A colour television camera with "Plumbicon" camera tubes

H. Breimer, W. Holm and S. L. Tan

The introduction of the "Plumbicon" television camera tube has brought new concepts to colour television camera design. Optical systems, mechanical arrangements and electronic circuits have all profited from these new ideas. Various aspects in the design of a Philips colour television camera and all its accessory equipment are discussed in some detail in the article below, and there is a brief account of practical experience with these cameras.

Introduction

The "Plumbicon" [*] camera tube has a number of features which allow the development of a colour television camera with these tubes to be approached in a different way from the design of a camera with image-orthicon tubes. This is true for the optical and also for the mechanical and electronic design. With the much smaller dimensions of the "Plumbicon" tube and its associated system of deflection and focusing coils, a new colour separation system can be used which is not only optically better than previous systems, but also, because of its small size, permits a completely new mechanical design to be used for the camera. The result is a colour camera which is no larger or heavier than many conventional black-and-white cameras. The main electrical features of the "Plumbicon" tube are a linear tube characteristic, which is little affected by temperature and voltage fluctuations, a signal current which is virtually free from noise and interfering components, and a black level which is nearly constant owing to the negligibly low dark current. In the following we shall see how these features have been taken into account in the design of a colour television installation [1] [2].

A studio or outside broadcast television installation almost always consists of two parts: the camera, mounted on a movable stand, and the control unit in the control room. These two parts are connected together by a cable containing a large number of single cores and several coaxial leads. For outside broadcasts, this cable may be hundreds of yards long. All electrical adjustments are kept together at the control unit where they are under the control of a technician who keeps watch on picture quality. The cameraman is only concerned with aiming and focusing the camera. Colour television installations are similarly divided. Obviously, as the electronic section of such installations is rather large every attempt is made to include as much of it as possible in the control unit.

Fig. 1 shows the camera with the "Plumbicon" tubes which we shall discuss here. The associated control unit, which will also be discussed briefly, is illustrated later on in the article (fig. 8).

Before discussing the camera, let us first briefly recapitulate the simultaneous colour television system on which all colour television studio installations are now based. The cone of light which enters the camera through the lens is distributed in three directions by a set of two colour-selective mirrors so that only a certain wavelength range of the visible spectrum passes in each direction. This gives rise to three cones of light containing the red, green and blue colour extracts from the received image. The mirror system does not affect the convergence of the rays of light to form a sharp image in the image plane, and sharp and geometrically congruent images in the primary colours red, green and blue are therefore produced on three identical camera tubes arranged in the cones of light.

The colour signals R, G and B derived from these tubes by the normal scanning process form the basis for the later reconstruction of the complete colour picture in the receiver. These signals set up three pictures in the primary colours red, green and blue in accurate geometrical register on the receiver screen, and the simultaneous presence of these three pictures gives the observer the impression of a picture in its natural colours (additive colour mixing).

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[*] Registered trade mark for television camera tubes.

[1] The "Plumbicon" tube and its features are discussed in detail in E. F. de Haan, A. van der Drift and P. P. M. Schampers, Philips tech. Rev. **25**, 133-151, 1963/64.

[2] A comparison between the features of the "Plumbicon" tube and those of other television camera tubes is to be found in A. G. van Doorn, Philips tech. Rev. **27**, 1-14, 1966 (No. 1).

[3] The back-focus distance of a lens system is the distance between the image plane and the rearmost portion of the system, which is generally the holder of the final component lens.

The camera

The components of every colour television camera can be divided into three groups: the camera lens with the colour separation system; the pick-up section with the camera tubes and their deflection and focusing coils; and finally the electronic circuits. While the problems encountered in the first group are almost entirely optical ones, the second group requires attention to precision engineering, and the third group comes in the province of the electronic engineer. A few of the problems arising in these widely varying fields will now be dealt with.

The camera lens and the colour separation system

An essential difference between black-and-white and colour cameras is that the back-focus distance of the camera lens in a colour camera must be very long [3] so that the colour separation system can be inserted between the lens and the camera tubes. Such a system consists of the colour-selective mirrors mentioned above, which divert for example the red and blue cones of light, while the green is allowed to pass through directly to the "green" camera tube (*fig. 2*). The red and blue cones are reflected again by ordinary plane mirrors so that they take up a direction parallel to the main optical axis before they arrive at the appropriate camera tubes.

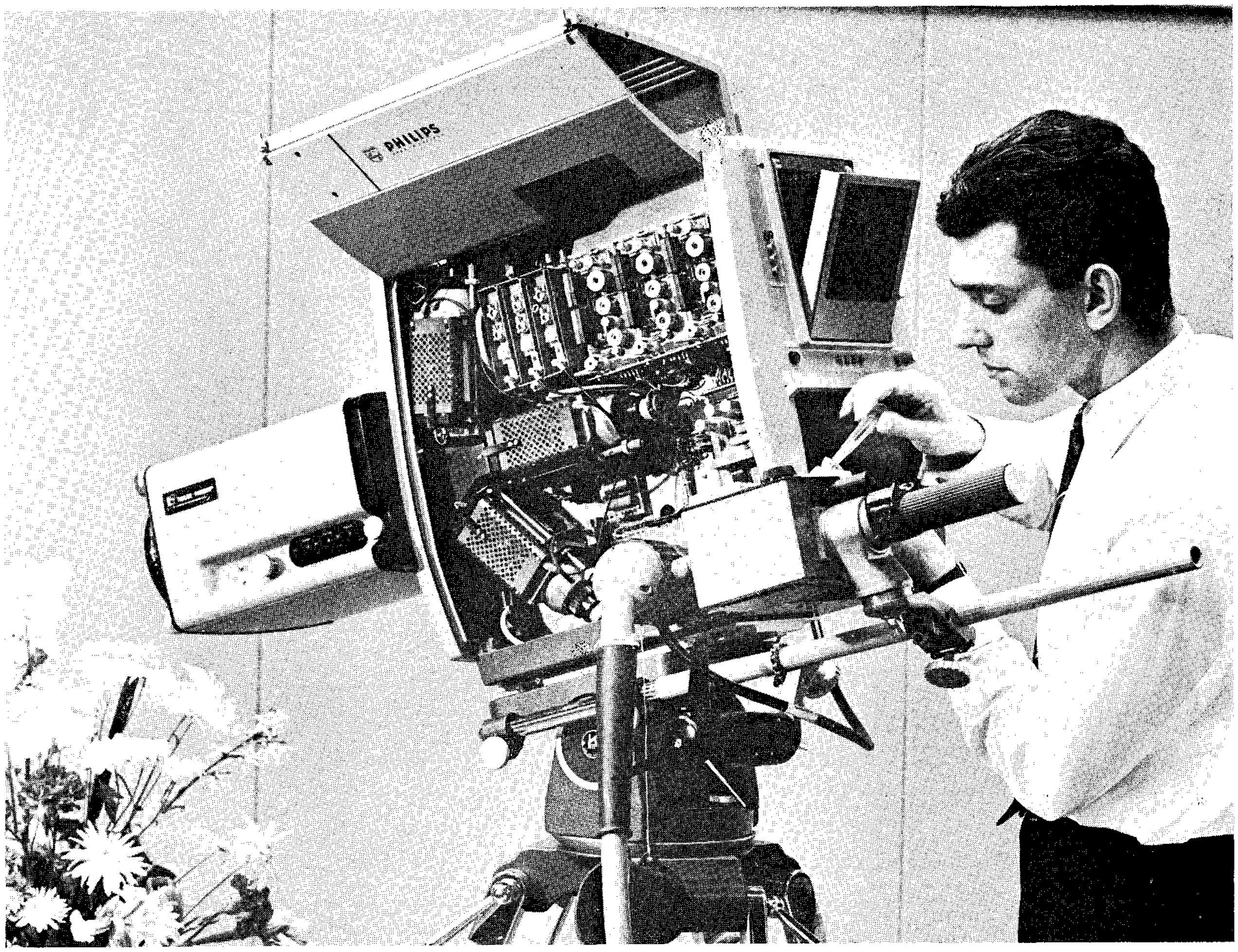

Fig. 1. The camera open but otherwise ready for use. The zoom lens in its housing, which also contains the servo drives, can be seen on the left. On its immediate right may be seen the small, encapsulated colour separation system, and the "Plumbicon" tubes, oriented in three different directions, with their deflection and focusing coil assemblies and preamplifiers. The remaining space in the camera is occupied by amplifiers and time-base circuits. The handle used for aiming the camera carries the servo controls for focusing and for choosing the focal length of the zoom lens.

The double reflection is important as it eliminates the lateral inversion which occurs in single specular reflection. This inversion could also be compensated by reversing the direction of scan in the camera tube. However, as the coil systems never have completely symmetrical deflection characteristics, there would be

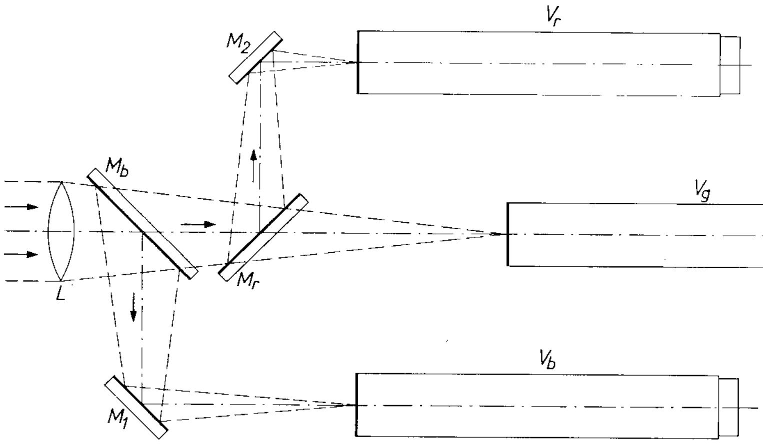

Fig. 2. Colour separation principle in television cameras. L camera lens, M_b and M_r colour-selective mirrors deflecting the blue and red components of the light successively, while the green component passes straight through to the camera tube V_g; M_1 and M_2 ordinary plane mirrors to reflect the deflected blue and red components of the light again, so that camera tubes V_r and V_b can be arranged parallel to V_g. The second reflection also eliminates lateral inversion.

differences in geometry between the normally scanned green image and the red and blue images scanned in the opposite direction. It is virtually impossible to correct for these differences, and the three primary colour pictures on the receiver screen would therefore not be completely in register.

The parallel arrangement of the camera tubes also assists the accurate register of the three pictures. With this arrangement, the effects of the Earth's magnetism or any other interfering fields on the deflection system are much the same for all three tubes, so that distortions of the scanning geometry are virtually identical for all three pictures.

In the camera described here these interfering effects are reduced adequately in another way, described below.

A colour separation system like that shown in fig. 2 requires so much room between the camera lens and the tubes that lenses with unsuitably long focal lengths and rather small relative apertures would have to be used. In image orthicon cameras, this difficulty is overcome by the addition of an optical system of long focal length (the relay system) which transfers the intermediate image obtained with a normal camera lens across the required large distance to the camera tubes (*fig. 3a*).

The small dimensions of the "Plumbicon" camera tube enabled us to develop a different method, described earlier in this journal [4], for our colour television camera. In this method the free space between the camera lens and the tubes is filled with glass at the location of the light beams. The convergence of the rays to the image plane is thus reduced and the effective back-focus distance of the lens increased. Numerically, this increase is roughly equal to the refractive index of the type of glass, $n = 1.52$ in the present case. The focal

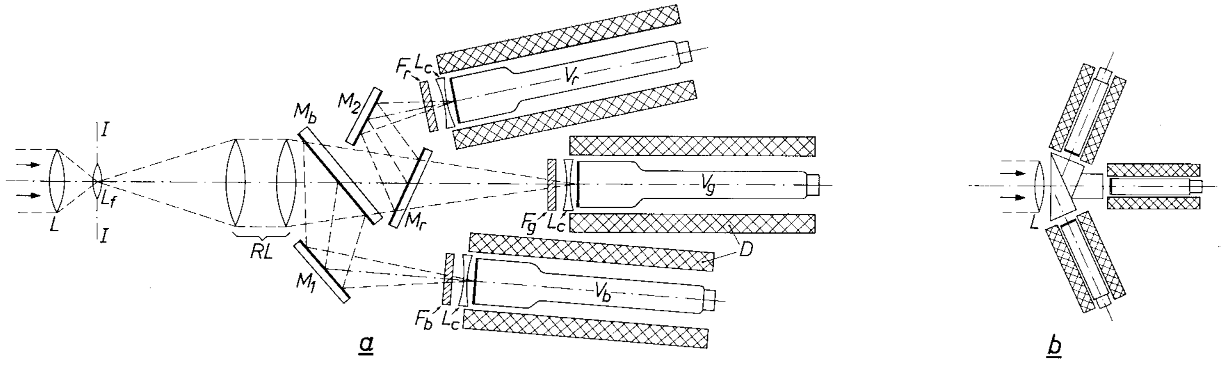

Fig. 3. Practical arrangement of the colour separation systems in *a*) image-orthicon cameras, *b*) the "Plumbicon" colour camera, the components being illustrated here *on the same scale* as those in (*a*).

In (*a*), L is the camera lens. To allow lenses with a large relative aperture and normal focal lengths to be used, an optical relay system RL is included. A focal length here of about 150 mm gives sufficient clearance for the colour separation system. L_f field lens for the concentration of the light beam in the optical relay system. The curvature of the image produced by L_f is compensated by the three correction lenses L_c. F_r, F_g en F_b are colour-correction filters to limit more sharply the wavelength ranges separated by the colour-selective mirrors. D deflection and focusing coil systems. The other letters are as in fig. 2.

length of the lens, the relative aperture and the magnification are unaffected by the added glass.

Colour separation must now take place inside the glass. This is achieved by sub-dividing the glass body into three adjacent prisms. The selectively reflecting layers are applied to the separating surfaces, while the re-reflection of the red and blue cones of light as mentioned above is obtained by means of total reflection (figs. 3*b* and 3*c*).

We can just briefly point out that with "Plumbicon" tubes, with their small image format (12.8 × 17.1 mm) and relatively small deflection-coil system, the method described gives considerably better results than a relay system. This has enabled the "Plumbicon" colour camera to be used with first-class lenses of relative aperture up to f/2 and a focal length down to 18 mm. These are the same as the values used with black-and-white cameras.

Because the number of optical components, and hence the number of transitions from glass to air, has been reduced to a minimum, the light losses of the entire optical system, which can amount to more than 50 % in relay systems, are greatly reduced here, to about 20 %. Moreover, definition and contrast of the image are considerably improved by the use of this method. Another advantage is that the light strikes the two colour-selective reflecting layers at relatively small angles. This means that polarization effects, which can lead to colour errors, particularly if there are specular reflections [4], occur only to a very slight extent. Finally, as we noted in the Introduction, the reduction of the size of the camera to that of a black-and-white model is primarily due to the compactness of the prismatic colour separation system. *Fig. 4* shows the prisms cemented together to form a block, while fig. 1 shows how the block with its protective housing is arranged between the camera tubes.

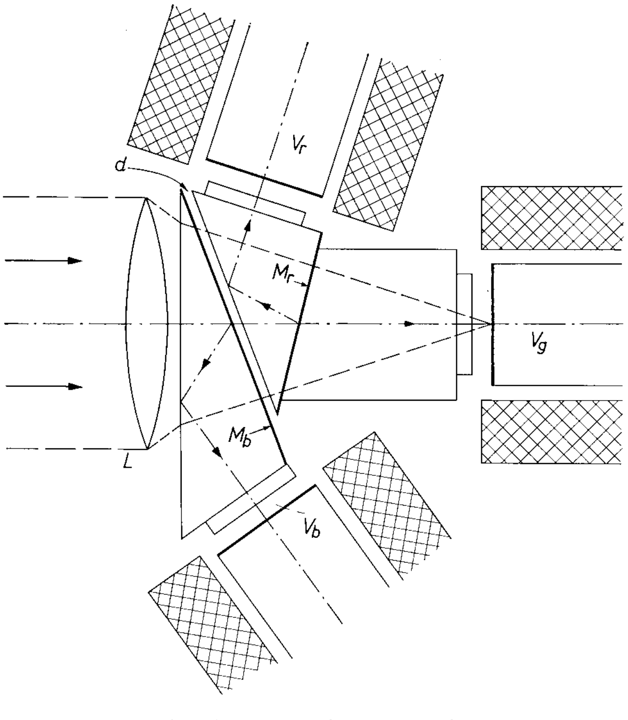

Fig. 3. *c*) Prismatic colour separation system of the "Plumbicon" camera as in fig. 3*b*, shown on a larger scale. *L*, again, is the camera lens. The colour-selective layers M_b and M_r are evaporated on to the rear of the two triangular prisms. The second reflection takes place by total reflection at the front of both prisms; a small air-gap *d* is provided for this purpose. The other letters are as in fig. 2.

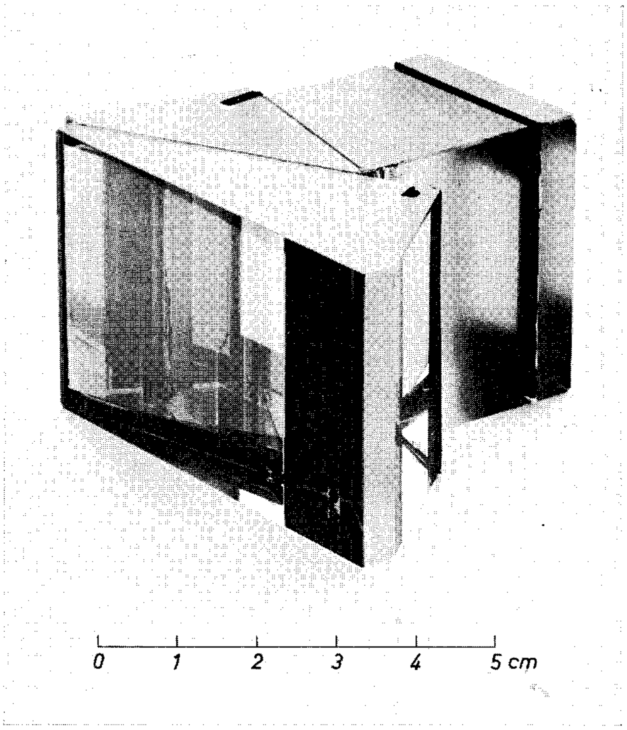

Fig. 4. The glass prisms in the colour separation system are cemented together to form one unit.

If this colour separation system is to be used, two conditions must be satisfied. First of all, the camera lens requires a slight additional correction because the light paths on one side of the lens are almost entirely in glass, not air. This is a matter for the manufacturers of the lenses, and presents them with no difficulties. Secondly, the camera tubes, which are not parallel as in fig. 2, must be given very effective magnetic screening to prevent interfering magnetic fields from causing different distortions of the scanning pattern in the three tubes. The screening is obtained by enclosing the tubes almost completely in mu-metal cases and by applying screening foil to the inside of the camera.

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[4] H. de Lang and G. Bouwhuis, Colour separation in colour television cameras, Philips tech. Rev. **24**, 263-271, 1962/63.

The pick-up section

Television studio work requires the camera tubes to be quickly and easily interchangeable. With colour cameras, we have the special problem that newly installed tubes must be very precisely positioned in relation to the cones of light from the colour separation system, so as to obtain congruent images on all the tubes. This means that the following conditions have to be satisfied:

1) The optical axis of each of the three cones must coincide with the longitudinal axis of the appropriate tube.
2) The three image planes of the lens must coincide with the surface of the signal electrode for each of the three tubes.
3) The horizontal direction in each of the three images must coincide with the direction of scan.

The mechanical design must be drawn up with this in mind, and the deflection coils and the camera tubes must be engineered to such a degree of precision that these three conditions can be met and continue to be met after a tube has been changed. In fact, the relatively simple construction of the "Plumbicon" tube and its set of deflection coils enabled a system to be devised for changing a tube without the need for mechanical readjustment. The initial setting of the three deflection-coil assemblies is carried out with the aid of an optical alignment device which permits six different adjustments to be made for each coil assembly. These adjustments are given by displacement along and rotation about three axes which are perpendicular to one another and pass through the centre of the signal electrode of the tube. (The rotation about the longitudinal axis of the tube is not in fact made during optical adjustment but by comparison with the horizontal direction of scan.)

Although we have been successful in eliminating the need for mechanical readjustment when a new tube is put in, a certain number of electrical adjustments are still required, as the electrode systems in different tubes are never completely identical.

The circuits

The circuits in a colour television camera may be subdivided into groups comprising of the three signal amplifiers, the deflection, focusing and blanking circuits, the supply section, the electronic view-finder and the signalling and telephone circuits.

The circuits in the first two groups mainly determine the performance of the camera and the quality of the pictures obtained. The design of these circuits is fundamentally affected by the particular features of the "Plumbicon" tube and its deflection system.

The "Plumbicon" tube supplies a signal current that, in practice, with appropriate lighting of the scene, can vary between about 0.3 μA at the points with the highest luminance and only a few nanoamperes in the darkest shadows. (The tube can be regarded as a source of high internal impedance, which means that the current supplied is almost independent of the load impedance.) These currents are extremely low, 50 to 100 times lower than those for image orthicons. This does not mean, however, that the image orthicon is 50 to 100 times more sensitive than the "Plumbicon". In fact, the sensitivity of a television camera is determined by the scene illumination at which a signal is obtained with a just tolerable signal-to-noise ratio. While the signal current of an image orthicon reaches this signal-to-noise ratio only at rather high values, the noise contribution in the signal current of the "Plumbicon" is negligibly low even at the smallest currents normally occurring in practice (see reference [2]). The signal-to-noise ratio of a "Plumbicon" camera is therefore entirely determined by the noise performance of the *signal amplifier*, which in turn is largely determined by its input stage. On this account the input stage is the one to which most attention has to be paid when designing the amplifier circuit.

To obtain a good signal-to-noise ratio, the amplifier must have as high an input impedance Z_i as possible. This can be understood in the following way. In our circuit, the input impedance consists of an input resistance R_i and a capacitance C_p connected in parallel. This capacitance C_p is formed by the input capacitance of the amplifier, in parallel with the signal-electrode capacitance of the "Plumbicon" tube, and the stray capacitance of the connecting leads. $|Z_i|$ (at frequency f) is then given by:

$$|Z_i| = \frac{R_i}{\sqrt{1 + (2\pi f R_i C_p)^2}} . \quad . \quad . \quad (1)$$

Since we can regard the "Plumbicon" tube as a constant-current source, the signal voltage v_s is proportional to $|Z_i|$:

$$v_s = i_s |Z_i|,$$

where i_s is the signal current. The noise, however, consists mainly of two contributions, one of which, the noise from the first valve or transistor in the amplifier, is independent of Z_i, while the other, originating in R_i, is given by

$$v_n = \sqrt{4\,kT\Delta f}\;\frac{\sqrt{R_i}}{\sqrt{1 + (2\pi f R_i C_p)^2}},$$

where v_n = effective noise voltage, k = Boltzmann's constant, T = temperature and Δf = bandwidth. If

$|Z_i|$ is increased, which, as equation (1) shows, may be done by making R_i greater or C_p smaller, the signal voltage increases proportionally to $|Z_i|$, while the first-stage noise contribution remains constant and the one due to R_i increases much less rapidly: the signal-to-noise ratio will therefore improve.

It can be seen from equation (1) that the term $(2\pi f R_i C_p)^2$ in the denominator indicates a decrease in $|Z_i|$ at higher frequencies, and thus a falling response. If we assume, for example, that $R_i = 1$ MΩ and $C_p = 25$ pF, and if the signal current i_s is 0.3 μA, the signal voltage decreases from 300 mV at zero signal frequency to about 0.5 mV at 5 MHz. This amplitude loss must be compensated in a later stage of the amplifier, by extra amplification of the higher-frequency components of the signal, but this compensation has the adverse effect of accentuating the amplifier noise from the first stage, which is not itself frequency-dependent. On this account, it is desirable to prevent too rapid a decrease of Z_i at high frequencies and therefore not to make the product $2\pi f R_i C_p$ too great. This is another good reason for keeping C_p as low as possible. Keeping R_i low, however, has an adverse effect on the signal-to-noise ratio, which as we have shown in the previous paragraph, requires a high value of R_i.

The two conflicting requirements for the value of R_i can be largely reconciled by the use of *negative feedback*, as will be seen in the following more detailed discussion of our signal amplifier.

To reduce the amplifier noise from the input stage, nuvistor input circuits (the nuvistor is a small thermionic triode system) have usually been used both for "Plumbicon" and vidicon cameras, although the vidicon cameras were otherwise fully transistorized. Nuvistors give considerably less noise than *P-N-P* or *N-P-N* transistors. Their noise performance has however been surpassed by that of the field-effect transistors which are now available. Moreover, these give a lower input capacitance than nuvistors. For the input stage of the signal amplifier we have therefore chosen a combination of a field-effect transistor and an *N-P-N* transistor. This gives a signal-to-noise ratio 2 to 3 dB better than that obtained with a nuvistor; in an experimental version the improvement was as much as 7 dB.

The basic circuit of the input stage, a cascode circuit with feedback, is given in *fig. 5*. Part of the signal voltage amplified in *Tr1* and *Tr2* and taken from emitter follower *Tr3* is fed back to the input via R_3 and R_2. The actual control voltage of *Tr1* then becomes:

$$v_i = i_1 Z_1 + (i_1 + i_3) Z_2.$$

Z_1 and Z_2 are the impedances of the circuits formed by R_1 with its parallel capacitance C_1 (which is significant here), and by R_2 and the trimming capacitance C_2. After substituting

$$i_3 = \frac{-g v_i - i_1 Z_1}{R_3 + Z_2},$$

where g is the total amplification between *Tr1* and the emitter of *Tr3*, then:

$$v_i = i_1 \frac{Z_1 + \dfrac{Z_2 R_3}{Z_2 + R_3}}{1 + g \dfrac{Z_2}{Z_2 + R_3}}$$

and the "dynamic" input impedance is:

$$Z_i = \frac{v_i}{i_1} = \frac{Z_1 + \dfrac{Z_2 R_3}{Z_2 + R_3}}{1 + g \dfrac{Z_2}{Z_2 + R_3}}.$$

This expression can be reduced to the form for a simple *RC* circuit if $R_2 C_2$ is made equal to $R_1 C_1$ with the aid of the trimming capacitance C_2 and if $R_2 \ll R_1$. Then:

$$Z_i = \frac{R_1}{1 + g \dfrac{R_2}{R_2 + R_3}} \cdot \frac{1}{1 + j\omega C_1 \dfrac{R_1}{1 + g \dfrac{R_2}{R_2 + R_3}}}.$$

The total impedance presented to the signal current i_s

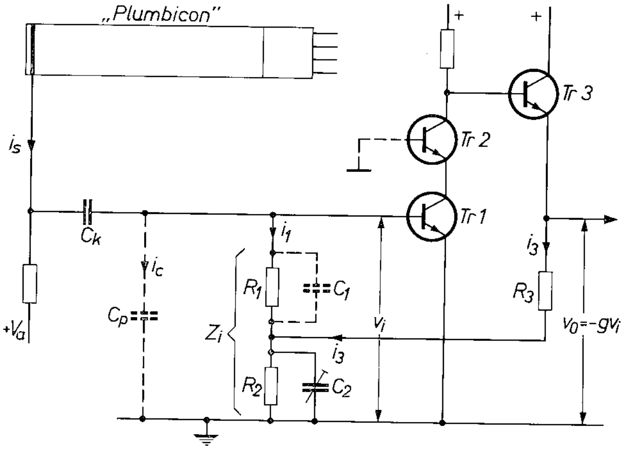

Fig. 5. Simplified diagram of the input stage of a signal amplifier for the "Plumbicon" tube with negative feedback cascode. The tube, which may be regarded as a source of constant current, supplies a signal current i_s, part of which (i_c) flows through the stray capacitance C_p, while another part (i_1) passes through the input impedance Z_i of the amplifier. The amplified feedback current i_3 generates an opposite voltage across $R_2//C_2$ so that the control voltage v_i is lower than that calculated from the product $i_1(R_1//C_1 + R_2//C_2)$. The input impedance is therefore reduced by the feedback.

supplied by the "Plumbicon" tube is that due to Z_i in parallel with the stray capacitance C_p, and is thus:

$$Z_{tot} = \frac{kR_1}{1 + j\omega kR_1(C_1 + C_p)},$$

where

$$k = \frac{1}{1 + g\dfrac{R_2}{R_2 + R_3}}.$$

This means that, for a given amplitude-frequency response, R_1 may be $1/k$ times greater than in a non-feedback circuit. To put it another way, the later stages will now only have to compensate for a k-times smaller reduction in amplitude at higher frequencies.

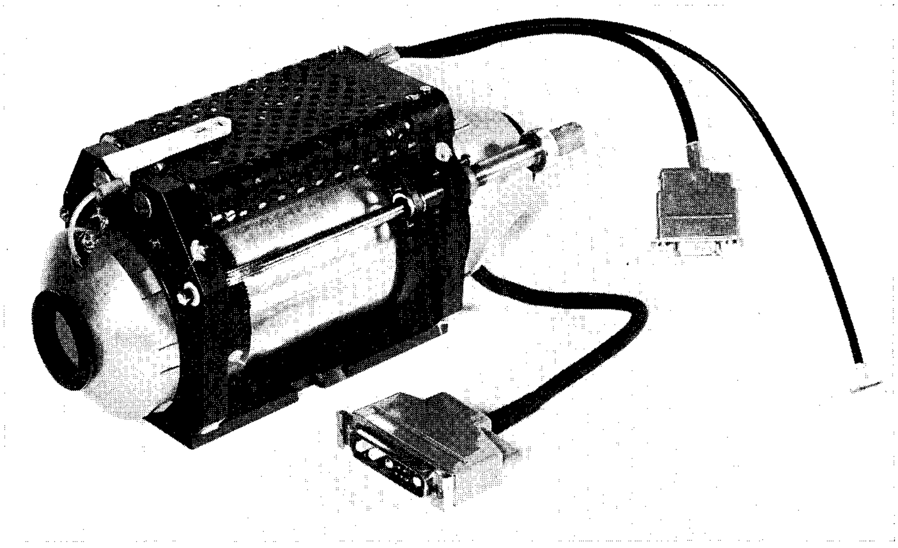

Fig. 6. Deflection and focusing coil assembly for a "Plumbicon" tube with the preamplifier fitted to it and protected by a perforated screening plate. (In the model illustrated here, the preamplifier is an earlier version, with nuvistors.)

With the circuit in question, we have obtained a signal-to-noise ratio of 45 dB at the signal current of 300 nA quoted above and a bandwidth of 5 MHz [5].

To keep the stray input capacitance C_p as low as possible, the three preamplifiers, which are printed wiring boards carrying the input stages, are each fitted directly on top of the appropriate deflection systems, giving a very short distance between input stage and the signal electrode of the "Plumbicon" tube (see *fig. 6*). With this arrangement, interference due to stray electric fields at the input lead is also kept to a minimum.

Each preamplifier contains only the input stage and emitter follower. From the low output impedance of the emitter follower the signals are fed via screened leads to further amplifier stages in the camera. The reduction in amplitude which we mentioned earlier is compensated in these stages, so that signal components at frequencies up to 6 MHz are fed to the camera cable at equal amplitude. The level of these components lies far above that of any interference that might be picked up in the long cable between camera and control unit.

The excellent noise performance of these signal amplifiers ensures a low interference level in the picture, and their linearity and stability ensure very faithful colour rendering. Another important factor in the quality of a colour television picture is the accuracy of register of the three primary colour pictures: this is determined by the characteristics of the deflection circuits. The designs of the vertical and horizontal deflection circuits are quite different, because of the difference in scanning speed.

The *vertical* deflection circuit is located in the control unit and the three finally-shaped saw-tooth currents for vertical deflection in the three tubes are fed directly to the deflection coils via the camera cable. All the controls and adjustments can thus be made at the control unit. As the impedance of the deflection coils is very nearly purely resistive at the low frequency of the saw-tooth currents (50 Hz), this method presents no difficulty. Sufficient stabilization of the desired shape and amplitude of the saw-tooth currents against fluctuations in the temperature of the camera cable and the deflection coils is obtained by current feedback in the output stages of the deflection circuits.

Matters are not so simple for the *horizontal* deflection circuits. A pair of horizontal deflection coils requires a current with a saw-tooth wave form between −100 and +100 mA and a repetition rate of 15 625 kHz. The resistance R of the pair of coils is 3 Ω and its inductance L is 1 mH, so that the impedance at a frequency of 15 kHz is $Z = R + j2\pi fL = 3 + 100j$ (Ω). In order to obtain a saw-tooth current in this almost pure inductance, a pulsed voltage is required whose amplitude is given by the expression:

$$v_L = L\frac{\mathrm{d}i_{\mathrm{st}}}{\mathrm{d}t}.$$

In practice, a peak voltage of about 60 V is used. Because of the ohmic resistance, a saw-tooth component

$$v_{\mathrm{st}} = Ri_{\mathrm{st}}$$

has to be added to this voltage (see *fig. 7*).

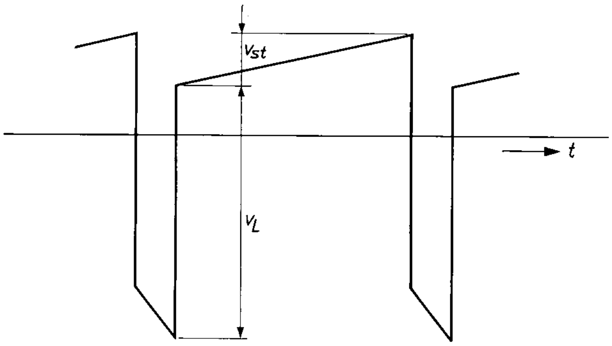

Fig. 7. The voltage waveform required for the horizontal deflection coils of a "Plumbicon" tube. v_L pulse voltage which sets up a saw-tooth current in the coils; v_{st} saw-tooth voltage for linearizing the saw-tooth current.

While the value v_L determines the amplitude of the saw-tooth current, and hence the scanning width, the linearity of the saw-tooth current and the scanning sweep is governed by v_{st}. Apart from these two parameters, the position of the pulsed voltage in relation to the zero line is significant, as this determines the symmetry of the scanning sweep in relation to the vertical centre line of the signal electrode of the camera tube. This requires the addition of an adjustable d.c. component.

For practical reasons, these three important adjustments are made in the central control booth, i.e. at the control unit, and not at the camera. Up to now it has been usual for the basic horizontal deflection waveforms for colour cameras to be generated at the control unit, and distributed from there to the three channels. The three adjustments mentioned above for each channel were also made at the control unit and the individually adjusted waveforms were fed to the deflection coils in the camera via three coaxial leads in the camera cable. This method not only involved appreciable wastage of power on account of the 75 Ω characteristic impedance of the cable (cf. the coil resistance of 3 Ω), there were also considerable complications in maintaining the correct voltage waveforms when cables of different lengths and types were used and when there were temperature variations.

The development of very stable transistor circuits has made it possible to shift the whole of the horizontal deflection circuit for the colour camera with "Plumbicon" tubes to the camera itself and so to eliminate the difficulties just mentioned. Now only a trigger pulse for the pulse generator circuit in the camera — this pulse is not critical in shape or amplitude — and a number of d.c. voltages for the control of amplitude, linearity and the d.c. component of the scan are fed through the camera cable. The controls for these voltages are arranged on the control unit and remain thus under the charge of the technician responsible for all the adjustments in the camera installation.

The accurate alignment and focusing of the electron beam in each tube are also important for the precise register of the primary colour images from the three camera tubes. Since the electrode system is never perfectly symmetrical, the beam from the electron gun is generally at a slight angle to the axially directed magnetic focusing field in which the entire tube is located. An oblique entry gives a helical motion to the beam, which upsets not only the exact focusing but also the deflection geometry. This fault can be remedied by aligning the beam with the aid of a transverse magnetic field, adjustable in strength and direction, arranged immediately in front of the electron gun. It is possible to align the beam correctly only if the magnetic focusing field is homogeneous and parallel to the axis. Disturbances of the homogeneity of the field within the tube and especially in front of it must therefore be prevented. The deflection and focusing coils must on this account be manufactured and fitted with the utmost precision. The currents in the focusing coils and in the coils for beam alignment are of course stabilized.

The other circuits in the camera are little different from those of other cameras. For completeness we shall just give a very brief description of the function of these circuits.

The *blanking circuit* is designed to suppress the scanning beam during the horizontal and vertical flyback of the scan to prevent partial erasure of the charge pattern on the tube target in these periods. This is done

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[5] In television, the signal-to-noise ratio is regarded as the ratio between the maximum signal amplitude at a black-and-white transition and the r.m.s. value of the noise. For the "weighting" of the noise and the associated filter, see reference [2], page 5. Measurement with a noise-weighting filter, as used for black-and-white television, has under the given conditions indicated a signal-to-noise ratio of as high as 60 dB.

with blocking pulses obtained from the horizontal and vertical deflection circuits in the camera and combined to form a common series of pulses. These pulses are added to three negative d.c. voltages adjusted individually at the control unit and fed to the camera via the cable. The sum of these d.c. voltages and the blanking pulses is applied to the control grids of the three "Plumbicon" tubes. The d.c. voltages determine the beam currents of the tubes.

In television cameras, the *electronic view-finder* replaces the optical type found on cine cameras and allows the cameraman to aim his camera accurately. The view-finder is simply a small monitor which displays as a black-and-white picture the video signal received from the control unit after processing for transmission. In the vast majority of cases the green picture is most suitable for black-and-white reproduction, but, by pressing the appropriate button, the cameraman can select the red or blue picture or any combination of the three for display in black-and-white on his view-finder screen. Furthermore, the signal from another camera can be superimposed on his own view-finder image; this is very useful in special work where pictures from two cameras are combined.

The *signalling* and *telephone* circuits which include various indicator lamps arranged at suitable points on the camera and two headphone connections, give a communication link between cameraman and assistant and the technician in the control room and the director. These circuits are also used to give an indication to those in the studio that the camera is on the air. The indicator lamps for this are switched on automatically as soon as the camera signal is applied to the preview monitor in the control room, giving the final check before the actual transmission.

The control unit

The control unit of every colour television camera has four main functions: the "refinement" in various aspects of the three colour signals supplied by the camera, which takes place in the *processing amplifiers*; adjustment of the signals for optimum colour rendering under different conditions of illumination; adjustment for optimum register and definition of the three primary colour images; checking these adjustments with the aid of a signal monitor and a picture monitor; and finally the provision of power for the entire installation.

Instead of fitting all the components for these functions into a single constructional unit, as in the camera, it is preferable to arrange them according to their function in sub-units on a vertical rack. This facilitates check measurements and servicing. All important units are of the slide-in type and the circuits are arranged on quickly interchangeable printed-wiring boards.

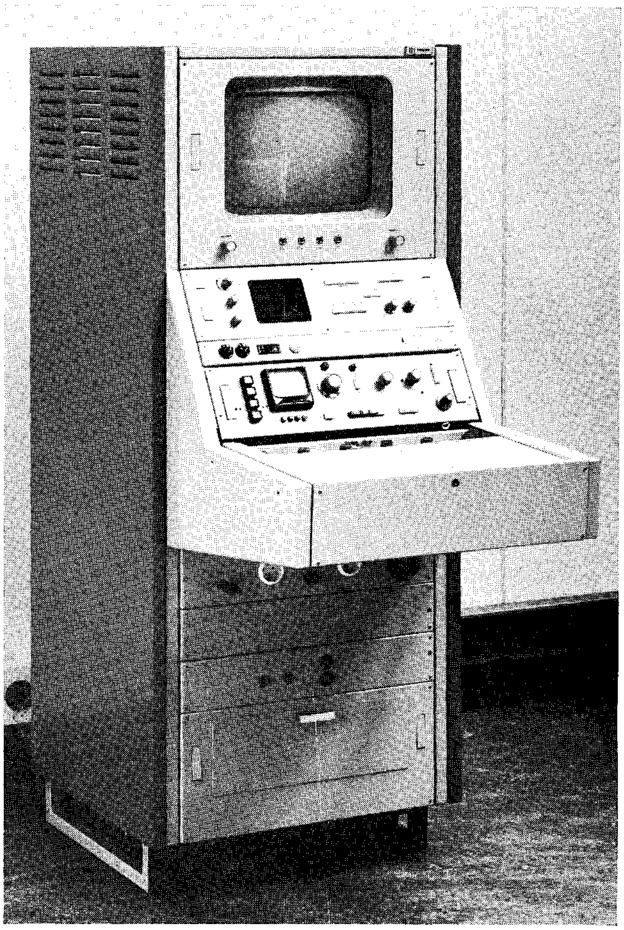

Fig. 8. Control unit for the "Plumbicon" colour television camera. From top to bottom: the picture monitor; the signal monitor; operational panel with controls for diaphragm adjustment, maximum and zero level setting (right-hand half), meter for indicating the focal length of the zoom lens, and main switch ; this panel also contains push-buttons for selecting the signal to be displayed on the picture monitor and for the signalling system. The desk section contains all the control knobs for adjusting the colour balance and the register of the three primary colour pictures. The lower part of the cabinet is occupied mainly by the supply section and a few auxiliary circuits. It also contains a circuit with a selector switch for adjustment of the correction for different lengths of camera cable.

Fig. 8 illustrates the complete control unit. Those sections which have not yet been dealt with will now be discussed.

The processing amplifiers

As stated, the processing amplifiers "refine" the camera signals in various aspects. The maximum and zero levels are firmly established, extreme peaks in the signals are rendered innocuous, special measures are applied to improve the definition of the picture, and "gamma correction" is applied to compensate for the non-linear response of the receiver picture tube. Finally the blanking signal prescribed in the television standards is added to each signal to obtain the three primary colour signals, which can be combined to form a composite colour signal in an encoder appropriate for the transmission system to be used.

We shall discuss these functions in slightly more detail with reference to the block circuit diagram (*fig. 9*) of one of the three almost identical processing amplifiers.

First of all, firm zero levels are established in the signals arriving from the camera. Due to the blanking during each flyback period, the picture signal would contain a zero level, but this level generally shows a certain sinusoidal variation as a result of an interference voltage induced in the electrodes of the tube during the rapid reversal of the line-deflection field. In practice it is sufficient to establish a firm zero level each time just for the short period during which the clamping pulses are effective in the following amplifier stages. For this reason, a small pulse adjustable in amplitude and polarity is derived from the clamping pulses, and added to the signal in the first stage of the amplifier. This pulse is adjusted for each tube in such a way that the interfering voltage is exactly compensated during the pulse (see *fig. 10*).

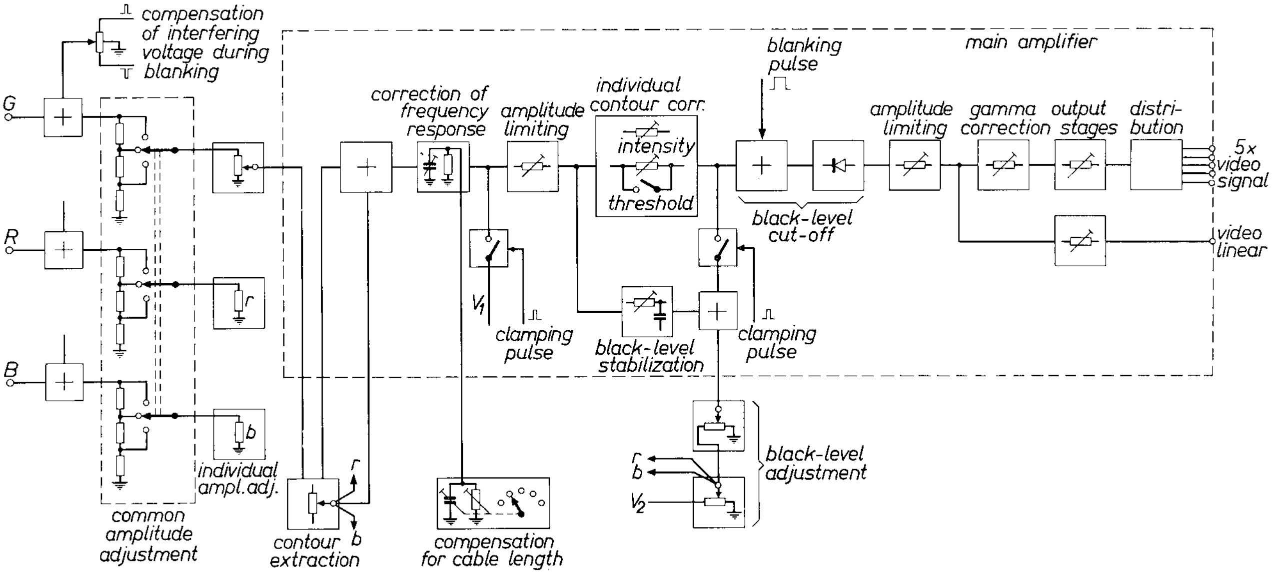

Fig. 9. Block circuit diagram of the processing amplifier for the "green" signal with the external adjustments. Apart from the contour extraction for the common aperture correction (on the "green" amplifier only), all three amplifiers are identical.

Each amplifier also contains an individual aperture corrector; both the amplitude and the threshold of the signal at which this correction should start can be adjusted.

After passing through the gamma corrector and after a final adjustment of the frequency response, the signal is distributed over five independent outputs. The signal as it was before gamma correction is available at the sixth output for measurement purposes.

After common coarse amplitude adjustment of all three signals and an individual fine adjustment (highly important for faithful colour rendering), a process is applied which has recently acquired great significance, particularly for colour cameras: this is the improvement of the definition by the electronic accentuation of contours, known as *aperture* or *spot correction*. We shall go into this in slightly greater detail.

Contours in the image give rise to sudden changes in amplitude in the electrical signal from the camera tube. For a number of reasons, in particular the finite diameter of the scanning spot, the changes in amplitude are not abrupt but take the form of more or less gradual

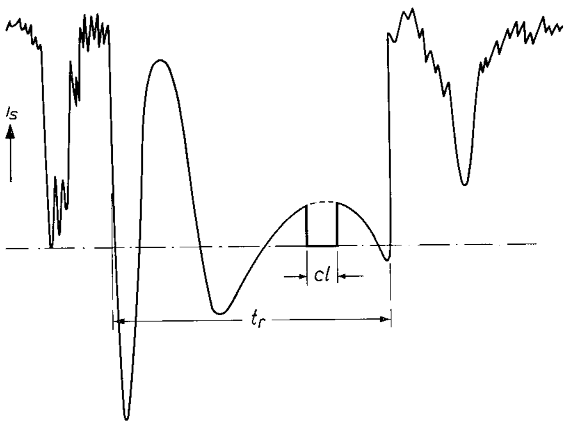

Fig. 10. The beam is suppressed during every horizontal scanning flyback period t_r and the picture signal supplied by the "Plumbicon" tube drops back to zero (chain-dotted line). Since, however, during this period there is a substantially sinusoidal voltage due to interference, the zero level is set exactly during the clamping pulse *cl* (falling within t_r) by compensating the momentary interference voltage with an adjustable voltage pulse.

transitions (see *fig. 11a*). This decreases the sharpness of the contours in the received picture.

There are several methods of aperture correction to compensate for this loss of definition, and, because the image is scanned in successive lines, a distinction must be drawn between "horizontal" and "vertical" aperture correction. A method of horizontal aperture correction which we have found very useful with the "Plumbicon" camera is to make the signal transition even worse by restricting the bandwidth to 2 MHz and then to subtract this degraded signal from the original signal (see fig. 11*b*). The result is a pure contour signal, i.e. a signal whose average level is zero and which consists only of small "pulses" of opposite polarity at those points in the picture where the scanning beam cuts a contour (fig. 11*c*). This contour signal, added at the correct amplitude to the original signal, provides a noticeable accentuation of the changes in amplitude of the original signal and thus an accentuation of the contours of the picture (fig. 11*d*).

It is easy to see that this accentuation is most effective for *vertical* contours, and decreases as the contours depart from the vertical. The effect is zero where the contours are exactly in the direction of the scan. Contours like this are much more difficult to accentuate as this requires signals of successive lines to be subtracted from one another. After a thorough investigation of existing methods, we developed the following method for the colour camera with "Plumbicon" tubes (see *fig. 12*).

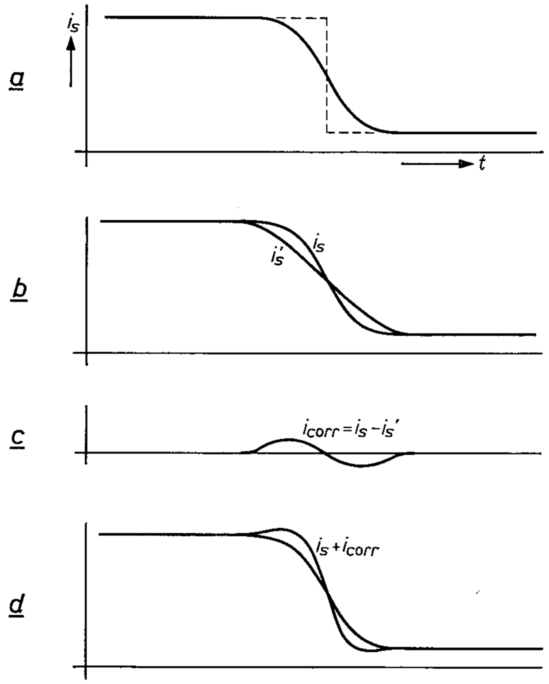

Fig. 11. Electronic accentuation of *vertical* image contours.
a) With a sharp image contour, the abrupt change in amplitude shown in the dashed line should occur in theory. In reality, however, the change in signal amplitude is continuous, as shown in the solid line, for a number of reasons.
b) An even more "blurred" signal i_s' is obtained by limiting the bandwidth, and this signal is subtracted from i_s.
c) The difference between i_s and i_s' is a pure contour signal i_{corr} with an average value of zero.
d) Adding the contour signal i_{corr} to the original signal i_s accentuates the abrupt transition and thus improves the definition of the vertical contours.

Part of the video signal is delayed by exactly twice the line period (2×64 μs) by converting it into ultrasonic vibrations and sending these vibrations along two special glass rods of appropriate length, connected in cascade. The conversion between electronic and ultrasonic signals is made by means of piezo-electric transducers. The amplitude of the double-delayed signal i_{s2} is halved and its polarity is reversed. The same occurs with the original undelayed signal i_s, and both signals are added in a mixing stage to an unattenuated signal of the original polarity, which has been delayed by only one line period (i_{s1}). *Fig. 13* shows the whole process. The addition of $\frac{1}{2}i_s$ and $\frac{1}{2}i_{s2}$ has the same effect as the bandwidth limitation in fig. 11 and the result of the complete operation is a pure contour signal i_{corr} which is at its greatest for *horizontal* contours, decreases as the contours depart from the horizontal and disappears for vertical contours.

If both the undelayed signal i_s and the double-delayed signal i_{s2} are limited in bandwidth to about 2 MHz (by *LP* in fig. 12) before they are fed to the mixing stage, then we have also in a rather simple way included the accentuation of the vertical contours as described above. We then have effective contour accentuation for *all* directions of contour.

The reader may wonder why a separate contour signal $i_{corr} = i_{s1} - \frac{1}{2}(i_s + i_{s2})$ is derived in the circuit we describe, instead of a directly corrected picture signal $i_{s1} + i_{corr} = 2i_{s1} - \frac{1}{2}(i_s + i_{s2})$. Such a signal could readily be obtained if the signal delayed by one line period was doubled before being fed to the mixing stage. There would indeed be some point to this for black-and-white signals [6], but not for colour signals. In fact, in colour television, the idea is not just to accentuate each separate signal — which could be done by such a "direct correction" — but, in the final instance, to improve the definition of the total picture, which is obtained by the superimposition of the three pictures in the primary colours. Since it is virtually impossible to obtain the ideal case where the three pictures are exactly in register over the entire surface of the screen, accentuation of the contours of each *separate* signal provides not only no essential improvement, but may even adversely affect those points of the

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[6] Cf. also the method described in this journal some time ago: C. F. Brockelsby and J. S. Palfreeman, Philips tech. Rev. **25**, 234-252, 1963/64.

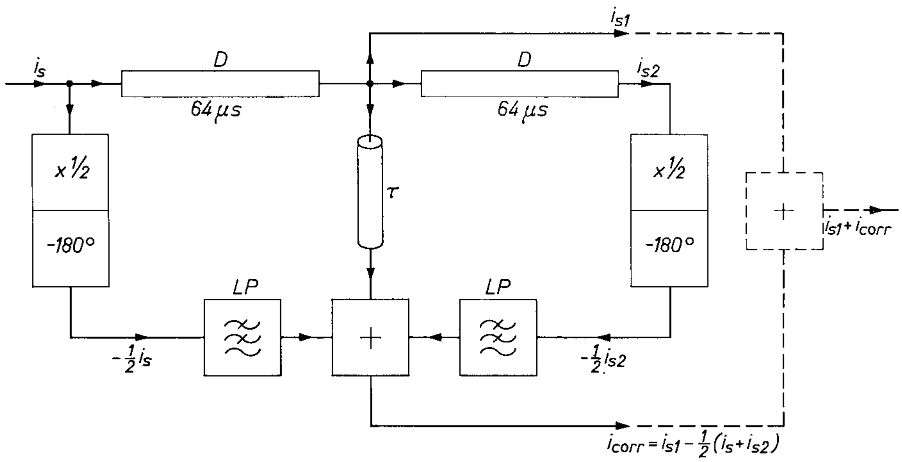


Fig. 12. Block circuit diagram of the arrangements for the electronic accentuation of *horizontal* contours. The signal i_s is delayed by exactly one line period (64 µs) in each of the two delay lines *D*. The undelayed signal i_s and the twice-delayed signal i_{s2} are each reduced to half amplitude and their polarities are reversed. They are both added to the signal i_{s1}, which has been delayed by one line period (cf. fig. 13). The result is a pure contour signal which, on being added to the signal i_{s1} (dashed lines), accentuates the horizontal contours.

The bandwidth of the signals i_s and i_{s2} that are used for correction is limited to 2 MHz, by filters *LP*. This provides at the same time in a simple manner the accentuation of the *vertical* contours as shown in fig. 11. The result is therefore a contour signal i_{corr} that accentuates *all* the contours. The bandwidth limiting gives the signals i_s and i_{s2} a small extra delay τ; this delay must also be given to signal i_{s1} before the addition is made.

picture where there is a discrepancy between the primary colour pictures. These faults are then made even more apparent. It is much better to use a *common* correction signal and, since it must be usable for three different colour extracts, this can, of course, only be a pure contour signal.

In theory there are several ways in which such a common contour signal could be derived from the three colour signals and added to the composite colour signal. In our opinion, the best method is to derive the contour signal from the *green* signal only and then to add it at equal amplitude to all three. This means that, whether or not the three pictures are in themselves completely congruent, they are all given congruent contour lines. Discrepancies between the pictures are thus not only not accentuated but may even disappear if they are small. The addition of the contour signal at equal amplitude to all three picture signals accentuates the

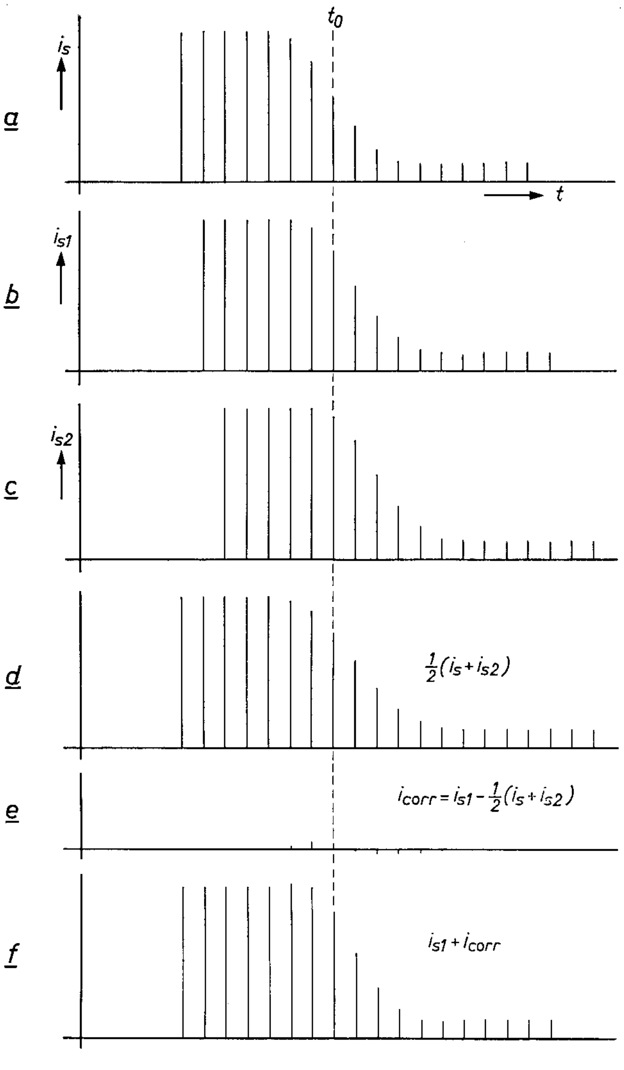


Fig. 13. Operation of the circuit in fig. 12.

a) Signal amplitudes i_s at points exactly one beneath the other in successive lines in a picture at an abrupt transition from light to dark in the scene. The transition is gradual because of blurring. The line at time t_0 is half-way between light and dark.

b) The same signal amplitudes as in (*a*) but delayed by one line period with respect to t_0.

c) Signal amplitudes i_{s2} delayed by two line periods with respect to t_0.

d) Half the sum of i_s and i_{s2}.

e) The difference $i_{s1} - \frac{1}{2}(i_s + i_{s2})$ is a pure correction signal i_{corr} with an average value of zero.

f) The addition of the contour signal i_{corr} to the signal i_{s1}, which is delayed by one period, gives an accentuated transition in amplitude and thus an improvement in the impression of sharpness for horizontal contours.

contours, so to speak, in black-and-white (a method which has also been found to be successful in colour printing). The level of the added signal i_{corr} can be set visually to the optimum value (the facility of such a simple adjustment is another advantage over "direct correction"). The green signal is the preferred choice for the common correction signal because, unlike blue and red, it occurs in most natural colours, and often predominates; in white, for instance, the proportion of green is 59 %. It has, in fact, been found that extremely good results are obtained with "contours from green" on black-and-white receivers — and for a number of years these will still be the receivers most widely used for receiving colour television broadcasts.

For the sake of completeness we should mention that the "contours from green" method which has just been described is just as powerless as any other to correct lack of register between pictures which may be caused by a fault in the receiver.

Apart from the provisions for the common contours-from-green improvement of definition, the block diagram in fig. 9 also shows an *individual* aperture correction for the red, green and blue signals. Level and threshold of this correction are adjustable. This allows the user to make a further correction, if desired, to the definition at the camera; this can be useful for the highest signal frequencies.

We now come to *gamma correction*. The characteristic of the "Plumbicon" camera tube is linear, i.e. the signal current is proportional to the locally varying luminance of the received image. In contrast to this, however, picture tubes have a non-linear characteristic such that the luminance increases with (at least) the square of the control voltage, so that low signal amplitudes are reproduced by a luminance which is relatively far too low. This would lead to very "hard" pictures in black-and-white television, but in colour television there would also be errors in colour, since the intensity ratio of the three sets of colour information is no longer correct at different signal amplitudes. The remedy here is to reshape the colour signals before transmission in an amplifier stage whose amplitude characteristic has the opposite curvature to the characteristic of the picture tube (see *fig. 14*). If the picture tube has a characteristic $L \propto v_{\mathrm{g}}^{\gamma}$, where L is the luminance, v_{g} the control voltage at the Wehnelt cylinder and γ the exponent corresponding to the curvature, the characteristic of the correction stage must be $v_{\mathrm{o}} \propto v_{\mathrm{i}}^{1/\gamma}$, where v_{o} and v_{i} are the input and output voltages. Such a characteristic can be obtained with a semiconductor diode whose current-voltage characteristic has the desired shape at the beginning of the conducting range. This correction circuit, which can be basically very simple, should allow the degree of curvature to be adjusted between about $\gamma = 0.4$ and $\gamma = 1.0$; the circuit is made slightly more complicated by the additional requirement that when making adjustments the maximum amplitude of the signal, once set, should not vary.

We should point out here that gamma correction is always effected in the studio equipment and not in the receiver. With compensation at the camera the transmitted signal becomes less sensitive to any interference that can arise along the transmission path.

The prerequisite for the correct operation of a gamma correction circuit is a well-established zero level that remains stable under all lighting conditions. As the application of gamma correction has the result that changes in the lowest signal amplitudes receive the greatest amplification there is the danger that annoying colour errors could occur in the shadows if the zero levels of the three signals are not perfectly stable. An unacceptable change in the zero level was found to occur with large fluctuations of the average luminance of the scene. The explanation for this is that a considerable amount of the light striking the signal electrode of the "Plumbicon" tube is scattered from it, and in spite of anti-reflection measures in the colour separation system, is reflected back to the tube as faint, diffuse light. Variations in the average luminance of the scene then cause proportional variations in the scattered light and thus an incorrect zero level.

This difficulty was eliminated by using a control circuit which automatically alters the zero-level setting for each of the three camera tubes in proportion to and

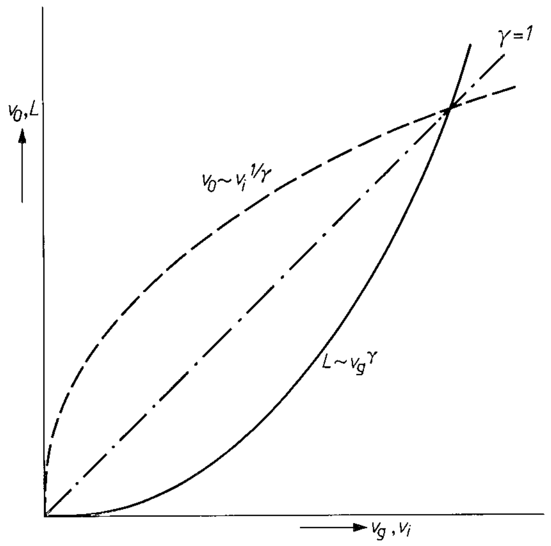
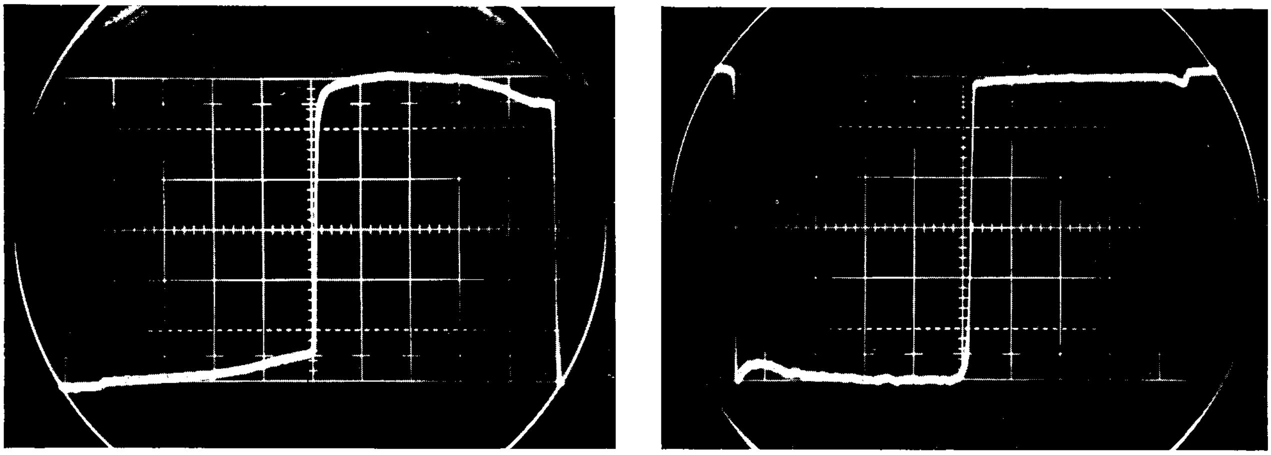


Fig. 14. Principle of gamma correction. The luminance L in the picture tube of the receiver varies with the control voltage v_{g} as $L \propto v_{\mathrm{g}}^{\gamma}$, where $\gamma \approx 2.2$. The marked curvature of this line can be pre-compensated in the processing amplifier of the camera installation with the aid of the oppositely curved characteristic of a crystal diode. This requires the diode characteristic to be $v_{\mathrm{o}} \propto v_{\mathrm{i}}^{1/\gamma}$.

in the same direction as the change in average signal strength (the proportionality factor can be accurately set).

Here we should mention another annoying phenomenon that is connected with scattered light: this is the halo effect. Total reflection in the glass faceplate of the "Plumbicon" tube produces an annular brightening of the picture around the highlights. The surface of the signal electrode looks slightly reddish, and the halo effect is therefore most marked in the tube in the red channel. An adequate cure for this has now been found [7]. The thickness of the window of the tube is increased to more than 7 mm by cementing a plane-parallel ground glass plate to it. The totally reflected light now falls upon the blackened cylindrical rim of the plate and is absorbed there. *Fig. 15* shows two oscillograms demonstrating the effect of the glass plate.



a b

Fig. 15. Elimination of the halo effect by a plane-parallel glass plate cemented to the window of the "Plumbicon" tube. The curve of the signal at a black-white transition is recorded on an oscillograph *a*) for a tube without and *b*) for one with a glass plate. The error in amplitude caused by the halo effect is 9.5% in (*a*) and only 2% in (*b*). (Taken from [7].)

In colour television, the accurate setting of the maximum signal level (equivalent to the white level in black-and-white television) is just as important as the stabilization of the three zero levels. Specular reflections in the scene to be taken are almost inevitable. While with expert adjustment the "Plumbicon" tube can handle bright spots of luminance up to 6 to 8 times the normally occurring maximum value without unfortunate side effects, a result of the linear characteristic is that these bright spots give peaks in the tube current which are 6 to 8 times the rated maximum. This rated maximum is the most important parameter for the entire transmission channel and all the circuits are therefore based on it. The occurrence of unexpected bright spots would, therefore, lead to overloading, with all its adverse consequences on picture quality.

To prevent this, there is an amplitude limiter at two points in each processing amplifier. In one of the first stages, all signals above 130% of the rated maximum are clipped, thus protecting the following stages from being overloaded. The second limiting occurs after the circuit for setting the zero level and accurately determines the maximum signal amplitude, for which a peak value of 1 V is usually chosen.

Monitoring and control circuits

After this description of the most important functions of the amplifier section, we shall just mention a few of the special features of the other circuits.

The signal monitor serves to check whether the signal levels and the gamma characteristics of the three processing amplifiers have been properly adjusted. This monitor is a cathode-ray oscilloscope with three identical vertical amplifiers and a time-base which can be synchronized with either the horizontal or the vertical deflection of the camera tubes. Electronic switching allows the three colour signals to be displayed beside one another or superimposed, thus facilitating very precise relative adjustment of these signals. Once this adjustment has been made, the signal monitor is used during normal operation solely for checking the maximum level of the signals. Deviations from the rated values are then simply compensated by the readjustment of the camera lens diaphragm or, if an abrupt change is permissible, by the common coarse amplitude adjustment.

The signal monitor is the only instrument that is actually necessary for checking during normal operation.

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[7] F. W. de Vrijer, S. L. Tan and A. G. van Doorn, Advanced techniques for "Plumbicon" cameras, J. SMPTE **75**, 1080-1082, 1966 (No. 11).

The picture monitor is required in the first place for the preliminary mechanical and electronic setting of the camera tubes and for checking and adjusting the scanning geometry and hence the register of the primary colour pictures. Because of space restrictions a colour monitor is not used; instead there is a black-and-white monitor, which can display any of the primary colour pictures or all three of them superimposed. During normal operation, the picture monitor is only used to check on camera operations and to see if everything is proceeding according to plan.

From the above it can be seen that the adjustments can be divided into settings that must be made before and those that have to be made during operation. The only ones made during operation are the setting of the diaphragm, the common regulation of the maximum level and the common adjustment of the zero level. The control knobs for these adjustments are on the operational panel, but their connections can also be switched over to a second, identical, panel which may be arranged in a common control desk for several cameras. The technician at this desk then has to compare the brightness and contrast of the pictures from the different cameras with the aid of monitors and bring them into line with one another.

It is usually necessary to make the numerous adjustments to the camera tubes, signal amplifiers and deflection circuits only when camera tubes have been changed or after the installation has been in use for a considerable time. The appropriate controls are to be found on the desk of the control unit (*fig. 16*). They are protected against inadvertent or unauthorized operation. The prerequisite for the reliable operation of all controls and circuits is, of course, careful stabilization of all supply voltages and protection of the circuits from any kind of interference or interaction effects.

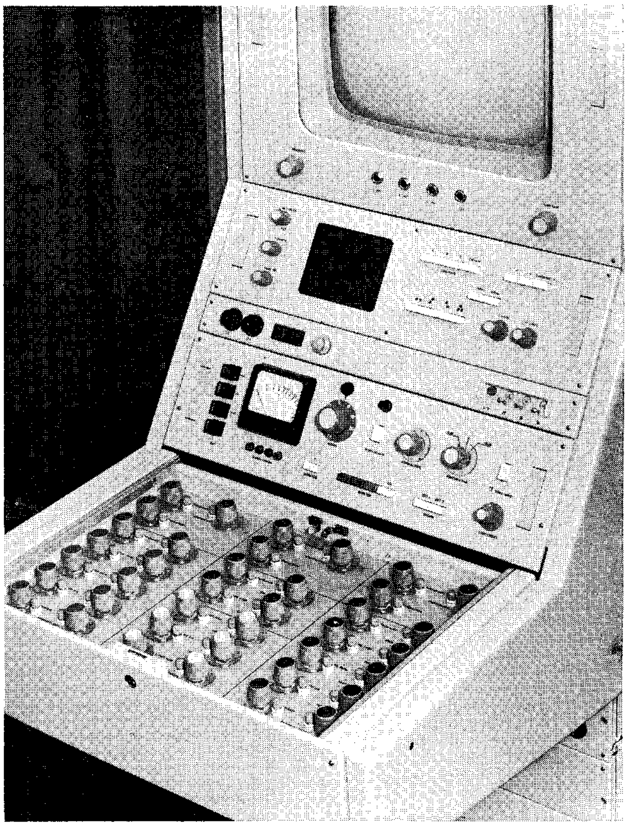

Fig. 16. Control desk with controls for setting the signal amplifiers to the correct colour balance and the deflection circuits for the best possible register of the primary colour pictures. These controls do not need to be operated during shooting, and are then protected by a cover from inadvertent alteration. In the figure, the cover has been pushed back into the cabinet.

Practical results

The practical experience obtained with the type of camera described has completely fulfilled our expectations of the use of "Plumbicon" tubes in colour television cameras. The whole installation is simple to operate and the operations are easy to grasp. No complications have been found in the adjustments before operation, and the set values remain stable and need no further readjustment for considerable periods of time. The results obtained are hardly affected at all by fluctuating ambient temperatures, and extreme changes in the lighting, such as those which occur when changing from indoor to outdoor shots, are handled without difficulty and without any loss of quality.

These cameras have now been in use in many colour television studios for more than two years, either for normal programme production, as in the United States, Canada and Japan, or for experimental colour television work, as in most of the countries of Western and Central Europe. To obtain an assessment of the performance of the camera and the quality of the pictures it gives, many comparisons have been made, under fully controlled conditions, with other colour cameras, of both the three- and the four-tube types. The three-tube type includes the conventional image-orthicon camera, and the four-tube type includes those with one image orthicon for the luminance signal plus three vidicons for the colour signals and those with four "Plumbicon" tubes, where the fourth is used for the luminance signal.

All comparisons have shown that the type of camera described here requires markedly less light for high-quality studio shots than the others, including four-tube types. The colour rendering of the camera in outdoor scenes, where the lighting is generally considerably less uniform than in the studio, is clearly better than that of the other types. The contrast range of the scene which can be dealt with is better under all conditions than the range which can be handled with image-orthicon cameras. The definition and the register of the three primary colour pictures is considerably better than in three-tube image-orthicon cameras and as good as those in such cameras with four tubes. We should like to emphasize once more that the picture definition is important not only for reproduction in colour receivers but also for reproduction of the colour transmissions in black-and-white receivers (this is the compatibility requirement). The good results which we have obtained in this respect with the camera with three "Plumbicon" tubes — due to the use of "contours from green" — may perhaps settle the question, discussed over the past few years, as to whether three or four tubes are best. As compared with the theoretically and practically more complicated four-tube cameras, which were primarily developed to provide sharper reproduction of colour programmes in black-and-white receivers, we now have one three-tube camera which is their equal in this respect, but provides better colour rendering and much simpler operation.

Even though we already have results which are excellent, the scope for the further development of this type of camera is considerable. Such development may be directed towards further circuit refinement made possible by the recent rapid progress in solid-state components, towards the increasing use of automation in television practice, and towards further perfection of the "Plumbicon" camera tube, which is still a relatively recent development.

Summary. The small size of the "Plumbicon" camera tube and its relatively simple operation in comparison with image orthicons permit the design of a colour television camera in which the mechanical and optical arrangements and the circuits are different from those in conventional cameras. This article discusses the most important features of the new prismatic colour separation system, the simple, practical methods of adjusting the camera tubes, and the specially developed amplifiers and deflection circuits. The performance of the circuits is greatly assisted by the linear characteristic of the "Plumbicon" tube and the negligibly low noise level of its signal current, provided that these particular features are taken into account in the design of the circuits. Finally, an account is given of the practical experience gained so far in ordinary studio work. The conclusion drawn is that the type of three-tube camera described is to be preferred to cameras with four tubes.

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