*c*) *Resultant spectrum after sampling.*
Only real component of spectrum shown. The imaginary component is treated similarly.
Sampling interval τ. *One sample taken at* $t=0$.

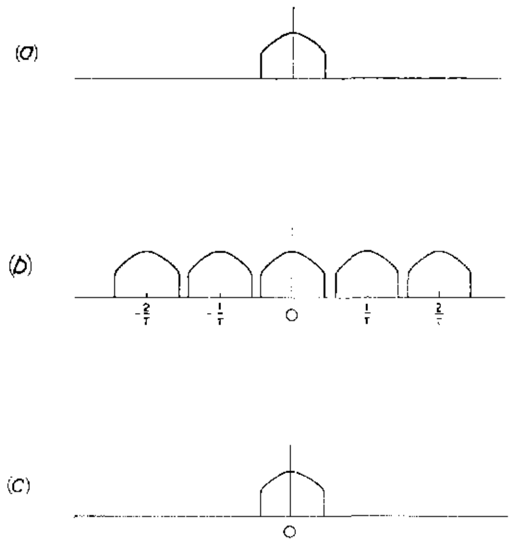

Fig. 3 — *Elimination of effect of scanning lines by bandwidth restriction in Networks D* and E*.*

(*a*) *Spectrum after bandwidth restriction by Network D.*
(*b*) *Spectrum after sampling.*
(*c*) *Spectrum after further bandwidth restriction by Network E.*
* *See Fig.* 1.

It is important to realize that the bandwidth must be restricted by both filters D and E in order to remove the effect of sampling. Thus, if network E were removed altogether, the pattern of horizontal lines would be present on the display tube. Alternatively, if D were removed there would be no regular pattern of horizontal lines on the display tube, but the spectrum of the signal applied to this tube would still be contaminated by displaced versions of the original spectrum (extraneous components). In this latter condition a number of undesirable effects would remain. The most obvious of these is the occurrence of moiré patterns by a process illustrated in Fig. 4. Suppose that the scene contains a series of horizontal stripes at a spacing only slightly different from that of the horizontal lines produced by the sampling process. In the spectrum at the output of the flying-spot scanner, these will produce peaks in the neighbourhood of frequencies $\pm 1/\tau$. Two of the displaced versions of the spectrum produced by sampling will contain corresponding peaks near to zero frequency, and these will be present in the resultant spectrum after sampling. Bandwidth restriction in network E may remove the horizontal line structure, and at the same time prevent any true reproduction of the horizontal stripes in the scene, but it will not remove the peaks in the spectrum near to the origin, which cause coarse horizontal bands.

Another effect caused by the extraneous components associated with excessive bandwidth before sampling is the occurrence of errors in the position of horizontal edges. These edges may be portrayed with a kind of sharpness that is spurious, in that it is not a true guide to the accuracy with which the position of these edges are defined in the image. This effect is familiar in suppressed-field telerecording, producing steps on inclined edges. A similar effect occurs if a very narrow horizontal object is portrayed; it may become more or less visible according to its position relative to the horizontal lines.

Of all the effects referred to, the most serious is line beating, i.e. the horizontal moiré pattern produced when rescanning an image that has itself been formed by scanning, and it is always considered essential to remove it. Opinions often differ as to the desirability of making sacrifices in some other direction in order to avoid the other effects.

It has been pointed out that with the system shown in Fig. 1b the effect of sampling can be removed by making networks D and E rectangular phase-corrected band-pass filters, with a cut-off frequency $1/2\tau$. The impulsive response of such a filter is

$$\frac{\sin(\pi t/\tau)}{\pi t}$$

It follows that the same effect would be produced if the networks were removed while at the same time both scanning spots were broadened according to the line profile.

$$g(y)=\frac{\sin(\pi y/h)}{\pi y} \qquad (3)$$

where h is the spacing between horizontal scanning lines and y is distance measured vertically from the centre of the line. The portrayal of vertical detail would still remain

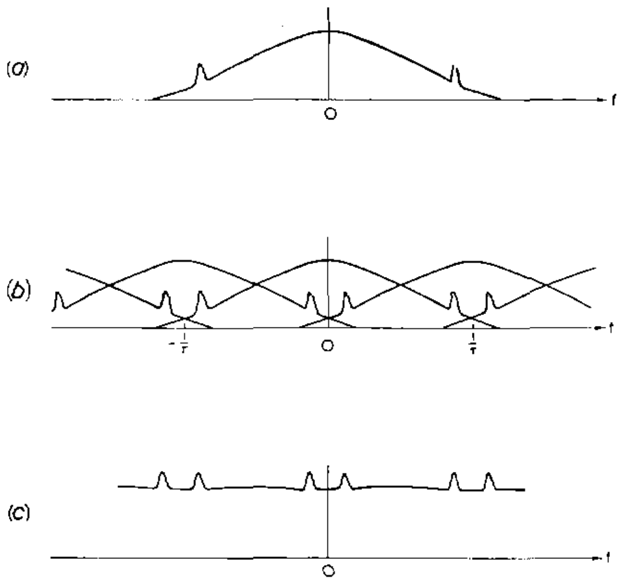

Fig. 4 — *Formation of moiré patterns.*

(*a*) *Original spectrum.*
(*b*) *Original spectrum and displaced versions produced by sampling.*
(*c*) *Resultant spectrum after sampling.*

unchanged by reverting to the horizontal scanning system of Fig. 1a while retaining the line profile of equation (3). Such a line profile is, in fact, impossible, since negative brightness would be required, but this difficulty will be overlooked for the present. Later it will be seen that negative brightness can sometimes be simulated.

The analogue system with vertical scanning, having served its purpose, will not be considered further. It has been shown that the use of the line profile of equation (3) would eliminate all effects associated with scanning in horizontal lines from a sequential picture. It would render the portrayal of vertical detail the same as that of horizontal detail, assuming a uniform frequency response with a sharp cut at a frequency $v/2h$, where v is the horizontal scanning velocity and h is, as before, the distance between the horizontal scanning lines.

It may be the case that horizontal detail is displayed more pleasantly if the video-frequency response characteristic begins to fall off gradually before the cut-off frequency is reached. If so, a similar falling off in the vertical frequency response characteristic would be desirable, and the line profile should be less oscillatory than that represented by equation (3).

Assuming the best line profile to have been chosen, the Kell factor (for a sequential system) would have been made equal to unity. In fact, the required line profile cannot be realized in the display tube of a receiver, but it might be applied to a sequential system with a small number of scanning lines used for transmitting television through a narrow-band circuit. Assuming any improvement in the picture to be offset by reducing the number of lines, the departure from unity of the Kell factor for a normal sequential picture is a measure of the greatest economy in bandwidth that might be made in this way.

5. Interpolation

5.1 *General*

In the previous section the line structure was visualized as the result of sampling, and its removal was considered in terms of filtering. It is instructive to explore an alternative approach in which the removal of the line structure from a displayed picture is regarded as interpolation. Suppose that a display tube has an infinitely small spot, so that the picture is displayed in fine lines separated by dark bands. The problem is to replace this picture by another in which the brightness is unchanged along the original scanning lines, but is no longer zero between these lines, varying smoothly from one line to the next.

The first step towards the solution of this problem is to determine what the brightness ought to be at a given point. This interpolation problem is illustrated in Fig. 5a. Suppose that we wish to determine the brightness required at an arbitrary point P. A line is drawn through P perpendicularly to the scanning lines, intersecting them in points . . ., P_{-2}, P_{-1}, P_0, P_1, P_2, . . . One of these points, P_0, is arbitrarily chosen as origin, so that the position of P is specified by $y=P_0P$. The required brightness at P could be determined by plotting the brightness at the points P_0, P_1, etc., against y, and joining the ordinates by a smooth curve as shown in Fig. 5b. The brightness required at P, or at any other point on the line P_{-1}, P_0, P_1, etc., can then be read off.

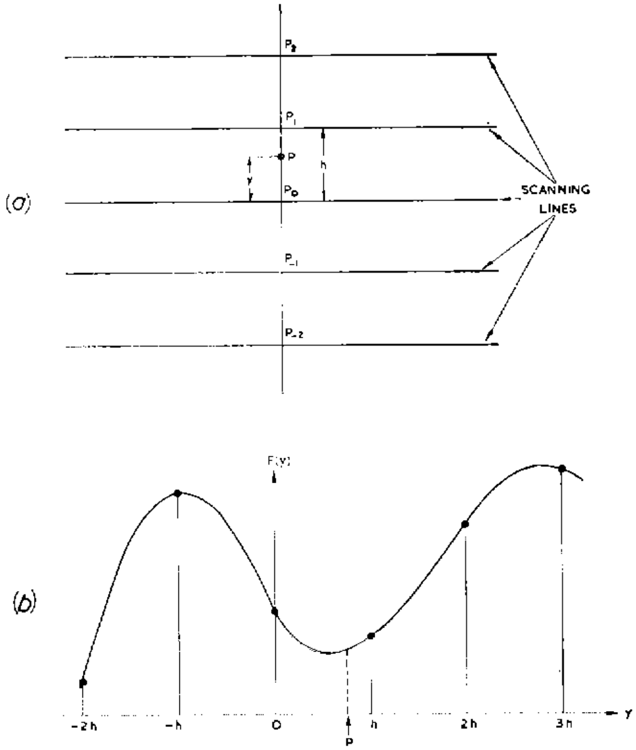

Fig. 5 — Interpolation between scanning lines.

In order to dispense with the judgment required to obey the instruction 'draw a smooth curve', numerical interpolation could be performed. The methods most used may be grouped under the heading 'polynomial interpolation'. In effect the range of the independent variable is divided into sections, and it is assumed that within each section the function can be represented by a polynomial. A graph representing the interpolated function therefore comprises a number of sections, each taking the form of a straight line, parabola, cubic, or higher polynomial curve. The interpolation process is termed first order, second order, etc., according to the order of the polynomials.

5.2 *Orders of Interpolation*

Zero-order interpolation (Fig. 6a) is the crudest method. The function is taken to have the same value as the nearest ordinate. Thus, writing $y=nh+y'$, the function is expressed as

$$F(nh+y')=F(nh) \tag{4}$$

where

$$-\tfrac{1}{2}h<y'<\tfrac{1}{2}h$$

First-order interpolation (Fig. 6b) is also termed 'linear interpolation' since the ends of the ordinates are joined by straight lines. The resulting function is expressed as

$$F(nh+y')=\left(1-\frac{y'}{h}\right)F(nh)+\frac{y'}{h}F(\overline{n+1}h) \qquad (5)$$

where $0 \leqslant y' \leqslant h$

A number of methods of second-order interpolation, also termed 'quadratic interpolation', are known. In all of them a graph of the function is made up of a series of sections of parabolae. Some of them are not symmetrical as normally used, in that the ordinates used to determine each section are not disposed symmetrically with respect to that section. Only the most commonly used symmetrical method will be considered here. As shown in Fig. 6c, one parabola is fitted to the first, second, and third ordinates, another to the second, third, and fourth ordinates, and so on. In the interval between each pair of adjacent ordinates the mean of the two parabolae available is taken as the interpolated function. The function is then represented by the equation,

$$\begin{aligned}4h^2F(nh+y')=y'(y'-h)F(\overline{n-1}h)+(h-y')(y'+4h)F(nh)\\+y'(5h-y')F(\overline{n+1}h)+y'(y'-h)F(\overline{n+2}h) \qquad (6)\end{aligned}$$

where $0 \leqslant y' \leqslant h$

There is no need to consider the third and higher orders of interpolation in detail. Of them the odd orders are the simplest, since they achieve symmetry without the need for taking the mean of two polynomials, as was necessary with second-order interpolation. In interpolation of the $(2n-1)^{th}$ order, a polynomial of the $(2n-1)^{th}$ degree is fitted to $2n$ ordinates. The interpolated function is taken to be equal to the polynomial between the two central ordinates.

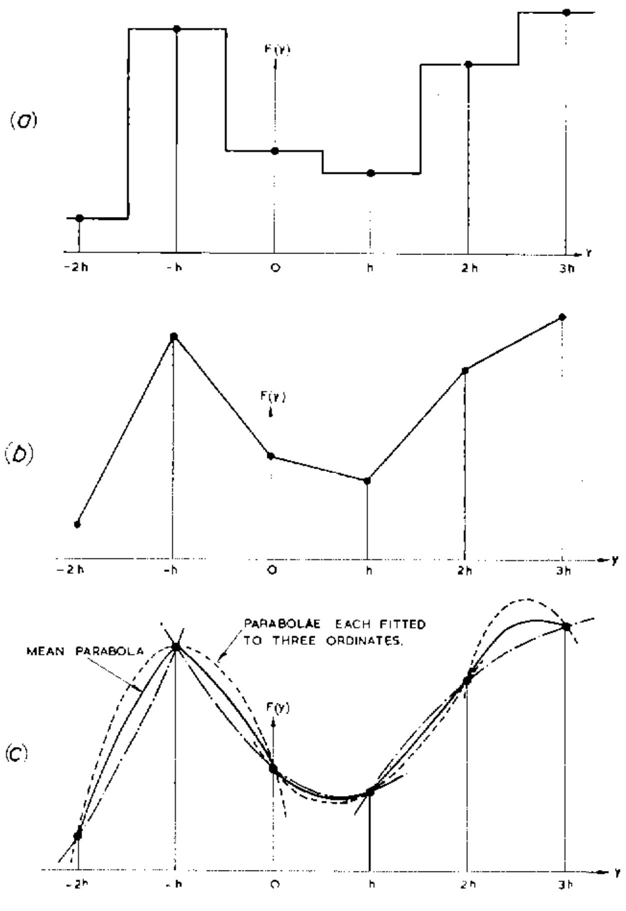

Fig. 6 — Orders of interpolation.
(*a*) *Zero order.*
(*b*) *First order* (*linear*).
(*c*) *Second order* (*quadratic*)

5.3 *Method of carrying out Interpolation*

Although first-order interpolation is termed linear because the sections of the resulting curve are straight lines, all the methods of polynomial interpolation are linear in another sense, in that the value of the function for any value of the variable is always obtained as a linear combination of the ordinates. Equations (4) to (6) may therefore be replaced by the more general equation,

$$F(y)=\sum_n \psi(y-nh)F(nh) \qquad (7)$$

where the summation extends over all the ordinates. The function ψ, which depends on the method of interpolation used, defines the way in which the contribution of an ordinate to the value of the interpolated function depends upon the distance (in terms of the independent variable) from the ordinate.

In numerical work formulae such as equation (7) are probably never used, since it is more convenient to begin by preparing a difference table, and then to express the function in terms of the elements of this table. A method that is more easily adaptable to the present problem is to use equation (7), beginning by drawing a curve representing the function ψ. A series of displaced reproductions of this curve are then drawn, one being centred on each ordinate and scaled in proportion to it. All the curves are then added together. Curves of the function ψ for the three orders of interpolation considered are shown in Fig. 7. Fig. 8 shows the process of building up a function from displaced versions of ψ, taking linear interpolation as an example.

It is not difficult to see that the whole interpolation process could be performed automatically by broadening the scanning lines in such a way as to make the line profile the same as the function ψ.

Zero-order interpolation may be performed by using a rectangular line profile. It is interesting that a rectangular profile has sometimes been regarded as the ideal one; although it corresponds to the crudest type of interpolation known. The triangular profile illustrated in Fig. 7b gives linear interpolation. In fact, a triangular profile may be built up by using two line-broadening processes, each of which alone would produce a rectangular profile. The combination of two processes in this way is discussed further in Section 8.

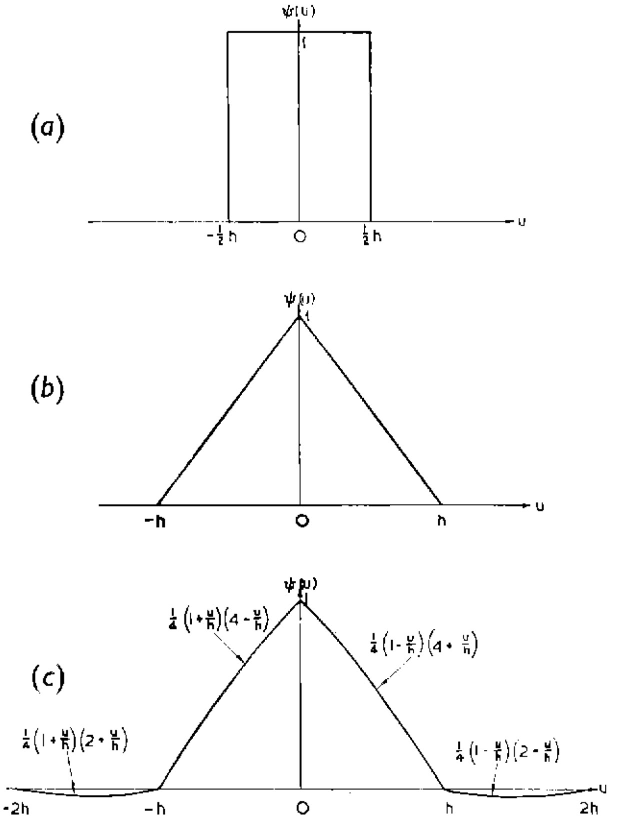

Fig. 7 — *The function* ψ.
(*a*) *Zero-order interpolation.*
(*b*) *First-order interpolation.*
(*c*) *Second-order interpolation.*

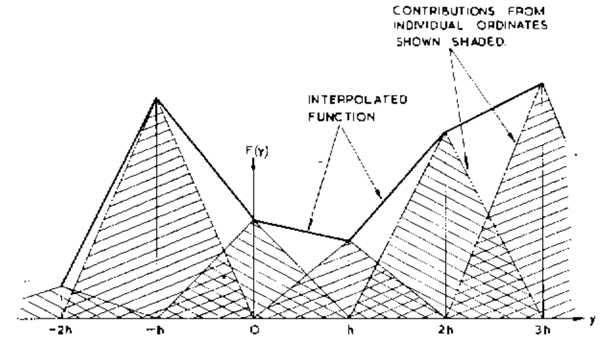

Fig. 8 — *Interpolated function as a sum of contributions from individual ordinates* (*illustrated for first-order interpolation*).

Orders of interpolation higher than the second will not be considered separately, but it may be shown that the general form of the line profiles continues a sequence of curves of which Figs. 7b and 7c are the first two. In each case the curve shows a central lobe as in Fig. 7c, the width between zeros being $2h$. This central lobe is flanked on either side by n half-cycles of oscillation, where the order of interpolation is $2n$ or $2n+1$. For the odd orders at least, it may be shown that as n increases, the half-cycles of oscillation increase in amplitude, while the discontinuities of gradient at integral multiples of h become less sharp. It may also be shown that in the limit as the order tends to infinity,

$$\psi(\mathrm{h}) \text{ tends to } \frac{\sin(\pi y/h)}{\pi y/h}$$

It is interesting to note that this is precisely the same line profile as that arrived at by considering sampling (equation (3)).

6. Choice of Line Profiles for Picture Source and Display Tube

6.1 *Sequential Systems*

In this section attention will be confined to a sequential television system comprising a picture source and a display tube.

At first sight it might appear that the optimum line profile is of the $(\sin x)/x$ form, discussed in Section 4 (ignoring the fact that this cannot be realized on a display tube), and this may indeed be the case. Extraneous components associated with scanning would be eliminated from the vertical spectrum, but there are two reasons why this would not necessarily give the best results. In the first place it might prove advantageous to retain a certain proportion of the extraneous components in the vertical spectrum, in order to avoid throwing away too much of the normal detail. This possibility could apply both to the picture source and to the display. In the second place, even if it is best to ensure that there are no extraneous components, a flat response up to the maximum permitted vertical spatial frequency might not be the best. A similar question arises in relation to horizontal resolution, when a definite bandwidth is allocated to a vision signal and the attenuation outside this band must be made very high. It is not known whether it is better to aim at a uniform response at frequencies within the band or to round-off the response characteristic towards the edge of the band, thereby sacrificing sharpness in order to reduce the oscillations associated with a sharp transition.

It is important to emphasize that there is no reason why the optimum line profile should be the same for the picture source and the display tube. Moreover, the two optimum profiles cannot be determined independently; for example, the optimum profile for the display tube will depend upon the profile in the picture source. Experimental determination of the optimum combination of profiles for a sequential system would be highly desirable.

6.2 *Interlaced Systems*

With an interlaced scanning system there are two kinds of defect associated with line structure. In the first place there will be the defects observed in a sequential system having the same number of lines. Secondly, there will be defects appropriate to the number of lines in a single field, and these effects will always alternate in sign at picture frequency. For example, with a 400-line interlaced system it is the 200-line structure of a single field which gives rise to line crawling on the display tube, even if the 400-line structure is completely eliminated by line broadening. Moreover, if the vertical resolution of the picture source is sufficient to resolve 200 lines, horizontal edges in the picture will vibrate at picture frequency, an effect that may be termed 'twittering'. When the scene contains horizontal stripes, such as venetian blinds, a coarse moiré pattern is sometimes seen to flicker at 25 c/s.

It is well established that with a 400-line interlaced system, the visibility of the lines is associated almost entirely with the 200-line structure of a single field. The lines are far less noticeable with a 400-line sequential system. It is not known whether the use of sufficient line broadening to eliminate the 200-line structure would be advantageous, since this would certainly entail an appreciable loss of normal detail. It would be instructive to conduct experiments on the British 400-line interlaced system to determine the line profiles on both source and display giving the most pleasing result and to repeat this experiment with a 625-line system. It would be interesting to know whether the advantage of the 625-line system would be reduced.

7. Formation and Rescanning of Intermediate Image

7.1 *General*

It is sometimes necessary to break the electrical connection between the source and display in order to display the information as an image and rescan it. The principal reasons for doing this are to make film telerecordings and rescan them for transmission later, and to effect conversion from one television standard to another. This kind of process may be repeated several times; the following probably represents the most extreme case:

1. A French outside broadcast is telerecorded in Paris.
2. The telerecording is rescanned and signals are sent to England on the 819/50 standard.
3. The signal is displayed on a cathode-ray tube in the standards converter at Tolsford Hill.
4. The picture is scanned by a camera giving an output on the 405/50 standard.
5. The signal is telerecorded at Alexandra Palace.
6. The film is scanned in the cablefilm equipment.
7. The cablefilm signals are recorded on film in the cablefilm equipment in New York.
8. The film is scanned by a telecine machine in New York for transmission.

At each stage line beating must be avoided, since if a coarse moiré pattern is formed in this way it cannot be removed later. It may therefore be necessary to apply line broadening several times, and an appreciable loss of vertical resolution may result.

If noise and non-linear effects could be ignored, it would not matter whether line broadening were applied in forming the intermediate image or in rescanning it. For example, it would not be necessary to use line broadening both in telerecording and in a telecine process. If it is used in both processes the two line profiles are, in effect, convolved together to produce a resultant profile (see Section 8).

7.2 *No Change in the Number of Lines*

An image may be formed on a screen and rescanned without changing the number of lines, in order to delay transmission. For example, a delay of hours or years may be achieved by making a telerecording and scanning it for transmission. A delay of less than 20 milliseconds, required for coupling an unsynchronized picture source into a network, may be obtained by using a cathode-ray tube and a television camera in a process resembling standards conversion. Since processes of this kind are not always used, they should ideally be arranged to have no effect, other than a change of timing, on the signal. We may compare the simpler problem which arises, in relation to the portrayal of horizontal detail. The circuit connecting a picture source with a viewer's receiver is a long chain containing a large and variable number of links. In order to permit as much freedom as possible, it is best to give each link in the chain a flat frequency response up to the limit of the band to be transmitted. Any 'roll-off' which may be desirable to avoid ringing is best restricted to the source and/or the receiver, since otherwise the insertion of additional links in the chain would cause a reduction in resolution. The same principles can be applied to the portrayal of vertical detail. Any intermediate process of forming an image and rescanning it should maintain a response flat to the highest vertical spatial frequency that can be passed without encountering line-beating effects associated with slight inaccuracy of scanning. This result can be achieved only with the $(\sin x)/x$ type of line profile discussed in Section 4.

In order to avoid line beating, it is sufficient to apply line broadening either when forming the image or when rescanning it. If, however, the ideal $(\sin x)/x$ type of profile could be realized exactly, it would not matter if it were applied both in the formation of the image and its rescanning. If, however, it is not possible to realize a profile having negative values, it will be impossible to avoid some falling off in the vertical frequency response towards the higher frequencies. This effect is likely to be less when line broadening is applied only to one of the two parts of the process. Unfortunately, it is often essential to apply line broadening to both parts for other reasons. For example, it may be essential to use it in telerecording in order to achieve sufficient contrast range, since otherwise the negative produced will have picture information recorded in narrow lines, the film between the lines being unexposed. In a positive print the space between the scanned lines will be dark, but will transmit some light as a result of limitations inherent in the photographic process, and of veiling glare in the telerecording and printing equipment. When the positive print is scanned (with line broadening) any transmission through the spaces between the lines will effectively lower the contrast range. In a telecine process line broadening will reduce phosphor and film-grain noise.

7.3 *A Change in the Number of Lines*

The number of lines is changed both in standards conversion and when a telerecording is exported to a country using a different number of lines. It remains true that for the elimination of line beating, line broadening need be applied in forming the image only or in rescanning it, but it may not, at first sight, be obvious whether the minimum amount of line broadening required is determined by the number of lines in the incoming picture or by the number in the outgoing picture. In fact, the amount of line broadening necessary and sufficient to avoid line beating is that which would be sufficient to remove the line structure from the displayed intermediate image. This is true even if the line broadening is applied only when rescanning this image, but for the sake of simplicity it will be supposed in the following argument that line broadening is applied only to its formation.

It is, of course, obvious that removal of the line structure from the displayed intermediate image is sufficient to eliminate line beating, but it is less obvious that this condition is always necessary, particularly when converting to a greater number of lines. The reason may be illustrated in terms of conversion from the British television standards with about 190 active lines per field to the French standard with about 370 active lines per field. It will be supposed that conversion takes place field by field rather than picture by picture. Suppose that the line broadening is applied to the display tube in such a manner as to leave some of the fundamental component of the line structure of a single British field, 190 c/p.h., while eliminating all the harmonics of this vertical spatial frequency. The vertical spectrum of an unmodulated raster displayed in this way will be shown by the full lines in Fig. 9.[*] Since we are supposing for the sake of convenience that all the line broadening is applied in the display tube, it is permissible to assume that the scanning lines in the camera are infinitely fine. If then the converted picture is displayed on a French receiver with perfect vertical resolution, the vertical spectrum of a single field will be modified by the addition of displaced versions spaced 370 c/p.h. apart of which only the central two need be considered. These are indicated by broken lines in Fig. 9. The major components at 0 and ±370 c/p.h. represent the French line structure. There are also intermediate components at ±180 and ±190 c/p.h., which will give a coarser structure in which alternate lines of the French field are emphasized. It might be supposed that this coarser structure is comparatively harmless, being no worse than that to which the British viewer is accustomed, but in fact the effect will be worse. The fact that there are two closely spaced minor components between adjacent major components (for example at 180 and 190 c/p.h.) means that there will be a 185 c/p.h. structure *modulated* by a coarse moiré pattern. Although the effect will be less than that of an *added* moiré pattern, since the 185 c/p.h. structure could be eliminated by viewing from a sufficient distance, it would probably be more irritating than a British raster. More important is the effect of non-linearity. Unless the converter camera is followed by gamma correction that corrects perfectly for the transfer characteristics of all French receivers an *added* coarse moiré pattern will be produced by intermodulation. When interlaced fields are viewed on the French receiver there will be bands in which lines on the British scale will be visible. The added moiré pattern resulting from imperfect gamma correction will flicker at 25 c/s. The flicker is likely to be the most objectionable effect.

When converting to a much higher number of lines, the ideal $(\sin x)/x$ line profile would probably not be the best, since the sharp restriction in the vertical spectrum would cause some ringing. However, this point is probably of academic interest, since in practice it would be difficult to make the restriction sharp enough.

A similar argument arises when converting to a much smaller number of lines, since the vertical resolution of the picture source used on the higher line standard might be excessive for the lower line standard. Again this is probably not of practical importance.

8. Combination of Different Means of Line Broadening

Even if only one method of line broadening is employed deliberately, instrumental imperfections will also contribute their effects. For example, the effect of spot wobble (see Section 9.2) on a cathode-ray tube will be supple-

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[*] For the sake of simplicity, it will be assumed that the origin of vertical position corresponds to the centre of the central line. The vertical spectrum, in exponential form, is then real.

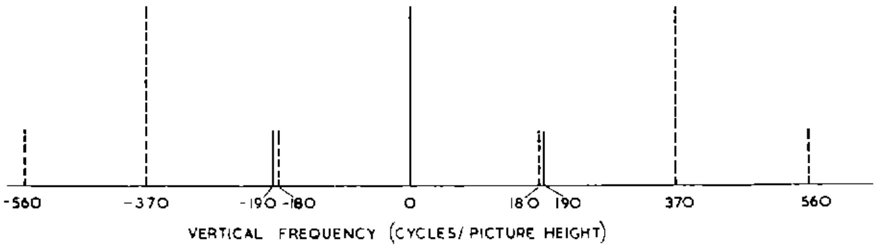

Fig. 9 — Vertical spectrum of one field of a French raster converted from the British standard.
——— *Vertical spectrum of British field.*
- - - - - *Displaced versions added by standards conversion.*

mented by the finite cross-section of the scanning beam, and if a lens is used to form an image of the raster its aberrations will also contribute to the total line broadening.

If non-linear effects, such as those occurring in film, phosphors, and television cameras, are excluded, it is not difficult to see that the vertical frequency response characteristics appropriate to the various means of line broadening are simply multiplied together. The resultant line profile may be derived by convolving together the individual profiles.

The latter statement is the one more easily verified. Suppose, for example, that spot wobble is applied to a cathode-ray tube. The line of finite breadth produced in the absence of spot wobble may be divided longitudinally into narrow elements. Each element will be broadened by the spot wobble to give the line profile appropriate to the spot wobble waveform employed. The resultant profile is obtained by adding together the displaced versions of the spot-wobble profile corresponding to the individual elements. This is just another way of describing the convolution process referred to above.

A line profile is analogous to the impulsive response of a two-port network. If two networks are connected in cascade, the resultant frequency response characteristic is obtained by multiplying the individual frequency response characteristics.

Two line profiles are not combined by convolution when each is associated with the aberrations of a lens, if light passes through both lenses without the intervention of a diffusing surface. The reason is that brightness, the dependent variable in the convolution process, is equivalent to power density, not to the amplitude of any electromagnetic vector. For this reason the contributions made to the brightness of an image by light arriving via different routes combine additively only when they are not coherent. When an imperfect lens forms an enlarged image of a point source, the light forming different parts of this image is coherent, and this coherence is preserved if a second lens forms a second image from the first. If the second lens is imperfect also, some light from different parts of the first image may arrive at the same point of the second image, and the resultant brightness at that point will depend on the phase relationship between the contributions. An example of the failure of convolution is provided by a pair of poor lenses whose aberrations tend to cancel one another. This situation does not commonly arise in connection with line broadening and will not be considered further.

If it is essential to produce a zero in the vertical frequency response characteristic, it is necessary that at least one of the means of line broadening employed should produce a zero at that frequency. This statement tends to contradict the commonly expressed view that the amplitude of spot wobble required—for example, to eliminate line beating in a standards converter—depends on the spot size. Consider for example the vertical frequency response characteristic associated with sinusoidal spot wobble (Fig. 10b, curve 2). Finite spot size will cause this characteristic to be multiplied by one falling off, probably monotonically, with frequency. The zeros will not be displaced, and it will not therefore be necessary to reduce the spot-wobble amplitude to bring the first zero back to line frequency. There will, however, be a general reduction in the amplitude of the response at the higher frequencies, so that the precise location of the first zero will become less critical. It might therefore be possible to reduce the spot-wobble amplitude very slightly below that theoretically required.

9. Methods of Line Broadening

9.1 *General*

While discussing methods of line broadening, a few examples of line profiles, together with the corresponding vertical frequency response characteristics, will be compared. In order to facilitate this comparison the following assumptions will be made in all cases:

1. In the absence of deliberate line broadening, it will be assumed that the scanning lines are of infinitesimal width. The line profiles calculated on this assumption can have discontinuities, and may even become infinite.
2. Line profiles will be expressed in terms of an independent variable chosen to make the first zero of the Fourier transform—i.e. of the vertical frequency response characteristic—occur at the line frequency. Thus, assuming a raster containing N lines, the first zero in the vertical frequency response characteristic will eliminate the frequency $1/N$ c/p.h. Some of the profiles considered will also suppress all integral multiples of $1/N$ c/p.h. and hence, will eliminate the line structure completely.
3. Line profiles will be scaled to make the infinite integral equal to $1/N$.
4. Vertical frequency response characteristics will be normalized to give unit response at zero frequency.

Some line profiles and the corresponding vertical frequency response characteristics are given as formulae in Table 1, and as curves in Fig. 10. The numbers given in the left-hand column of the table correspond to those marked on the curves.

Item 1 is the ideal $(\sin x)/x$ type of profile discussed in Section 4. Since this extends over an infinite range of the independent variable it cannot be realized in practice. Even an approximate version extending over a finite range is difficult to achieve since negative values are required. The problem of attaining a line profile with negative values, for example, one possessing overshoots disposed symmetrically on either side of the central lobe, is in essence the problem of vertical aperture correction. Some methods will be discussed in Sections 9.4 and 9.5. The simpler methods discussed in Sections 9.2 and 9.3 exclude line profiles attaining negative values.

Consideration of curves 2 to 6 in Figs. 10a and 10b illustrates the fact that a purely positive line profile cannot result in the elimination of spurious components in the vertical spectrum, since the vertical frequency response characteristic is not reduced to zero at vertical frequencies

TABLE I

Line Profiles and Vertical Frequency Response Characteristics

No.	*Possible methods of generation*	*Line profile* $g(y)$	*Vertical frequency response characteristic* $f(v)$
1		$\dfrac{\sin \pi N y}{\pi N y}$	$1 \cdot 0 \quad (v<N/2)$ $0 \quad (v>N/2)$
2	Sinusoidal spot wobble	$\dfrac{1}{\cdot 381\pi}\left\{1-\left(\dfrac{Ny}{\cdot 381}\right)^2\right\}^{-\frac{1}{2}} \quad \left(\|y\|<\dfrac{\cdot 381}{N}\right)$ $0 \quad \left(\|y\|>\dfrac{\cdot 381}{N}\right)$	$J_0(2 \cdot 40v/N)$
3	Triangular spot-wobble waveform or astigmatic optical system with rectangular stop	$1 \cdot 0 \quad (\|y\|<1/2N)$ $0 \quad (\|y\|>1/2N)$	$\dfrac{\sin(\pi v/N)}{\pi v/N}$
4	Astigmatic optical system with rhombic stop (or No. 3 used twice)	$1-N\|y\| \quad (\|y\| \leqslant 1/N)$ $0 \quad (\|y\| \geqslant 1/N)$	$\left\{\dfrac{\sin(\pi v/N)}{\pi v/N}\right\}^2$
5	Astigmatic optical system with circular stop	$\dfrac{4}{3 \cdot 83}\sqrt{1-\left(\dfrac{2\pi Ny}{3 \cdot 83}\right)^2} \quad \left(\|y\| \leqslant \dfrac{3 \cdot 83}{2\pi N}\right)$ $0 \quad \left(\|y\| \geqslant \dfrac{3 \cdot 83}{2\pi N}\right)$	$\dfrac{2J_1(3 \cdot 83v/N)}{3 \cdot 83v/N}$
6	Astigmatic optical system with specially shaped stop	$\cos^2(\pi Ny/2) \quad (\|y\| \leqslant 1/N)$ $0 \quad (\|y\| \geqslant 1/N)$	$\dfrac{\sin(2\pi v/N)}{(2\pi v/N)(1-4v^2/N^2)}$

NOTES: y is in units of picture height
v is in cycles per picture height

above $1/2N$. Moreover, there is some falling off in the characteristic at frequencies below $1/2N$. The greater the extent to which frequencies above $1/2N$ are suppressed, the greater is the (undesirable) suppression of frequencies below $1/2N$.

9.2 *Spot Wobble*

This method was invented by Barthelmey.[2] Sinusoidal spot wobble (Item 2 in Table 1 and Fig. 10) is the method of line broadening most usually employed. The line profile, which is independent of the horizontal scanning velocity, becomes infinite at points corresponding to the edges of the broadened line on the assumptions made. In practice, finite spot size in the absence of line broadening suppresses these infinite values, but the broadened scanning lines often show a doubled appearance.

It will be seen from Fig. 10b that sinusoidal spot wobble suppresses only the fundamental component in the vertical frequency response characteristic, but harmonics of this component are reduced in amplitude to a useful extent; for example, the second harmonic is reduced by 12 dB. This effect contradicts the view sometimes expressed that sinusoidal spot wobble merely replaces each scanning line by two spaced lines, since the latter procedure would leave the even-order harmonics at full amplitude.

Other spot-wobble waveforms may be used. In the cable-film equipment[14] a triangular spot-wobble waveform was used to generate a rectangular line profile (Item 3). This could be done because the scanning frequencies were very low; it would probably be impracticable with normal television scanning. The response associated with a rectangular profile falls off more rapidly than that due to sinusoidal

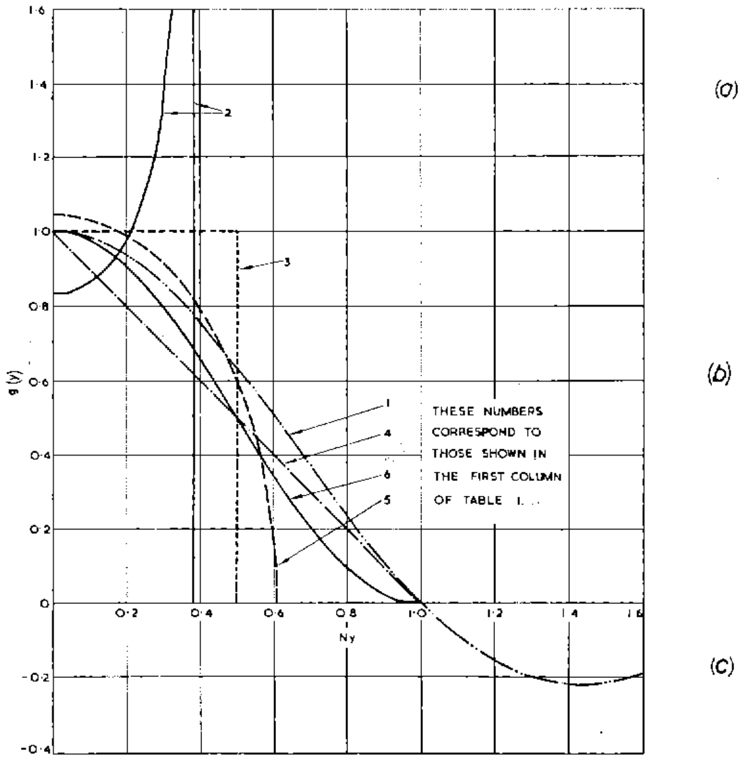

Fig. 10*a* — *Line profiles and vertical frequency response characteristics—Line profiles.*

spot wobble, so that the picture should be less sharp but should contain less extraneous components.

If two rectangular line profiles are combined (see Section 8) the result is a triangular profile (Item 4). This represents the effect produced if, for example, rectangular line profiles are used both in a telerecording process and a telecine process. Referring to Section 5, it will be recalled that a triangular line profile carries out a linear interpolation process.

9.3 *Astigmatic Optical Systems*

This method is applicable only when an image of a raster is formed by a lens. It could not be applied to a display tube viewed directly.

The use of a defocused spherical lens and an appropriately shaped aperture was used by Engstrom,[3] and later by Graham and Reynolds,[8] to simulate in an optical system some of the characteristics of a television picture.

If a lens free from all aberrations is defocused, the image of a point source is not a point, but an illuminated patch having the shape of the lens stop. (It is assumed that diffraction can be neglected.) In the absence of vignetting this patch is nearly uniform in brightness unless the aperture of the lens is very large indeed. If the object is not a stationary spot but a fine horizontal line, the image of the line will be broadened. The line profile is related very simply to the shape of the lens stop. Apart from scale factors it is the same as the function relating the width of the stop as a function of height above some arbitrary origin. For example, a rectangular stop with two sides vertical will give a rectangular profile. Only positive profiles can be realized. Unfortunately, the horizontal resolution is impaired unless the stop is made long and narrow, like a nonuniform vertical slit, and then too much light is lost for most television applications.

A better method of avoiding the loss of horizontal resolution[9] is to add a cylindrical component to the lens system, with the axis of the cylinder horizontal or vertical, and

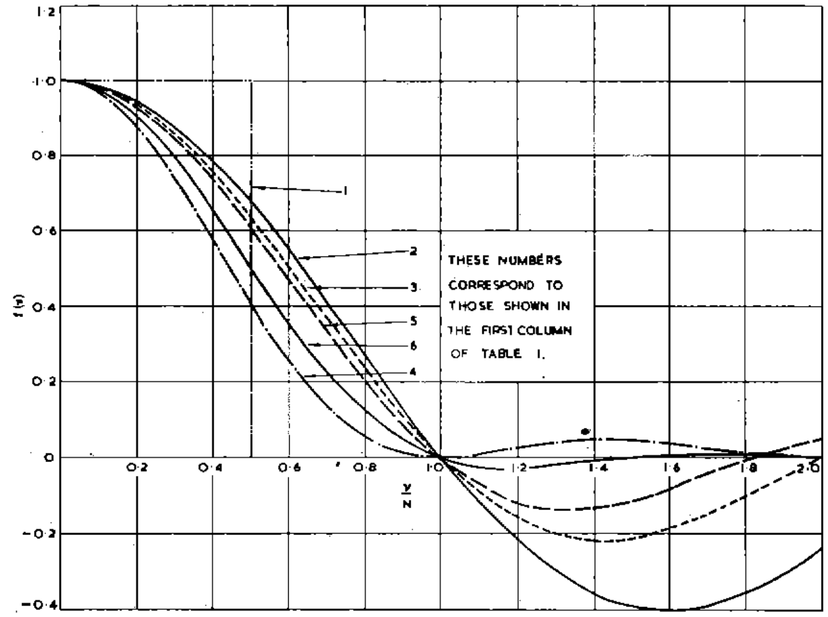

Fig. 10*b* — *Line profiles and vertical frequency response characteristics—Vertical frequency response characteristics.*

to focus in such a manner that the image of a point source is a vertical line. The line profile is then determined by the shape of the stop in the same way as before, the width of the broadened lines being proportional to the height of the stop and to the power (in diopters) of the cylindrical component.

Adjustment of the line width can be performed either by changing the height of the stop or by varying the cylindrical component of the lens. One method is to use two equal cylindrical lenses of the same sign and to rotate them in opposite directions. The cylindrical component is then maximum when the axes of the cylinders coincide, and zero when they are perpendicular. Alternatively, two cylindrical lenses of opposite sign can be used.

The use of a circular stop will give the line profile shown as Item 5. A square stop will give a rectangular profile (Item 3) when two sides of the square are vertical, or a triangular profile (Item 4) if a diagonal of the square is vertical. One other example, a profile of the 'cosine-squared' type, is given in Table 1 and Fig. 10 as Item 6. Cosine-squared time functions have been used for testing television links, presumably because they resemble bandwidth-limited functions about as nearly as possible without attaining negative values.

The accuracy with which a prescribed line profile can be achieved can be impaired severely by imperfection in the spherical lens. For the reasons discussed in Section 9 the effect of these imperfections cannot be deduced simply by convolution. W. N. Sproson has shown that curvature of the field caused by the spherical lens can cause serious errors.

9.4 *Modulated Spot Wobble*

This term is proposed for some processes that modify, or effectively modify, a line profile produced by spot wobble. The principle is similar to that of synchronous spot wobble, which was invented by Blumlein[10] and developed by Jesty,[11] Sarsen and Stock.[12] In synchronous spot wobble the portrayal of vertical detail is improved by applying spot wobble to the picture source and to the display in synchronism, at the same time increasing the video bandwidth to accommodate signal components around the wobble frequency.

The simplest process is applicable to a cathode-ray tube used for flying-spot scanning. The beam current of the tube is modulated with a waveform that is locked to the spot-wobble waveform. It may be easier to do this than to realize a spot-wobble waveform giving the required profile directly, since the need to pass high harmonics of the fundamental spot-wobble frequency through deflecting coils is avoided. The modulating waveform could be derived conveniently by passing the spot-wobble waveform* through a function generator, that is a circuit displaying 'point-to-point' non-linearity. Alternatively, the spot-wobble waveform might be used to synchronize a separate waveform generator.

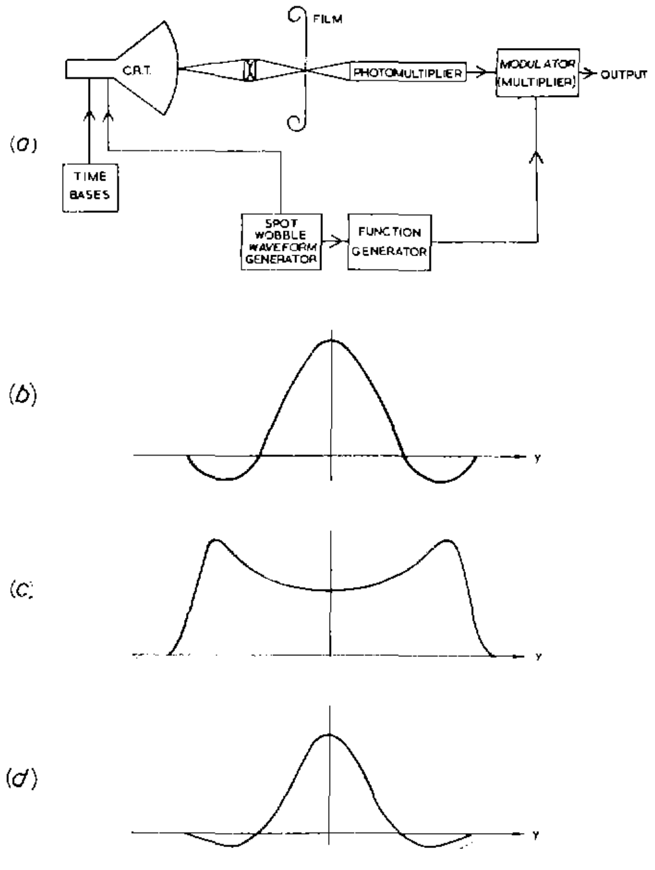

Fig. 11 — *Modulated spot wobble applied to a flying-spot scanner.*

(*a*) *Schematic diagram.*
(*b*) *Required line profile.*
(*c*) *Line profile due to spot wobble and adventitious broadening.*
(*d*) *Output of function generator.*

y = *Height above centre-line of broadened scanning line.*

In the case of a display tube, the modulating waveform would have to be applied to a modulator so as to modulate the picture signal, the result being applied to the grid of the cathode-ray tube. Gamma correction of the picture signal could take place before or after modulation, but the modulating waveform would depend on the alternative chosen. In the former case correction could not be made perfect if the cathode-ray tube did not display a constant 'point gamma'.

The methods mentioned above cannot result in a line profile having negative values, and it would therefore be possible to achieve the same result more simply by using an astigmatic optical system. In certain cases, however, it is possible to simulate a profile with negative values.

Reverting to a cathode-ray tube used for flying-spot scanning, the arrangement proposed above may be modified by applying the modulating waveform, not to the grid

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* The waveform passed to the function generator must be the waveform of spot deflection. If magnetic deflection is used the function generator operates on a waveform corresponding to the *current* in the deflecting coils.

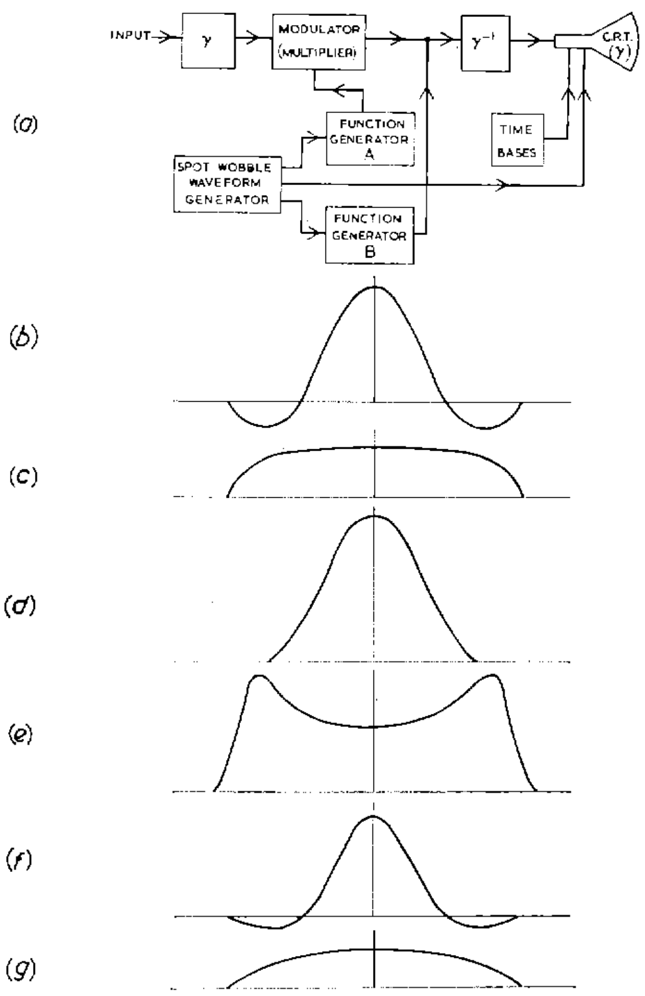

Fig. 12 — *Modulated spot wobble applied to a display tube.*

- (*a*) *Schematic diagram.*
- (*b*) *Required line profile.*
- (*c*) *Line profile associated with added 'sit'.*
- (*d*) *Sum of* (*b*) *and* (*c*).
- (*e*) *Line profile due to spot wobble and adventitious broadening.*
- (*f*) *Output of function generator A* [*equal to* (*b*)/(*e*)].
- (*g*) *Output of function generator B* [*equal to* (*c*)/(*e*)].

of the cathode-ray tube, but to a modulator modulating the output of the photocell. This arrangement, which is illustrated in Fig. 11, is essentially the same as a method, proposed by Nuttall,[13] of applying vertical aperture correction to a picture source. Suppose, for example, we wish to simulate the line profile shown at (b) in Fig. 11, which might be regarded as an approximation to the $(\sin x)/x$ type of profile. Sinusoidal spot wobble, together with accidental broadening due to imperfections, would give the profile shown at (c). Dividing (b) by (c) we obtain (d). The modulator is arranged to multiply the output of the photocell by a factor proportional to the ordinate in (d), the abscissa representing the amount by which the spot is instantaneously deviated by the spot wobble. If a waveform corresponding to this deviation is fed into the function generator shown in Fig. 11a, the output characteristic of this generator will be represented by the curve 11d.

It would be practicable to use the circuit of Fig. 11a in conjunction with slide-scanning equipment to investigate the relative merits of different line profiles.

In view of the fact that Sarsen and Stock[12] had some success in applying synchronous spot wobble to a 4½-in. image orthicon camera, it would appear that modulated spot wobble could be used in a camera channel without insuperable difficulty.

Even on a display tube, it is possible to simulate a line profile having negative values, but only if the addition of a component of brightness spread uniformly over the picture ('sit') can be tolerated. This could certainly not be tolerated on a display tube used for viewing, but it might be tolerable when the tube is used for standards conversion or some specialized form of telerecording. A possible arrangement is shown in Fig. 12a.

Two function generators, *A* and *B*, are excited by the spot-wobble waveform. The incoming picture signal is brought to a gamma of unity in the unit marked 'γ', modulated by the output of function generator *A*, augmented by the output of function generator *B*, and gamma-corrected for the display-tube characteristic in the unit marked 'γ^{-1}'. The addition of the output of function generator *B* takes place at a point where the electrical signals are linearly related to brightness on the cathode-ray tube.

Function generator *A* acts in the same manner as the function generator in Fig. 11a. For example, if Fig. 11b represents the required line profile, and if Fig. 11c represents the profile resulting from spot wobble with a constant beam current (taking into account finite spot size), then Fig. 11d represents the output/input characteristic of function generator *A*. If the profile attains negative values then the output of the modulator in Fig. 12a will attain negative values, and cannot be applied directly to the gamma corrector and cathode-ray tube. This difficulty is overcome by adding the output of function generator *B*. This is arranged so that, if it alone were applied to the gamma corrector and cathode-ray tube, it would produce a profile satisfying the following conditions:

1. Like other profiles under consideration, it eliminates the line structure.
2. When added to the wanted profile scaled for peak-white input signal, it produces a function which is nowhere negative.
3. The infinite integral, which is proportional to the additional 'sit' produced, must be as small as possible.

The various functions are illustrated in Fig. 12b to 12g. for a possible case. Here (b) is the wanted line profile scaled for a peak-white signal, and (c) is a profile satisfying the conditions outlined above. The sum of (b) and (c) shown at (d) is everywhere positive. (e) is the profile that would be produced by spot wobble and finite spot size for a constant beam current. The output/input character-

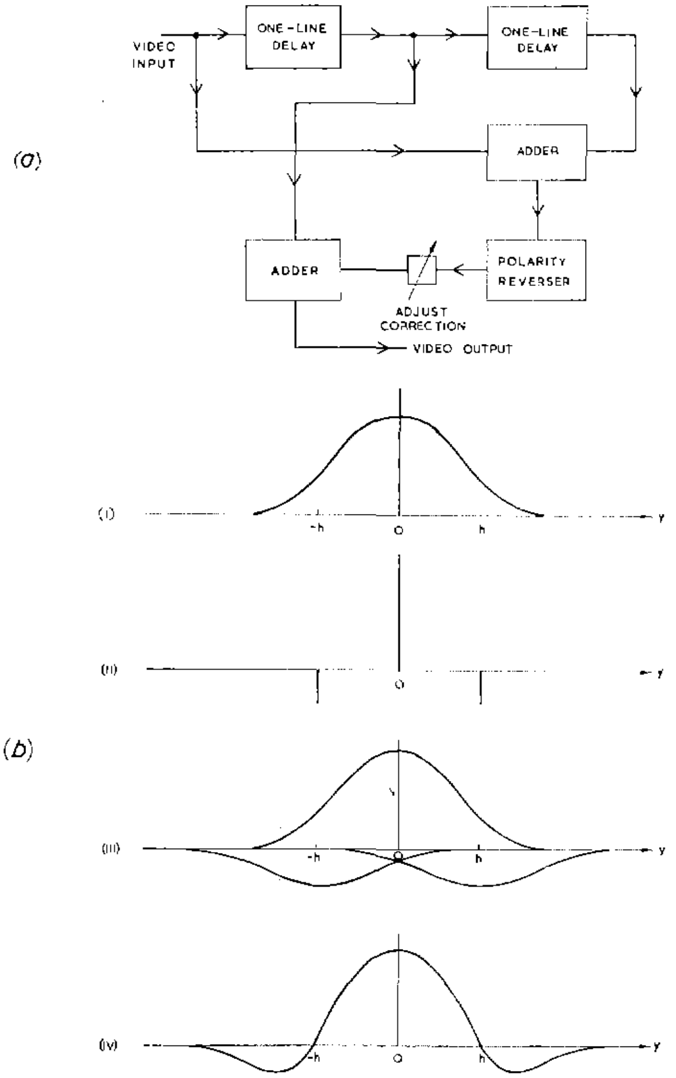

Fig. 13 — *Use of delay lines for vertical aperture correction.*
- (*a*) *Schematic diagram.*
- (*b*) *Line profiles.*
  - (*i*) *Without vertical aperture correction.*
  - (*ii*) *Vertical aperture correction alone.*
  - (*iii*) *Displaced versions subtracted.*
  - (*iv*) *Resultant.*

istic of the function generators A and B, shown at (f) and (g) respectively, are obtained by dividing (b) and (c) respectively by (e).

It is doubtful whether the addition of such a complex circuit as that shown in Fig. 12a to a standards converter would be justified, even though a useful improvement in picture quality might be obtained (with careful adjustment). In any case, the method to be described in Section 9.5 appears superior.

9.5 *Use of Delay Lines*

Gibson and Schroeder[15] have proposed a method of vertical aperture correction employing delay lines. The input signal is passed through two equal delay lines in cascade, and contributions to the output signal are taken from the input signal and from the outputs of the delay lines. By suitably combining these contributions with due regard to sign, a signal characterized by the function $F(t)$ is changed to one characterized by

$$F(t-\tau)-\lambda\{F(t)+F(t-2\tau)\},$$

where t is the time, τ is the delay of each delay line, and λ is a positive constant. Such an arrangement, with τ equal to or less than the duration of one picture element has been used for horizontal aperture correction. In order to obtain vertical aperture correction, Gibson and Schroeder made τ equal to the duration of one scanning line.

In Fig. 13, (a) is a schematic diagram of the arrangement and (b) illustrates the way in which it modifies the line profile. Consider in the first place a picture source, and suppose that its line profile is given by curve (i). The vertical aperture corrector will modify this profile by convolving it with the set of three impulse functions shown at (ii), thereby adding inverted profiles on either side of it, as shown at (iii). These are displaced from the original profile by h, the spacing between scanning lines. The resultant line profile is shown at (iv).

The methods of line broadening, or of modifying the line profile, discussed in earlier sections were all associated either with the scanning spot of a picture source, or with that of a display tube. The discussion in Section 4 made it clear that a given line profile has different effects when applied in these two places—before and after the sampling process respectively. The delay-line method is exceptional, in that it is not associated especially with the source or the display, since it can be applied at any point in the circuit connecting them. Its effect may be assessed in terms of a modification of the line profile of either the picture source or of the display. Thus the explanation illustrated by Fig. 13b could be applied without modification to the display instead of to the source. The reason for this freedom of choice is that the delay-line method produces a line profile that is the sum of three impulse functions (Fig. 13b(ii)) separated by h. This profile is unaffected by sampling at line frequency, and it therefore does not matter whether it is combined by convolution with the line profile of the source, or with that of the display. An alternative view is that the vertical frequency response characteristic associated with the aperture corrector is a periodic function with a period equal to the line frequency. This function is unaffected in shape when suitably displaced versions of itself are added to it by sampling.

Both the delay-line method and the modulated spot-wobble method shown in Fig. 12 enable a line profile attaining negative values to be realized on a display tube. It is, however, impossible to avoid adding 'sit' when the modulated spot-wobble method is used. There is less need for this with the delay-line method because the essential subtraction process is performed electrically rather than optically. If no 'sit' is added the process will fail only when the resultant electrical signal applied to the display tube attains a value representing negative brightness. This means that the vertical aperture corrector will fail to operate correctly in the darker tones. Fortunately, the eye is less sensitive to detail in this region. This partial failure also occurs when horizontal aperture correction is applied by means of electrical networks.

Gibson and Schroeder[16] envisaged two applications of their vertical aperture corrector. The first was to correct for adventitious line broadening due to imperfections in the picture source. The second was to realize a line profile like that shown at (iv) in Fig. 13b, intending this as an approximation to the ideal $(\sin x)/x$ type of profile required to eliminate the effect of the scanning lines. They envisaged the use of simple methods of line broadening, giving purely positive line profiles, in the picture source and in receivers. These measures would remove the evil effects of scanning in lines, but would cause excessive loss of normal picture detail. This loss they proposed to make good by the use of the vertical aperture corrector in the transmission chain, in effect changing the line profiles in picture source and receivers to a form resembling that in Fig. 13b(iv).

Gibson and Schroeder also proposed a vertical aperture corrector using delays of one field plus one half-line and one line respectively. This would enable the combination of contributions from three adjacent lines in the same picture, rather than from three adjacent lines in the same field.

9.6 *Orthogonal Scanning*

This is not strictly a method of generating a line profile of the required form, but of avoiding the need to do so. It is applicable to systems in which a television signal is converted from a broadcasting standard to a special standard for transmission by a circuit of restricted bandwidth and then converted back to the same or another broadcasting standard at the other end. A special standard is used in this way in the cablefilm system, when the film being sent is a telerecording, since the film may be regarded as a means of converting the signals to and from the 200-line sequential system used on the transatlantic cable. A similar double-standards conversion, using electronic means rather than film, might be used for a 'live' transatlantic television system in the future. If horizontal scanning is used in such a system, line broadening must be used in each of the two standards-conversion processes in order to avoid line beating, and if only positive line profiles can be generated there will be an unnecessary loss of normal detail.

The difficulty can be overcome very simply by using vertical scanning for the intermediate standard. It is then possible to remove the horizontal scanning lines of the original signal by a filter in the narrow-band transmission network. Unnecessary loss of vertical resolution is avoided and it is even possible to apply vertical aperture correction in this way. In the same way the vertical scanning lines of the intermediate standard can be removed by filtering the signal after the second standards conversion.

It is probably undesirable to abandon line broadening altogether, even though it is not required for the elimination of line beating. The use of fine scanning lines would reduce the contrast range when telerecording, and would accentuate film and phosphor grain noise both in recording and in reproducing processes. For these reasons it is desirable to use some line broadening in each of the two standards conversions, and to supplement this by filters. The filters will then have two purposes: to complete the elimination of the scanning lines and to provide some aperture correction.

It is true that vertical scanning will increase in the ratio 4 : 3 the amount of time occupied by line-blanking intervals, which are required for line flyback in scanning equipment, and for the transmission of synchronizing pulses, reference levels, etc., unless each interval can be shortened. It is, however, thought that if an intermediate standard is designed to use a narrow-band channel efficiently, the time wasted will be negligible. Moreover, the fact that the line-scanning frequency is higher should enable flyback to be faster. The higher repetition frequency of transmitted reference levels and carrier burst should permit each of these to occupy a shorter time.

If vertical resolution were the only problem it would be advantageous to perform an ordinary conversion between different broadcasting standards in two stages, converting first to an intermediate standard with vertical scanning. In the present state of the art, however, any improvement in vertical resolution would be more than offset by the degradation resulting from an additional conversion.

10. Conclusions

The purpose of this monograph has been, firstly, to revive interest in vertical resolution and the line structure, and to shed some light on these properties of a television picture, and secondly to discuss methods of eliminating the line structure. It must be admitted that no precise proposals have been made for improving television equipment, because there is a lack of knowledge of the subjective effects involved. To make good this deficiency the following three lines of inquiry would appear worthwhile:

1. *Determination of the Kell factor for interlaced scanning as defined in Section* 3
   In view of the definition proposed for the Kell factor, the experiment would amount to the determination of the best way of using a given bandwidth.
2. *Experiments on line broadening*
   Investigation 1 could be extended to determine whether, and to what extent, the Kell factor can be increased by the use of line broadening in the picture source and display. The results would help to ensure that subjective comparisons of different television standards were conducted fairly, using the optimum resolution in the picture source for each standard. Otherwise the use of a high-resolution picture source, such as a slide scanner, might exaggerate the inferiority of systems having few scanning lines.
3. *Experiments relevant to narrow-band systems*
   One of the methods of passing television signals through a circuit of narrow bandwidth is to perform

standards conversion to a sequential system with a small number of lines, and to convert back to a broadcasting standard at the other end of the circuit. Such a system is thought to offer the greatest advantage from a careful choice of line profiles. It would be highly desirable to perform experiments using both horizontal and vertical scanning for the intermediate sequential standard. In the case of horizontal scanning, it would be necessary to use modulated spot wobble or the delay-line method of vertical aperture correction.

One simple experiment could be performed using multi-standards slide-scanning equipment without much modification. This is the determination of Kell factors in sequential television systems using a comparatively small number of lines. Spot wobble should be employed on the display tube so as to eliminate the fundamental component of the line structure, since it would be essential to do this in a narrow-band system. Variable amounts of spot wobble, or line broadening with an astigmatic optical system, should also be employed in the picture source. It is suggested that both horizontal scanning with 180 lines and vertical scanning with 240 lines should be used.

The amount by which the Kell factor is less than unity for horizontal scanning will provide a guide to the maximum improvement (or reduction in bandwidth without loss of quality) that can be achieved with one of the more refined methods of line broadening, including orthogonal scanning.

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