

# The Plumbicon: a new approach to camera tubes

Similar to a vidicon in both size and principle, this new camera tube uses a lead target to gain certain advantages.

MANY TV stations in the U.S. are presently using the Plumbicon type of color pickup tube in their color cameras. The name "Plumbicon" was chosen by its developers, Philips, because, as will be shown, the photoconductive target is made from lead monoxide and *plumb* is derived from *plumbum* which means lead (*Pb*) in Latin.

According to the manufacturer, compared to the vidicon the Plumbicon has higher sensitivity, slightly lower resolution, faster response, and lower dark current that results in an absence of black shading and a more accurate black level. This latter is a spurious temperature-dependent flow of charge carriers in the photoconductive layer that prevents good picture contrast under certain conditions. In size and principle of operation, the vidicon and Plumbicon are similar.

Basic operation is shown in Fig. 1. The target consists of a conducting but very thin layer of stannous oxide ( $\text{SnO}_2$ ) that has been deposited on the glass window to form the signal-collecting electrode. A very thin layer of lead monoxide ( $\text{PbO}$ ) is evaporated on top of the  $\text{SnO}_2$  to form the actual target. The target is held at about 30 volts with respect to the cathode while the inside surface of the  $\text{PbO}$  layer is scanned by the electron beam from the gun. The mesh anode screen serves to provide a uniform field between the target and the anode.

The lead monoxide layer is actually three layers thick. The center portion is almost pure  $\text{PbO}$  which is an intrinsic semiconductor. The portion being scanned by the electron beam is doped to create a *p*-type layer. The  $\text{SnO}_2$  layer is a strong *n*-type making the portion of the  $\text{PbO}$  layer adjacent to it an *n*-type region.

When the tube is in operation, the target structure makes up a reverse-biased *p-i-n* diode with an electric field and a capacitance existing across it. The overall capacitance across the target can be considered as consisting of a very large number of very small capacitors, one for each element point of the focused image.

Shunting each of these capacitors is a small current source formed by the charge carriers (electrons and holes) that have been liberated within the target material as a result of the incident illumination at that point. When the scanning electron beam contacts the face of one of these capacitors, the capacitor starts to charge from the 30-volt source. As soon as the scanning beam leaves that capacitor, it starts to discharge through the combination of resistor and current source between the target and cathode. The rate at which each capacitor discharges depends on the flow of photocurrent which is dependent on the intensity of the focused illumination at that point. Therefore, voltage developed across the series resistor is proportional to the light intensity at the target point

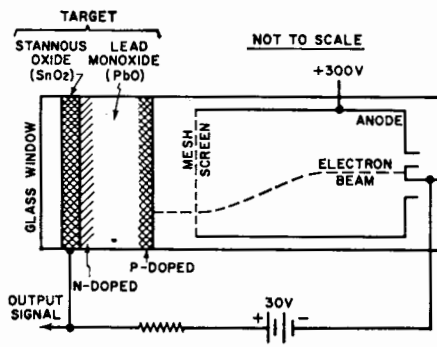
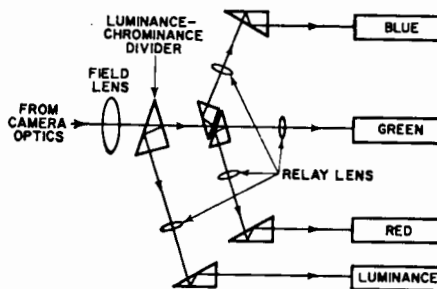


Fig. 1. Exaggerated view of a Plumbicon target shows that the lead monoxide is both "n"- and "p"-doped with center an intrinsic semiconductor. Signal pickup is from stannous oxide conducting layer.

Fig. 2. Basic four-Plumbicon color-TV camera has separate tube for luminance signal. This system uses prismatic light splitting in place of dichroic mirrors.



being scanned by the deflected beam.

The sensitivity of the Plumbicon comes from the fact that there is a high electric field across the target because the bulk of the  $\text{PbO}$  is a relatively poor conductor. Thus, almost all the charge carriers liberated in the target by the incident light are caused to drift and contribute to the photocurrent. The Plumbicon has a very small dark current because of the blocking action of the *p*-type and *n*-type layers to electrons and holes not generated by light activation.

## Color Camera Use

TV studio engineers have been using the Plumbicon in a unique four-tube color-TV camera. This camera, shown in Fig. 2, provides a separate luminance (black-and-white) output besides the three color signals.

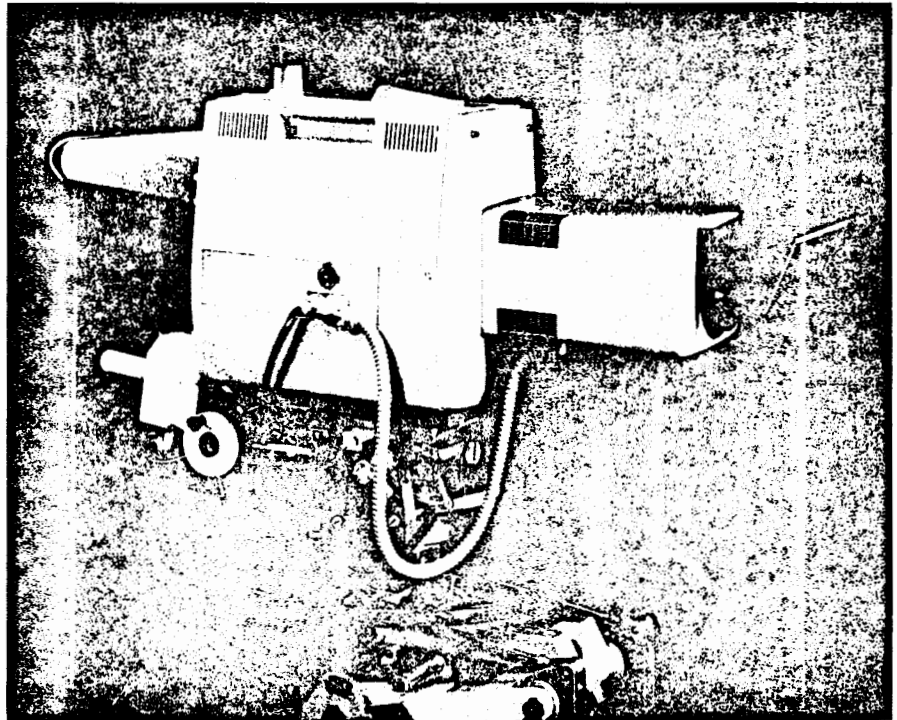
In a conventional three-tube camera, the luminance signal is created by matrixing the signals from the three separate color pickups, and it has been claimed that registration of the three color tubes is difficult and that long-term stability of both camera and associated electronics is hard to achieve. In the four-tube camera, the luminance signal is independent of the optical registration of the three color tubes, and monochrome picture degradation caused by one of the color pickups being defective is minimized.

The optical system shown in Fig. 2 uses prismatic-type light splitting instead of the dichroic mirror system being widely used. This new system was adopted because it occupies less space than the dichroic mirror system and avoids ghost images, spurious color degradation across the picture, and unfaithful color rendition with polarized light (e.g., light reflected from hair).

The relay lenses are used to extend the light path from the input optics to the pickup tubes. These are used because it is difficult to form the input optical image directly on the pickup targets using only the camera's main lens system. This type of optical system is also useful in minimizing the influence of any stray magnetic fields that could damage color reproduction, as each of the image pickups is mounted parallel to the others and all have similarly oriented images. This system also permits the use of conventional camera lensing.

The luminance-chrominance divider prism splits the light path between the luminance and color signal pickups and can be replaced easily by a fully reflecting mirror in the event that the four-tube color camera is used for monochrome pickup. The surfaces of the remaining optical elements are treated so that each pickup tube receives the correct color image. Spectral trimming filters are inserted in each light path to make sure that the images formed at each color pickup are of the correct color quality. ▲

The "Plumbicon", the new type of camera tube developed at the Philips Research Laboratories in Eindhoven, has been greeted with considerable interest from the television world. The tube has all the advantages of the vidicon but none of its fundamental disadvantages, and is therefore suitable for applications previously reserved for image orthicons. This makes it desirable to compare the picture quality and other characteristic features of the various types of camera tube as objectively as possible, a comparison which necessitates careful regard to the differences in noise characteristics, setting of the operating point, the likelihood of over-exposure, etc. The "Plumbicon" gives a very good account



of itself for black-and-white television, and for colour television its superiority is unquestionable.

## The "Plumbicon" compared with other television camera tubes

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The heart of any television camera is the camera tube. In this, an optical image is converted into a pattern of electrostatic charges, which is scanned by an electron beam to produce electrical signals. The camera tubes in most general use at the moment are image orthicons and  $Sb_2S_3$  vidicons. These two types are based on different principles. The image orthicon makes use of photoemission and secondary emission to form a charge pattern; in the vidicon, the conversion is based on photoconduction. The characteristic features of these types of tube also differ considerably.

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As may be seen in *fig. 1*, the vidicon is much smaller than the image orthicon. Other features in its favour are its simple adjustment, its stability — and its price.

Image orthicons are nevertheless widely used because  $Sb_2S_3$  vidicons have a number of drawbacks that can seriously impair the quality of the picture. Their speed of response under normal lighting conditions is so slow that pictures of moving objects are blurred, and they may also have a fairly large dark current (signal arising when there is no light incident on the tube). Under certain conditions, and particularly at the normal illumination levels in the television studio, these undesirable effects can be so serious that

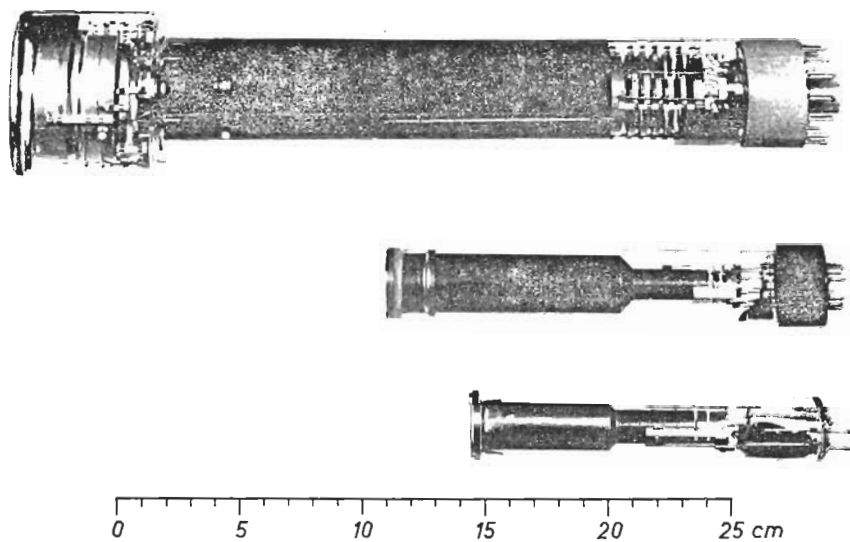


Fig. 1. Three types of camera tube. Top to bottom: a 3" image orthicon, a "Plumbicon" and a 1" vidicon. The type often used in studio cameras nowadays is the 4½" image orthicon, which is considerably larger even than the 3" type shown. There is also a ½" model of the vidicon, specially designed for very small, compact cameras.

acceptable picture quality becomes unattainable.

$Sb_2S_3$  vidicons are, however, unexcelled for many applications outside the television studio. The undesirable effects mentioned above are much less of a nuisance at high levels of illumination, while small size, light weight, simple (possibly automatic) operation, robust construction, low price and long life are all of special importance in such applications.

The development of the "Plumbicon" makes yet another type of camera tube available. This tube, like the  $Sb_2S_3$  vidicon, is based on the photoconduction principle, and is constructed in almost the same way (fig. 1). However, the use of a different photoconductive layer, with an appropriate method of operation, has almost completely removed the drawbacks of the  $Sb_2S_3$  vidicon, i.e. the poor response speed and the high dark current, while retaining the useful features. The "Plumbicon", therefore, can be used for purposes for which so far only the image orthicon has been suitable. The picture quality of the "Plumbicon" compares very well with that of the image orthicon, so that it will also be possible to put to good use in the studio the practical advantages which made vidicon-type tubes so attractive in other fields.

While the "Plumbicon" for these reasons is a very attractive proposition for use in black-and-white television, its special features really come to the fore, as we shall see, in colour television. In fact, one of the main motives behind the development of the "Plumbicon" was the need for a camera tube that was more suitable for colour cameras than either the image orthicon or the vidicon.

Various characteristics of the "Plumbicon" and the explanation of its physical principles have already been dealt with in an earlier article in this journal<sup>[1]</sup>. We now wish to go more deeply into the use of this new tube and to compare it with image orthicons and vidicons already in use. A detailed description of the operation of these other tubes will not be given, as there is sufficient information on the subject in the literature<sup>[2][3]</sup>. The only factors to be mentioned will be those necessary for mutual comparison.

The objective comparison of two types of tube

differing so widely in their operation and characteristic features as the "Plumbicon" and the image orthicon is a complicated undertaking. It is, in fact, virtually impossible to take into account and set off against each other all the factors that determine the quality of a television picture, such as resolution, tonal gradation, brightness range, signal-to-noise ratio, uniformity, etc., particularly as personal preference and habit also influence the eventual assessment of the picture. It is equally difficult to find a common denominator for features such as warming-up time, stability, life, sensitivity to interference, etc., that do not in the first instance affect the picture quality but are nevertheless important in operational practice.

We shall therefore restrict ourselves to those points which best lend themselves to an objective comparison, including the *illumination required for optimum picture quality*. For such a comparison the conditions of operation and the assumptions made must be rigidly specified. We shall first therefore discuss a few of the concepts involved, including the depth of focus, the light-transfer characteristic, and the signal-to-noise ratio.

#### Depth of focus

Fair comparison between different camera tubes must relate to conditions in which the cameras pick up exactly the same scene, as regards both foreground and background, and moreover with the same depth of focus in each case. It can easily be shown that the tubes will "see" the same scene only if lenses with focal length proportional to the linear dimensions of

the image rectangle are used (fig. 2). The image rectangle of the image orthicon is 24 mm × 32 mm, while that of the "Plumbicon" is 12 mm × 16 mm and that of the ordinary Sb<sub>2</sub>S<sub>3</sub> vidicon is about 9 mm × 12 mm.

If, moreover, the lenses have the same entrance pupil, the "equal depth of focus" condition is satisfied (fig. 3).

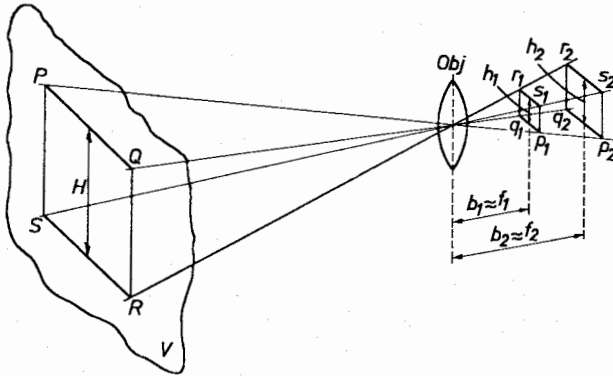


Fig. 2. A television camera with its lens at point *Obj* is assumed to take a scene in which the rectangle *PQRS* in the object plane *V* is sharply reproduced on the image rectangle *p<sub>1</sub>q<sub>1</sub>r<sub>1</sub>s<sub>1</sub>* of the camera tube. If a second television camera having a camera tube with the larger image rectangle *p<sub>2</sub>q<sub>2</sub>r<sub>2</sub>s<sub>2</sub>* is to take exactly the same scene (i.e. with the same foreground and background), its lens must be placed in position *Obj* and the rectangle *PQRS* must be sharply reproduced on the larger image rectangle. The figure shows that this is so if the image distances *b<sub>2</sub>* and *b<sub>1</sub>*, and hence because of the great reduction the focal lengths *f<sub>2</sub>* and *f<sub>1</sub>*, are in the same ratio as the heights of the image rectangles:  $f_2/f_1 \approx b_2/b_1 = h_2/h_1$ .

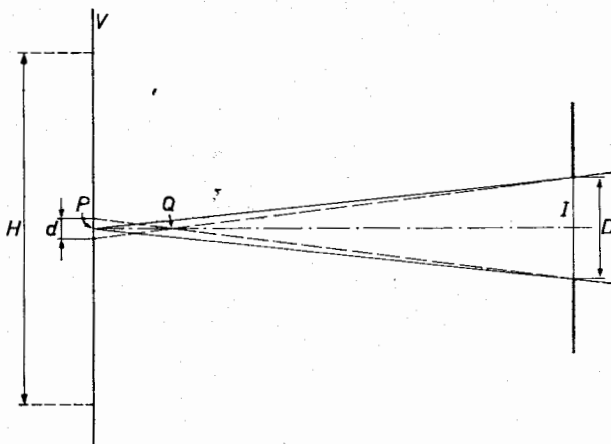


Fig. 3. The aperture *I*, of diameter *D*, represents the entrance pupil of the lens of a television camera. Point *P* of the scene in the object plane *V* is sharply reproduced on the photosensitive layer (not shown) of the camera tube. Point *Q* gives, on this layer, a spot (of diameter *d*) that coincides with the image of a disc of diameter *d* around point *P*, since each ray through *Q* and *I* behaves like a ray originating from this disc. If *H* is the height of the rectangle in *V* that is reproduced on the photosensitive layer as the image rectangle of height *h*, then  $d'/h = d/H$ , i.e.  $d'/H$  is a measure of the relative blurring of points *Q* belonging to the foreground or background. Hence, when one camera is replaced by the other, with *I* in the same position, the relative lack of definition, and thus the depth of focus, remains the same, provided that *D* is the same.

In practice, the focal length *f* and the relative aperture *D/f* of every lens are known. Here, *D* represents the diameter of the entrance pupil. The condition of equal entrance pupil means that the product of the focal length and relative aperture must also be equal. If a scene is reproduced with an image orthicon camera which has a 1:5.6/50 mm lens, then with a "Plumbicon" the corresponding camera must have a 1:2.8/25 mm lens, as the dimensions of the image rectangle of the "Plumbicon" are half those of the image orthicon. In comparing tube sensitivity, it is usual to assume that the lenses satisfy the above conditions. Questions such as the availability, quality and price of the lenses, and also the effect of the specified conditions on, for example, the dimensions of a lens, are not taken into consideration here [4].

### Light-transfer characteristic

In comparing different types of camera tube, it is hardly realistic to think in terms of the usual concept of sensitivity and to attempt to quote one single numerical value. One of the essential factors in the sensitivity of a camera tube, however, is its "light-transfer characteristic". This gives the signal current *I<sub>s</sub>* as a function of the illumination *E<sub>t</sub>* at the photoconductive layer. Fig. 4 shows examples of such characteristics for a "Plumbicon", an Sb<sub>2</sub>S<sub>3</sub> vidicon and three different types of image orthicon. These characteristics are plotted with logarithmic scales for both coordinates, so that a straight line indicates that the signal current is proportional to a power of the illumination:  $I_s \propto E_t^\gamma$ , the constant exponent  $\gamma$  being given by the slope. If the slope is unity, which is the case over a wide range of the characteristics of the image orthicon and the "Plumbicon", *I<sub>s</sub>* is proportional to *E<sub>t</sub>*.

The horizontal axis in fig. 4 shows the reduced illumination *E<sub>t</sub>* (in millilumens), i.e. the product of the illumination and the area of the image rectangle. This is the only way in which camera tubes with different image rectangle can be directly compared, for, provided that the illumination of the scene and the depth of focus are the same this quantity is independent of the size of the image rectangle.

[1] E. F. de Haan, A. van der Drift and P. P. M. Schampers, The "Plumbicon", a new television camera tube, Philips tech. Rev. 25, 133-151, 1963/64. This article is further referred to as 1.

[2] R. Theile and H. Fix, Eine vergleichende Betrachtung der heute verfügbaren Fernseh-Bildaufnahmeröhren, Radiomenter 25, 448-452, 1959.

[3] J. W. Wentworth, Camera tubes for studio use, J. SMPTE 72, 153-157, 1963.

[4] G. H. Cook, The performance of television camera lenses, J. SMPTE 69, 406-410 (and 867), 1960.

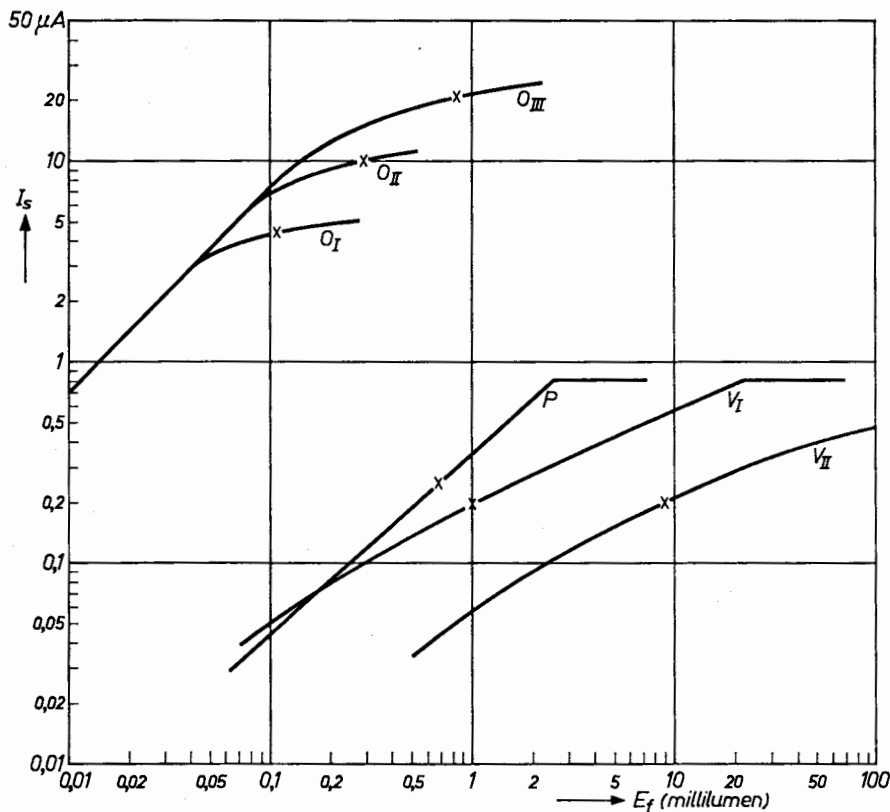


Fig. 4. Light-transfer characteristic of different types of camera tube. The signal current  $I_s$  is plotted as a function of the luminous flux on the photosensitive layer, the illumination being uniform.  $P$  applies to a "Plumbicon" of average sensitivity ( $350 \mu\text{A}/\text{lm}$ ),  $O_I$  to a very sensitive 3" image orthicon,  $O_{II}$  to a 3" image orthicon with the knee at a higher illumination, and  $O_{III}$  to one of the types of 4½" image orthicon now often used whenever the highest picture quality is required.

$V_I$  applies to an  $\text{Sb}_2\text{S}_3$  vidicon at a sensitive setting (signal plate voltage  $V_S =$  about 40 V, dark current  $I_d = 0.02 \mu\text{A}$ ), and  $V_{II}$  to a similar vidicon with a lower signal plate voltage ( $V_S =$  about 15 V,  $I_d = 0.005 \mu\text{A}$ ) and increased speed of response.

The operating point for optimum setting is given on each curve by a cross. The illumination required for this setting can be read on the abscissa.

If the tubes "see" exactly the same scene with lenses of the same entrance pupil diameter — the specified condition for fair comparison — the values of the illumination in lux at corresponding points on the photoconductive layer are inversely proportional to the areas of the image rectangles. The product mentioned above is therefore a quantity independent of this area.

The comparison of these characteristics should nevertheless be made with a certain degree of caution. With the image orthicon, for instance, the signal current is, indeed, much greater than in the "Plumbicon" and  $\text{Sb}_2\text{S}_3$  vidicon, but this does not necessarily imply greater sensitivity. The secondary emission multiplier built into the image orthicon provides this large signal current. The real criterion for the sensitivity is the position of the optimum operating point and the related value of the illumination. It will be seen that one of the important factors in the choice of this operating point is the signal-to-noise ratio in the television signal.

The small crosses in fig. 4 show some of the normal operating points used in practice. Various designs of image orthicon are employed, which will be discussed in greater detail later. Characteristics have been plotted for two different settings of the  $\text{Sb}_2\text{S}_3$  vidicon (from now on, for convenience, we shall refer to this simply as the vidicon). Only one characteristic has been given for the "Plumbicon", for a tube with an average sensitivity. The factors affecting the choice of the operating point will now be discussed in greater detail.

#### Signal-to-noise ratio

The signal-to-noise ratio of a television camera signal is generally taken to be the ratio between the useful signal  $S$  and the effective value  $N$  of the noise (the ratio is often expressed in dB). If  $S$  appears as a signal current,  $N$  is also considered as a noise current. If the noise in the signal is independent of  $S$ , the signal-to-

noise ratio is proportional to  $S$ , so that a given situation may be characterized by the value  $S_w/N$  alone, where  $S_w$  is the signal provided by the brightest part of the scene.

$N$  can however be a function of  $S$ . This is indeed so in the image orthicon, but with the "Plumbicon"  $N$  is even more strongly dependent on  $S$  because of the application of non-linear amplification for "gamma-correction". We shall, therefore, make use of an "equivalent noise"  $N_{eq}$ , which is independent of  $S$  and provides the same visual impairment as the actual noise. With the aid of statistical data and subjective assessments made by observers, Theile and Fix [5] have found that a useful expression for  $N_{eq}$  is:

$$N_{eq} = \frac{N_w + 3N_G + 2N_z}{6} \dots (1)$$

Here,  $N_w$ ,  $N_G$  and  $N_z$  represent the effective values of the noise in the signal corresponding to white, mid-

grey (the signal equal to 40% of that of white) and black (e.g. 2% of white).

Another factor important in the determination of the signal-to-noise ratio is the frequency spectrum of the noise, referred to as the "noise character". It is well known that high-frequency noise gives much less impairment than low-frequency noise. Several workers<sup>[5][6]</sup> have attempted to analyse this visual difference and to reduce it to numerical or graphical terms that could be used as a measure of the impairment given by different noise frequencies. These differences in impairment become even more significant if pictures are to be compared whose noise spectra differ widely, or if noise measurements have to be made on signals having different noise frequency spectra.

In image orthicons, the output current of the multiplier is so large that the noise contribution in the signal current comes entirely from the tube itself. This noise is almost independent of the frequency, so that the noise spectrum is practically a horizontal line. This is called white or "flat" noise.

Both the vidicon and the "Plumbicon" deliver much smaller signal currents and the noise contribu-

tion originates almost entirely from the very sensitive input circuit of the electronic signal amplifier. Such input circuits are designed for a minimum of noise, and this has the result that the noise is no longer independent of frequency. In most cases, the effective noise current increases practically linearly with the frequency. Thus, we refer to noise with a "triangular" spectrum.

In noise measurements, use is often made of a "noise-weighting filter", whose transmission-frequency curve approximates very closely to the average curve for the visual impairment effect of noise. Fig. 5a shows a diagram of such a filter and fig. 5b the resulting noise-weighting curve. To compare the image orthicon, with its flat noise spectrum, and the "Plumbicon", with its triangular noise spectrum, however, it is simpler to use one single numerical value for the relative impairment (noise weighting factor). This numerical value, which gives the difference between the impairment effect of flat noise and of noise with a triangular spectrum, may be set at 2.25 (7 dB) for a bandwidth of 5 Mc/s. Noise measurements made without a noise-weighting filter will give signal-to-noise ratio values for the "Plumbicon" and the vidicon which, for equal visibility of noise, are 7 dB lower than those for the image orthicon.

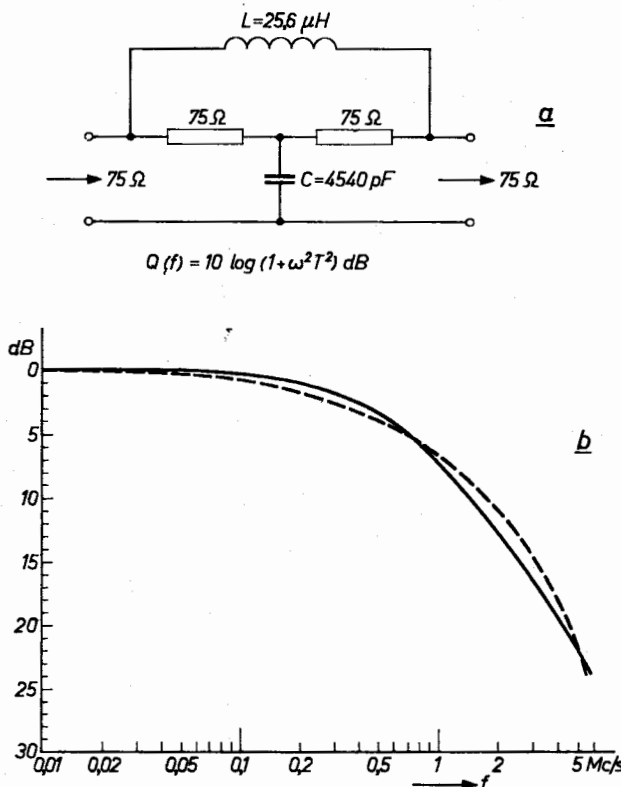


Fig. 5. a) A filter that can be used to take the visual impairment effect of noise into account in noise measurement. The component values have been selected so that  $T = 0.33 \mu\text{s}$  (CCIR recommendation).

b) Attenuation characteristic of this filter (solid line) compared with the statistically determined noise impairment curve (broken line).

#### Characteristics and operating point of vidicons

The light-transfer characteristic of a camera tube is always affected, to a certain extent, by the various d.c. voltages on the electrodes of the tube. In the vidicon, the characteristic is particularly strongly affected by the signal plate voltage  $V_s$ . This is clearly shown in fig. 4, which shows two characteristics for different values of  $V_s$ . Because of this dependence, the characteristic can be adapted over a considerable range to the illumination. Fig. 4 shows the vidicon characteristics as slightly curved lines, of slope varying between about 0.8 and about 0.4. It is seen from the characteristics for low values of  $V_s$  that, as the illumination  $E_t$  increases,  $I_s$  will show slight saturation: the characteristics gradually become horizontal. The characteristics for high values of  $V_s$  show a sharp transition to a horizontal line. The actual transition

[5] R. Theile and H. Fix, Zur Definition des durch die statistischen Schwankungen bestimmten Störabstandes im Fernsehen, Archiv elektr. Übertr. 10, 98-104, 1956. See also p. 64 of the second article mentioned in note [6].

[6] J. Müller and E. Demus, Ermittlung eines Rauschbewertungs-filters für das Fernsehen, Nachrichtentechn. Z. 12, 181-186, 1959. See also H. Fix and A. Kaufmann, Die spektrale Zusammensetzung der statistischen Schwankungen bei zur Zeit üblichen Fernsehkameraanlagen, Rundfunktechn. Mitt. 4, 60-65, 1960.

occurs at the point where the photocurrent has become so large that the electron current in the scanning beam (the beam current) is no longer capable of stabilizing the photosensitive layer at cathode potential. This is therefore an unstable state. If the beam current is increased, this transition point is shifted towards a higher value of  $I_s$ .

This point should never be exceeded, not only because with a horizontal characteristic all contrast is lost, but rather because unstabilized whites in the picture appear as washed-out areas with a tendency to spread, or "bloom", and which disappear only slowly if  $E_f$  drops below the transition point. With moving objects, very unnatural after-images and trailing effects are produced. These phenomena, which are bound to occur when scanning with "slow" electrons if the beam current is set at too low a value, arise similarly in the "Plumbicon", and even in the image orthicon a similar effect can come about due to a wrong setting.

In the vidicon, however, the signal plate voltage  $V_s$  also determines the dark current  $I_d$ , i.e. the signal current supplied by the tube when no light is falling on the photoconductive layer. As  $V_s$  increases,  $I_d$  increases more than linearly. For instance, when  $V_s = 15$  V, the value of  $I_d$  is about  $0.005 \mu\text{A}$ , while when  $V_s = 40$  V,  $I_d$  can have a value between  $0.02$  and  $0.1 \mu\text{A}$ . At the same time, the dark current depends to a great extent on the temperature. This dark current appears in the television signal as a non-uniform spurious signal, which gives a deterioration in picture quality. If the value of  $I_d$ , and hence the non-uniformity of the spurious signal over the image area, becomes too great, it may even become necessary to supply an electronic correction signal to compensate for the non-uniformity.

The speed of response depends almost entirely on  $E_f$ : it increases as  $E_f$  increases. Two factors limit the speed of response: the beam current lag, which is governed by the electron beam scanning mechanism and also depends on  $E_f$  (discharge lag), and the photocurrent lag. In fact, it takes a little time for the current through the photoconductive layer to respond when the value of  $E_f$  changes (see I, pp. 146 and 147).

The slow response at low values of  $E_f$ , which is a characteristic of the vidicon, is due entirely to the photoconductive lag. We shall see later that the lag in the "Plumbicon" is of a completely different nature. It does not depend on  $E_f$ , and is only slightly affected by  $V_s$ ; above a certain value of  $V_s$ , the photoconductive lag is negligible in relation to the discharge lag.

The interdependence of various parameters makes it difficult to specify one suitable operating point for the vidicon. We cannot make a choice without a

more thorough analysis of the effects of this on the picture quality. It is therefore simpler to select a few situations and examine the effects of the chosen setting on sensitivity, lag, picture quality, etc. What is evident from such an examination is the tremendous flexibility of the vidicon, since it is possible to deal with a considerable range of illuminations by adjusting  $V_s$  alone. This means that completely automatic cameras can quite easily be made.

A situation in which attempts are made to obtain the best picture quality in all respects merits special consideration.

Let us take as an example a setting for a useful signal current  $I_s = 0.2 \mu\text{A}$ , resulting in a very good signal-to-noise ratio; a dark current  $I_d = 0.005 \mu\text{A}$ , which is sufficiently low in relation to  $I_s$ ; and a sufficiently high illumination level at the photoconductive layer to ensure fast response. Under these conditions,  $V_s$  will be between  $10$  and  $20$  V, depending on the temperature and the differences between individual vidicons, and the appropriate luminous flux on the layer will be about  $10$  millilumens, corresponding to an illumination of the layer of about  $80$  lux ( $8$  foot-candles).

Another situation, where the picture quality may still be regarded as acceptable, but where slow response effects may become objectionable and the dark current  $I_d$  has increased to about  $10\%$  of  $I_s$ , is obtained with values of  $V_s$  of between  $30$  and  $40$  V. For  $I_s = 0.2 \mu\text{A}$ , and hence  $I_d = 0.02 \mu\text{A}$ , the luminous flux required is about  $10$  times lower and an illumination of  $8$  to  $10$  lux at the layer is required.

A very sensitive setting is obtained with values of  $V_s$  above  $50$  V. Here,  $I_d$  is  $0.1$ - $0.2 \mu\text{A}$  and is of the same order of magnitude as the useful signal current, while the slow response is extremely troublesome with moving pictures. Nevertheless, the picture quality at this setting, at which an illumination at the layer of  $2$  to  $3$  lux is adequate, is still quite acceptable for many industrial uses.

#### Characteristics and operating point of image orthicons

As we have already said, the behaviour of the image orthicon is quite different and is not easy to compare with that of the vidicon or "Plumbicon". The light-transfer characteristic is only slightly dependent on the voltage settings and is determined by other factors. As may be seen in fig. 4, it is possible to obtain different characteristics with the image orthicon, but these are obtained with *different types* of tube. The characteristic of one given type cannot easily be shifted by varying the settings without undesirable side-effects, and in practice different designs of the image orthicon are used for different purposes.

A closer look at the light-transfer characteristic shows that, over a certain illumination range, the signal current varies linearly with the illumination, and that above a certain value, the "knee", it quickly becomes saturated. Unlike that of the vidicon, the situation here is completely stable if the beam current is so set that brightnesses above the knee value can still be handled. This can be an important advantage in practice. The light control, i.e. the setting of the operating point, is not critical, as the knee acts as an automatic signal current limiter. It is therefore possible to handle a wide variety of scenes in which there are marked differences in the brightness of the white portions, including specular high-lights, without altering the setting. It is, moreover, possible to suit most of the scenes to be taken to the limited brightness range of the television system without difficulty. However, to obtain the best picture quality, the illumination of the sensitive layer, the photocathode, must be very carefully adjusted. This is done with the aid of adjustable diaphragms and grey filters. The optimum setting or operating point of an image orthicon is at or just over the knee. As a general rule the best setting is obtained when the illumination on the layer is such that white parts of a scene, in which a certain amount of detail must still be shown, are just above the knee of the given characteristic.

A further advantage, which we shall not discuss in detail here, but which is extremely important in setting up, is the increased resolution obtained when the knee is exceeded. It is rather difficult to define resolution here, but the same physical cause that gives rise to the knee in the characteristic of an image orthicon also gives rise to apparently enhanced contours at black-to-white transients. (The physical cause is in fact a redistribution of the electrons forming the charge pattern.)

Because of the fact, mentioned above, that the optimum setting is at or just above the knee, the signal-to-noise ratio of the most sensitive type of image orthicon (with the knee at the lowest illumination) is relatively poor. Fig. 4 in fact shows that, of the various designs, the most sensitive provides the weakest signal current. The signal-to-noise ratio — entirely determined by the camera tube, and proportional to the root of the signal current — is therefore at its worst for this type. The development of image orthicons over the past few years has been directed towards shifting the knee in order to obtain a better signal-to-noise ratio. The most significant improvement has been the  $4\frac{1}{2}$ " image orthicon, which has a higher knee than the 3" type, a better signal-to-noise ratio, a better resolution and which can pick up a greater range of brightnesses without undesirable side-effects.

The dimensions 3" and  $4\frac{1}{2}$ " in the designations of image orthicons refer to the diameter of the tube. The integral electron-optical image-forming elements make it possible for both types to provide optical images of the same size. However, the area of the target on which the charge pattern scanned by the electron beam is formed is about three times as great in the  $4\frac{1}{2}$ " model.

Apart from the size of this target, other factors also affect the position of the knee, so that various designs of both types are possible. Most of the characteristic features of the latest 3" types approximate very closely to those of an average  $4\frac{1}{2}$ " type, and, although the signal-to-noise ratio and resolution are basically better in the  $4\frac{1}{2}$ " type, the differences have become so slight that both types are used side by side.

The response speed is limited only by the discharge lag. At the optimum setting, this lag is quite small; it becomes noticeable only under poor lighting conditions, where the operating point is a long way below the knee.

It is a disadvantage that a certain amount of burning-in with stationary pictures, rather than speed of response with moving pictures, sets a limitation. Whenever an orthicon camera has been directed on one scene for some time, say a few minutes, a burnt-in image is formed, which can render the camera useless for a while. If it is used by inexperienced persons, this can even cause irreparable damage to the tube.

Fig. 4 shows that a  $4\frac{1}{2}$ " image orthicon at the optimum setting is only half as sensitive as a comparable 3" design. It has, however, an improved signal-to-noise ratio: where this is 36 dB in a 3" tube, it may be as much as 39 dB in a  $4\frac{1}{2}$ " model.

#### Characteristic and operating point of the "Plumbicon"

At low signal plate voltages  $V_s$ , the light-transfer characteristic of the "Plumbicon" exhibits a shift similar to that of the vidicon. Because of the special properties of the photoconductive layer of the "Plumbicon", however, the signal current rapidly becomes saturated as  $V_s$  increases. Above  $V_s = 30$  V, sensitivity virtually ceases to increase. In other words, for  $V_s > 30$  V the characteristic can be considered as fixed. If the illumination  $E_f$  is increased at a constant  $V_s$ , then, as with the vidicons, we find a point at which there is a sharp transition to a horizontal line, owing to the beam current being no longer adequate for stabilizing at cathode potential. It is also of course possible, with the "Plumbicon", to shift this transition point by varying the beam current.

One of the main differences, however, between the "Plumbicon" and the vidicon is that the characteristic of the former in the stable part is a straight line of unit slope, which means that  $I_s$  is proportional to  $E_f$ . Only in this case can the sensitivity be indicated by one single numerical value, expressed in microampères



per lumen. This sensitivity of the "Plumbicon" lies between 300 and 400  $\mu\text{A}/\text{lm}$ .

The determination of the optimum setting will now be explained and a more quantitative treatment will follow. In the image orthicon, the operating point was entirely determined by the knee of the characteristic, which also determined signal-to-noise ratio, permissible brightness range and sensitivity. For the vidicon, the choice of the operating point was a compromise between speed of response, dark current and the available quantity of light. For the "Plumbicon", it will be seen that the optimum setting likewise is determined by the effect of various factors.

As already mentioned in the introduction and described in detail in I, the "Plumbicon" has two significant advantages over the vidicon. In the first place, the dark current is negligibly low and does not become very much greater at higher values of  $V_s$ . Secondly, the photoconductive lag is very small and independent of the illumination  $E_t$ . The photoconductive lag is to some extent dependent on  $V_s$ , but at the usual values of  $V_s$  it is negligible compared to the discharge lag.

Because of these advantages, finding the right setting is simple. If the operating point is made low, the illumination required is also low (i.e. the sensitivity is high) and the signal current is small, while the signal-to-noise ratio is poor. With a higher operating point, more light is needed, but the signal current becomes proportionately larger and the signal-to-noise ratio proportionately better.

The amount of noise in the signal has thus become practically the only decisive factor in the choice of the setting, and all factors affecting this noise therefore directly affect the choice of the operating point.

As already described for the vidicon, an inadequate beam current can cause a sharp transition in the characteristic to a horizontal line, giving rise to an unstable state of "over-exposure". With the linear characteristic of the "Plumbicon" the risk of over-exposure due to a sudden increase in the illumination level, or to specular highlights, is higher than with the vidicon characteristic, which exhibits saturation. This must be given careful consideration, which means that the risk of over-exposure must be reduced by stopping down, using grey filters or adjusting the level of illumination of the scene. With a camera equipped with a "Plumbicon", therefore, it is of the utmost importance to have a fast and accurate light-control. It is, however, extremely difficult, if not impossible, to prevent accidental specular highlights, and these too must not give rise to over-exposure. The knee in the characteristic must, therefore, be far enough above the operating point to leave an adequate safety margin.

The knee can be shifted upwards by increasing the beam current, but this can prejudice resolution. In view of the safety margin required, therefore, it is recommended that the operating point should never be set higher than is necessary to obtain an acceptable signal-to-noise ratio.

#### *Quantitative determination of the operating point of the "Plumbicon"*

We shall now discuss in more detail the signal current necessary to obtain a given picture quality. The signal-to-noise ratio is our starting point since, as already mentioned, it is an important factor here. Let us assume that the signal-to-noise ratio of the output signal is to be 40 dB for flat noise — a value which can hardly be attained with the best image orthicons and which is generally considered fully adequate for studio use. As already stated (see p. 5), the most significant source of noise in both the vidicon and the "Plumbicon" is the input circuit of the signal amplifier, and this noise is frequency-dependent. If the signal-to-noise ratio is to be at least 40 dB for flat noise, then for triangular noise the ratio  $S/N$  between the peak signal current and the effective noise current must be at least  $100/2.25 = 45$ .

In *fig. 6* the elements of a camera signal amplifier that affect the signal-to-noise ratio of the output signal can be seen. These are the preamplifier  $A_v$ , the aperture corrector  $A_a$  and the gamma corrector  $A_\gamma$ . The preamplifier is always necessary; whether aperture and gamma correction are also required depends to some extent on circumstances, as will be seen later.

The camera tube, whose inherent noise may be neglected, is connected to the preamplifier  $A_v$  by means of a signal resistor  $R_s$ . Analysis [7] shows that as  $R_s$  increases — if we assume the output impedance of the camera tube to be infinitely high — the signal-to-noise ratio at the output of  $A_v$  approaches a maximum given by:

$$\frac{S}{N} = 22 \times 10^8 \frac{I_s}{FG_t \sqrt{FR_t}} \quad \dots \quad (2)$$

Here,  $F$  is the bandwidth,  $R_t$  the "equivalent noise resistance" of the input circuit of the preamplifier, and  $C_t$  the total parasitic capacitance in parallel with  $R_s$ . The constant  $22 \times 10^8$  is the value of  $\sqrt{3/(16\pi^2 kT)}$  at room temperature.

It may be seen from (2) that, at a given bandwidth,  $C_t$  and  $R_t$  set a limit to the value of  $S/N$ , and also that the parasitic capacitance is of prime importance. With practical values:  $F = 5 \text{ Mc/s}$ ,  $C_t = 25 \text{ pF}$  and  $R_t = 200 \Omega$ , equation (2) gives:

$$\frac{S}{N} \approx 5.6 \times 10^8 I_s,$$

so that a minimum signal current of  $0.08 \mu\text{A}$  (for white) is needed in order to obtain at the output of  $A_v$  a signal-to-noise ratio of 40 dB ( $S/N$  at least = 45). In practice, because of the noise contribution from  $R_s$ , a slightly worse ratio must be taken into account, and the real value for  $I_s$  must be taken as  $0.1 \mu\text{A}$ . (It should be pointed out that  $C_t$  and  $R_t$  may be made smaller by making use of more complex preamplifier circuits, using selected components and a very accurate setting<sup>[81]</sup>.)

retain the original value of 40 dB assumed for the signal-to-noise ratio, and make full use of the increased resolution obtained by aperture correction,  $I_s$  must be increased to  $0.13 \mu\text{A}$ .

Resolution has thus been improved at the expense of sensitivity. If enough light is available, this optimum correction is, of course, desirable, but if the lighting is poor (as for example during the evening), a compromise must be made between resolution and noise, by suitably setting the aperture correction.

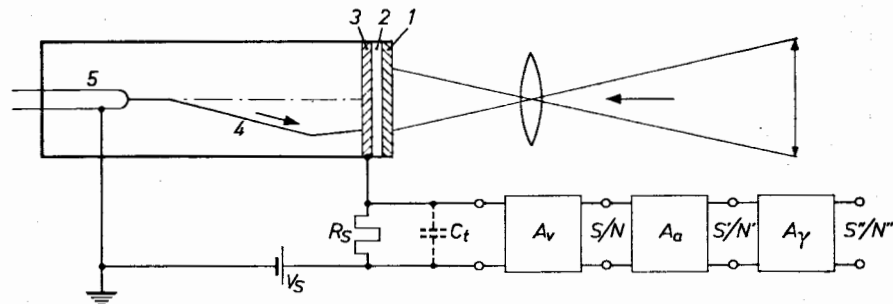


Fig. 6. Connection of a vidicon or "Plumbicon" to preamplifier  $A_v$  by means of signal resistor  $R_s$ . The equivalent noise resistance of the input stage of  $A_v$  and the parasitic capacitance  $C_t$  limit the signal-to-noise ratio at the output of  $A_v$ . 1 glass window, 2 transparent signal plate, 3 photosensitive layer, 4 electron beam and 5 cathode.  $V_s$  signal plate voltage (see 1, fig. 2),  $A_a$  and  $A_\gamma$ : circuits for aperture and gamma correction.

#### The effect of aperture correction

The resolution of the picture is determined by a number of factors. It depends, to a great extent on limitations in the camera tube itself (see I, p.144), but the optical section can also be significant. Zoom lenses, in particular, i.e. lenses with a continuously variable focal length, which are so often used nowadays, are certainly not ideal at large apertures. Spot correction, or, as it is more often called, aperture correction, which compensates for the effective size of the electron beam scanning spot exceeding the line width, can improve resolution. A simple electronic circuit giving amplification increasing with frequency, without the introduction of phase errors, can give optimum resolution at least in the horizontal direction<sup>[9]</sup>. Aperture correction gives no amplification at low frequencies, so that the amplitudes of the signal over large areas in the picture do not alter with the insertion of  $A_a$ , but the higher signal frequencies, and hence the higher frequencies in the noise spectrum, receive extra amplification.

At 5 Mc/s, the modulation depth of the average "Plumbicon" is only 50% of its value at 0.5 Mc/s, so that the amplification at 5 Mc/s must be at least twice as great (6 dB extra) for optimum correction. Further analysis shows that this causes the signal-to-noise ratio with a triangular noise spectrum to decrease by a factor of 1.3. If, therefore, we want to

#### The effect of gamma correction

The aperture correction mentioned above is also often used in vidicon cameras. Gamma correction, which we shall now discuss, is, however, only required for "Plumbicon" tubes.

This is because, in a picture tube, the luminance of the screen increases roughly with the square (at least) of the signal voltage applied to the control grid of the tube. To make the screen luminance proportional to the luminance of the original scene, the output signal of the camera must be approximately proportional to the root of the luminance of the scene. This is roughly what happens in the vidicon, as in the light-transfer characteristic  $I_s \propto E_t^{0.6}$ , while  $E_t$  is, of course, proportional to the luminance of the scene. The proportionality in the image orthicon is not so good, but the effect of the knee and the additional effect that the average scene content also has on the characteristic make gamma correction seldom necessary.

[7] V. K. Zworykin and G. A. Morton, *Television*, Wiley, New York 1954 (2nd edition), pp. 529-532.

[81] K. Sadashige, A study of noise in television camera pre-amplifiers, *J. SMPTE* 73, 202-206, 1964.

[9] Vertical aperture correction is possible, e.g. with the aid of delay lines. See: C. F. Brockelsby and J. S. Palfreeman, Ultrasonic delay lines and their applications to television, *Philips tech. Rev.* 25, 234-252, 1963/64.

In the "Plumbicon", however, where  $I_s$  is proportional to  $E_r$  and no limitation or saturation occurs right up to the point of instability, the gamma corrector  $A_\gamma$  is essential. This consists of a non-linear amplifier in which the output signal  $S''$  and the input signal  $S'$  are connected by the relationship (fig. 7):

$$\frac{S''}{S_w''} = \left(\frac{S'}{S_w'}\right)^\gamma \quad \dots \dots (3)$$

The subscript W again indicates the signal for white. The amplification  $S''/S'$ , dependent here on the signal level, is given by the slope of the chord to the origin (disregarding the constant factor  $S_w''/S_w'$ ). The noise  $N'$  superimposed on  $S'$  is also amplified, but this amplification is determined by the slope of the tangent at  $S'$ . For a parabolic characteristic ( $\gamma = 0.5$  in eq. 3), it can easily be verified that the signal amplification is always twice that of the noise.

In spite of this, gamma correction reduces the normalized signal-to-noise ratio. Although by definition we start from a noise level  $N'$  independent of the signal level  $S$ , the amplification of the noise does indeed depend upon the signal level. We shall, therefore, calculate the equivalent noise  $N_{eq}'' = \frac{1}{6} (N_w'' + 3N_G'' + 2N_Z'')$  (see eq. 1).  $N_Z''$  is determined by the practical consideration that, in a real gamma corrector, the tangent will never be vertical. If the characteristic has a slope 4 at the origin and gradually becomes a parabola, excellent tonal gradation is also obtained in the dark parts of the picture. In this case,  $N_Z'' = 4N'$ . Moreover, for white,  $N_w'' = 0.5N'$  and in the grey (for which it is assumed that  $S'' = 0.4S_w''$ ),  $N_G'' = 1.25N'$ , so that  $N_{eq}'' \approx 2N'$ .

Gamma correction, therefore, reduces the normalized signal-to-noise ratio by half, and, to maintain the desired signal-to-noise ratio of 40 dB, this must be compensated by a proportional increase in the signal current  $I_s$ .

Thus, if both aperture and gamma correction are used in a "Plumbicon" camera, the operating point must be set at  $I_s \approx 0.25 \mu A$  for the postulated signal-to-noise ratio. It should also be pointed out that scenes with limited brightness range may allow a different degree of gamma correction: an acceptable tonal gradation may for instance be obtained if the characteristic has a slope of 2 at the origin. In this case,  $N_{eq}'' = 1.4N'$ , and the operating point may be set at  $I_s = 0.18 \mu A$ .

If, on the other hand, the scene to be taken has a very wide brightness range and the most important parts of the picture are the dark ones, the operating point may have to be set at a higher  $I_s$  to prevent the noise in the dark parts of the picture from being too

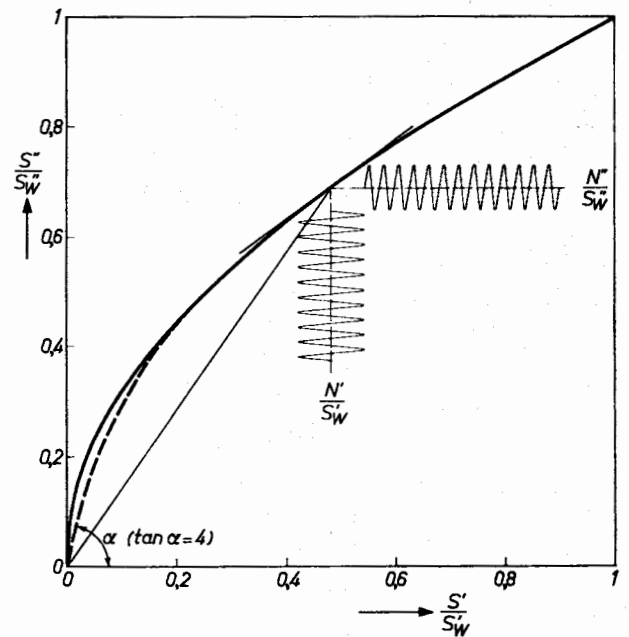


Fig. 7. Characteristic of the gamma corrector for a camera tube in which the signal current is proportional to illumination, as in the "Plumbicon".  $S'$  is the input signal,  $S''$  the output signal,  $S_w'$  and  $S_w''$  are the signal values for white. The slopes of the chord through the origin and of the tangent at  $S'$  determine the relative amplification of the signal  $S'$  and of the superimposed noise  $N'$  respectively. In theory, the characteristic must always be a curve with infinite slope at the origin (since  $\gamma$  is smaller than unity), but, in practice, a slope of 4 at the origin is sufficient for good tonal gradation (see the broken line).

pronounced at maximum gamma correction. The extent to which, if at all, this can be done, will depend upon the safety margin required to allow for specular highlights which, as mentioned previously, can cause a transition of the characteristic into that for the unstable state if the beam current is inadequate.

**Comparison between the "Plumbicon" and the image orthicon**

As we have said in the introduction, it is impossible to make a purely objective comparison between different types of camera tube. It is in fact quite reasonable not to attempt any comparison between the vidicon and the image orthicon, since these two types of tube are used for quite different purposes. The "Plumbicon", however, as stated in the introduction, does not have the fundamental limitations of the vidicon, and can, therefore, be considered for the same applications as the image orthicon. Thus it is both possible and useful to make a comparison between the "Plumbicon" and the image orthicon.

We shall be restricting ourselves to some of the characteristic features of particular importance: sensitivity, resolution, tonal gradation and the signal-to-noise ratio.

Fig. 4 and the determination of the operating points

have already shown that the sensitivity of the "Plumbicon" is roughly comparable with that of the best 3" image orthicons. Inspection of a large variety of scenes bears this out in practice. The "Plumbicon" is, however, more sensitive than the 4½" image orthicon, especially if one bears in mind that the sensitivity of image orthicons decreases as the number of operational hours increases, and sometimes even drops to half during their life.

The situation is different for resolution. Without special corrective measures the resolution of the "Plumbicon" is not as good as that of the 4½" image orthicon. The image orthicon, properly set to the knee of the characteristic, benefits here from the apparent "contour-enhancing" effect mentioned earlier, which accentuates transitions from black to white. The perceptible differences between the two types of tube do, however, diminish considerably if aperture correction is used, which is fairly simple for the horizontal direction. The differences also depend upon the beam current setting. Even the colour temperature of the light has some effect: outdoor scenes with a high colour temperature taken with a "Plumbicon" often give surprisingly sharp pictures.

On the subject of tonal gradation, it must first of all be said that many factors are involved here. "Plumbicon" pictures, with the appropriate gamma correction, are characterized by faithful, "photographic" gradation within a wide (albeit still restricted) range of brightness. In practice, however, the gradation in pictures from the image orthicon is equally acceptable, even though, to prevent the signal-to-noise ratio from being reduced, it is not usual in this case to apply gamma correction. The effect of the knee in the light-transfer characteristic of the image orthicon, which has already been described, makes it possible to find an acceptable setting for a wide variety of scenes. This has quite justifiably been regarded as a considerable advantage. Nevertheless, a better result can generally be obtained with a "Plumbicon" camera equipped with a signal limiter and an adjustable gamma corrector.

It is only in scenes with a very wide brightness range or with specular highlights that situations occur which adversely affect the picture quality of the "Plumbicon" — either by loss of resolution, or by trailing effects in the non-stabilized highlights, or by increase of noise in the image, due to the fact that the operating point has to be reset to a lower signal current  $I_s$ .

The signal-to-noise ratio for a given type of image orthicon is determined by the tube itself and, when noise is measured without a noise-weighting filter, is 34-36 dB in a 3" type and 37-39 dB in a 4½" type, depending on setting and operational life. The illu-

mination required for the "Plumbicon" in the discussions so far has been calculated on the basis of a signal-to-noise ratio of 40 dB. Here we have one of the most important differences between the image orthicon and the "Plumbicon". The signal-to-noise ratio of a given image orthicon can be improved only very slightly. If more light is available, the operating point can hardly be shifted since otherwise the knee in the characteristic would cause all gradation in the lighter parts of the image to disappear. In the "Plumbicon", on the other hand, the operating point may be displaced along the characteristic, so that if desired the signal-to-noise ratio can be still further improved.

This shows that, for applications where high picture quality is called for and the ordinary vidicon cannot be used because it is not sensitive enough, the "Plumbicon" is an interesting proposition, and can, in many instances, produce pictures of a quality comparable to that of the best image orthicon pictures.

#### Application in colour television cameras <sup>[10]</sup>

The requirements made of camera tubes for colour television cameras are more stringent and rather different from those for black-and-white cameras. The "Plumbicon" satisfies many of these requirements particularly well.

For a good colour balance and a correct colour gradation it is extremely important that the tube should have a well-defined light-transfer characteristic dependent on only a few parameters. The "Plumbicon", therefore, because its characteristic is independent of the illumination at the layer and of the average picture content, considerably simplifies the task of giving good, natural colour reproduction with a colour television camera under all kinds of conditions.

Spurious signals causing for instance an uneven and fluctuating black level are particularly undesirable in colour television because such signals are not the same for each of the three primary colours, and therefore give rise to colour impurities. The adjustment of a colour camera then becomes very complicated, especially if the spurious signals are dependent on temperature, focus, beam current setting or beam centring. The low dark current of the "Plumbicon" has been found to be highly significant in this connection and has made any form of shading (dynamic correction of the black level) superfluous. This considerably widens the brightness range that can be covered while retaining good colour reproduction. A uniform sensitivity over the whole area of the picture is also of importance. Differences in local sensitivity between

[10] For general concepts, see: F. W. de Vrijer, Fundamentals of colour television, Philips tech. Rev. 19, 86-97, 1957/58.

the various camera tubes produce colour shifts, which are particularly noticeable in scenes where the background is uniform.

The sensitivity of a colour television camera, which will, of course, be less than that of a black-and-white camera, is highly important, since an increase in the illumination in studios involves many other factors. These can include architectural and economic considerations (for instance, air-conditioning may be required). Sensitivity will be discussed separately in the next section, and it will be seen that in this respect the "Plumbicon" compares very favourably.

Moreover, it is obvious that the advantages of small size and smaller picture format, which vidicon-type camera tubes have compared with image orthicons, are more important considerations in the design of a colour television camera than in the design of black-and-white studio cameras.

Quite apart from all these factors, there is yet another, very important, and even perhaps, decisive requirement in the use of a particular type of camera tube in a colour television camera. The three primary colour pictures taken through three tubes must be geometrically exactly similar to one another. Primary colour pictures that do not precisely cover one another ("registration" errors) give rise to undesired coloured edges in the reproduced picture. This will affect not only the quality of the colour picture, but also the display of the picture in black-and-white, which should satisfy the colour monochrome compatibility requirements. It will be clear that "registration" errors will adversely affect the resolution of the picture received by a monochrome receiver, since, in the colour transmission system, the signal for black-and-white reception is built up from the three primary colour signals. With "Plumbicon" tubes no great difficulties are experienced in accurate registration of the three primary colour pictures.

All these factors make the use of the "Plumbicon" in colour cameras very attractive. The Philips Research Laboratories in Eindhoven had already developed colour television cameras incorporating the "Plumbicon" a few years ago. Very good results were obtained, and practical tests have shown that particularly for colour television, the "Plumbicon" has a great many advantages to offer.

#### *Sensitivity of a colour television camera*

In colour television, as in monochrome systems, the sensitivity is, to a large extent, determined by the signal-to-noise ratio. A difference is made in colour television, however, between luminance noise and chrominance noise. As the name implies, luminance noise relates purely to fluctuations in the total lumi-

nance, i.e. the sum of the luminances of the three primary colours in the reproduced picture, while chrominance noise relates to fluctuations in the particular colour.

Experience has shown that, taking the average of a large number of scenes, the determining factor is the luminance noise.

To compare this with the noise in monochrome television, let us consider a scene taken with a black-and-white camera and a colour camera, both fitted with "Plumbicon" tubes and identical lenses.

For a white area, the three camera tubes provide signals giving fractions  $f_R$ ,  $f_G$  and  $f_B$  respectively of the signal from the tube in the monochrome camera. The actual values of  $f_R$ ,  $f_G$  and  $f_B$  depend upon the colour-separating system, the spectral response of the "Plumbicon" and the colour temperature of the light sources used to illuminate the scene.

The spectral response curves for the three colour channels are given in *fig. 8*. This shows the ideal relative spectral response curves for optimum colour

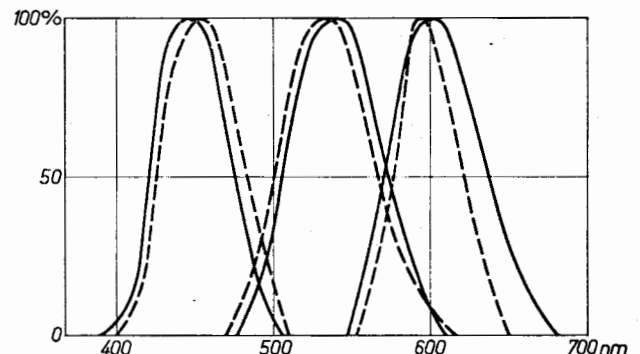


Fig. 8. Relative spectral response curves for the three colour channels in a colour television camera with "Plumbicon" tubes. The solid lines are the theoretical curves that, with certain assumptions, give the best possible reproduction of most colours. The broken lines are measured curves, which must be regarded as the best compromise. The cut-off at longer wavelengths in the red channel is caused by the limited red sensitivity of the "Plumbicon". This limitation could be removed by the use of a "Plumbicon" with an increased red sensitivity<sup>[11]</sup>.

reproduction, together with those that have been obtained in practice. With the standard "Plumbicon" and a colour temperature of 3200 °K for the light source,  $f_R$ ,  $f_G$  and  $f_B$  are 8, 20 and 12% respectively. For the present considerations gamma correction can be ignored, and as a starting point for the simple linear case we can assume a luminance signal  $E_y$  for which:

$$E_y = 0.3 E_R + 0.6 E_G + 0.1 E_B.$$

The primary colour signals are amplified in such a way that for "white":

$$E_R = E_G = E_B = E_y.$$

The differences between  $f_R$ ,  $f_G$  and  $f_B$  lead to different amplification factors, so that, for the effective value of the noise:

$$N_y = N \sqrt{\left(\frac{0.3}{f_R}\right)^2 + \left(\frac{0.6}{f_G}\right)^2 + \left(\frac{0.1}{f_B}\right)^2}.$$

$N_y$  thus becomes about  $5N$ , or, in other words, to obtain the same signal-to-noise ratio, the illumination level must be 5 times higher for a colour camera than for a black-and-white camera.

Things are, of course, a little more complicated for colour scenes, but, as long as the colours are not highly saturated and, in particular, large, highly saturated red areas do not occur, it is confirmed in practice that this factor of 5 is about correct.

Because  $f_G = 20\%$  and the illumination level has to be 5 times higher, the quite incidental result is that the "green" camera tube is set to the same operating point as that previously determined for a black-and-white camera. If there is ample light available, as is usual in outdoor work, then by making use of correction filters it is possible to set all three tubes to the optimum operating point. This requires 12 to 15 times as much light as for a black-and-white camera, but  $N_y$  now becomes smaller than  $N$ :

$$N_y = N \sqrt{0.3^2 + 0.6^2 + 0.1^2} = 0.68 N.$$

Under these conditions, therefore, with settings at the optimum operating point, the signal-to-noise ratio in the luminance signal is 4 dB better than that attained with a black-and-white camera at the optimum setting.

#### Colour television camera with image orthicons

Apart from the fact that a colour television camera employing image orthicons is rather bulky because of the large size of the tubes, and requires a very complex optical system, there are two other important factors.

Firstly, the image orthicons cannot be fully operated into the knee of the light-transfer characteristic, as the characteristic at that point is not so well-defined. This adversely affects the signal-to-noise ratio and the resolution. Secondly, the image orthicons for the three channels must be accurately set to the same operating point to obtain good colour balance, and this means that the values for  $f_R$ ,  $f_G$  and  $f_B$  are equalized. None

of them therefore can be made larger than 8 to 10%, with the result that such a camera is 10 to 12 times less sensitive than a black-and-white camera using the same type of image orthicon. A less favourable setting is therefore required.

In addition, extremely stringent requirements are made on the precision of the tube construction and the stability of the control voltages in order to keep "registration" errors to a minimum. All these factors make it clear that such cameras in practice are not altogether an attractive proposition. Attempts have been made to overcome the difficulties by using colour cameras with *four* camera tubes, the fourth being used solely to provide the luminance signal [12].

#### A colour television camera with "Plumbicon" tubes

The title photograph shows a colour television camera using "Plumbicon" tubes now in production. The colour-separation system is made up of prisms (fig. 9), following the method described in an earlier article in this journal [13]. Such a colour-separation system has various optical advantages and allows the colour television camera to be very compact. The camera has a variable-focus lens, and the adjustments,

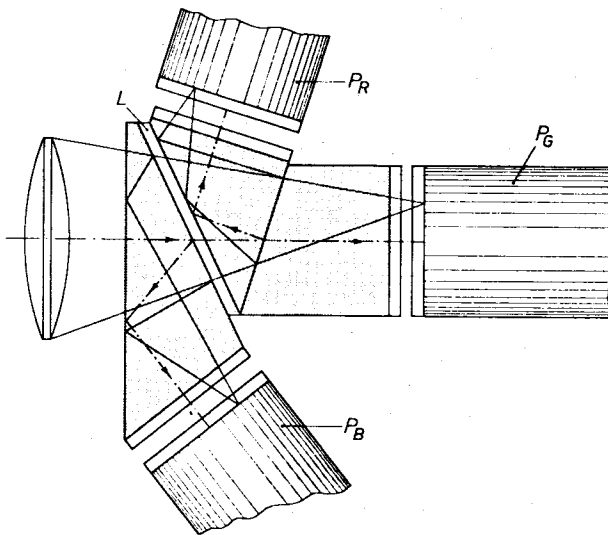


Fig. 9. Principle of a colour-separating prism arrangement in the optical system [13]. The light enters the first prism and strikes a layer that selectively reflects the blue component of the light. The angle of this plane to the optical axis is such that all rays reflected from it are totally reflected at the boundary of the prism. The blue component is thereby reflected downwards, towards the "blue" "Plumbicon"  $P_B$ . A second layer, which selectively reflects the red component of the light, is cemented between the second and third prism. By correct choice of the angles involved, the red light is reflected a second time by total reflection at a glass-air boundary between the first and second part of the prism ( $L$  is an air-gap), and thus reaches the "red" "Plumbicon"  $P_R$ . The green component of the light travels straight through and provides the image for the "green" "Plumbicon"  $P_G$ . Special trimming filters in each channel ensure that the spectral transmission curves are as close as possible to the ideal.

[11] E. F. de Haan, F. M. Klaassen and P. P. M. Schampers, An experimental "Plumbicon" camera tube with increased sensitivity to red light, Philips tech. Rev. 26, 49-51, 1965.

[12] W. Dillenburger, Gesichtspunkte für die Entwicklung einer Farbfernsehkamera, Radio-Mentor 30, 974-981, 1964.

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

such as focusing, focal length setting and iris control, are effected by servo systems. The focal length may be varied between 18 and 180 mm, with a maximum relative aperture of 1: 2.2. The lens is optically corrected for the prism system inserted in the path of the beam. It is even possible, with an alternative currently available lens, to vary the focal length from 50 to 600 mm.

The compact construction of this camera is also illustrated in *fig. 10*. The arrangement of the three "Plumbicon" tubes in a vertical plane is somewhat unusual; this is determined by the colour-separating system. With such an arrangement, magnetic screening is very important to prevent undesired magnetic fields from reaching the camera tubes and upsetting the relative geometry and the precise registration.

Some idea of the sensitivity of such a camera with "Plumbicon" tubes is readily obtained from the table below, which gives the conditions in a normal scene, the settings to be used for it and the signal-to-noise ratio attained:

incident light level	1500 lux (150 foot-candles)
reflection coefficient (of the white parts of the scene)	60%
colour temperature of the lighting	3200 °K
relative aperture	1 : 2.8
aperture correction	6 dB at 5 Mc/s
gamma correction	$\gamma = 0.5$ in a 1 : 40 range
normalized signal-to-noise ratio in the luminance signal	42 dB
signal-to-noise ratio (determined with a noise-weighting filter)	50 dB

At full lens aperture and with no spot correction, however, faithful colour pictures can still be made at an illumination of 200 to 250 lux with an acceptable signal-to-noise ratio in the luminance signal.

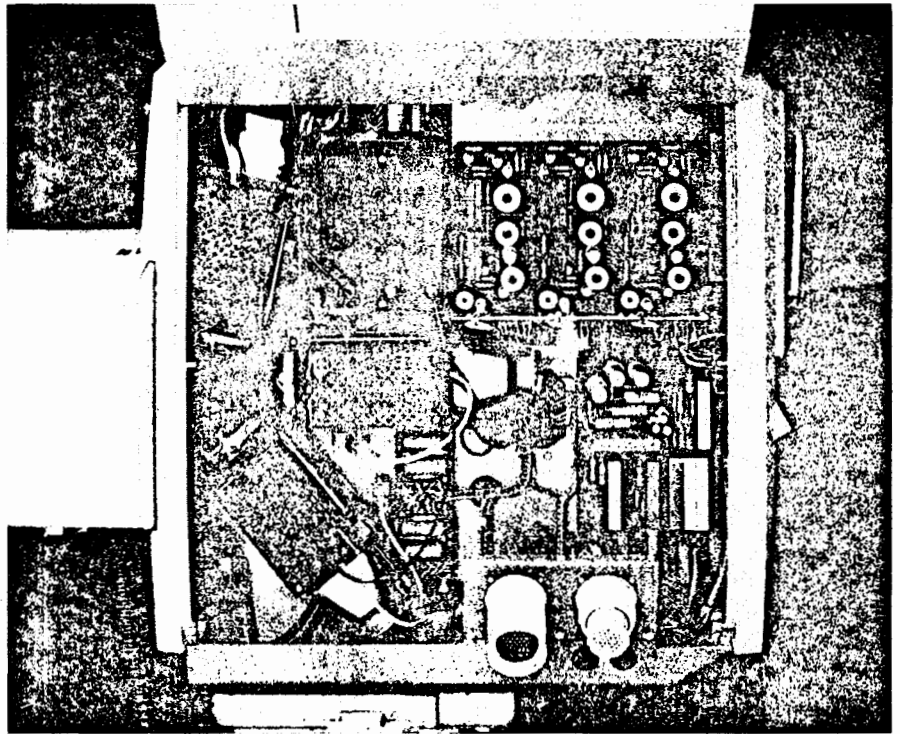


Fig. 10. A view inside a colour television camera equipped with "Plumbicon" tubes. Three identical, adjustable units are arranged around the colour-separating prism system. Each unit comprises a "Plumbicon" tube with its focusing and deflection coil and magnetic screening, as well as a signal amplifier. This side of the camera also contains the horizontal deflection circuits.

**Summary.** Because the "Plumbicon" does not have the drawbacks of the  $Sb_2S_3$  vidicon, i.e. poor response speed and excessive dark current, it is suitable for studio use. The factors to be taken into account in comparing its picture quality with that of the image orthicons used up to now include resolution, tonal gradation, brightness range, signal-to-noise ratio, uniformity, etc. A number of conditions for proper comparison are discussed, including the required focal length and diameter of the lens, the selection of the operating point on the light-transfer characteristic, and the measurement of the noise with a noise-weighting filter. Closer examination of the light-transfer characteristic of the different types of tube shows that the signal-to-noise ratio of the "Plumbicon" can be improved by shifting the operating point upwards, but there must be a safety margin to safeguard against "over-exposure" from specular highlights. If a signal-to-noise ratio of 40 dB (for flat noise) is required — a value hardly achieved by the best image orthicons — then in view of aperture correction and the gamma correction desirable for the "Plumbicon", the operating point must be set at a signal current of  $0.25 \mu A$  (and maintained there by controlling the light level). The sensitivity is then comparable to that of the best 3" image orthicons. The  $4\frac{1}{2}$ " image orthicon is not so sensitive, but gives better resolution. Better tonal gradation can usually be obtained with a "Plumbicon"-equipped camera than with an image orthicon camera. The "Plumbicon" is particularly suitable for colour television cameras, not only because of its small physical size and small image size, but also because its characteristic is independent of the illumination at the layer and of the average picture content, and further because in this case it is not very difficult to prevent annoying "registration" errors in the three primary colour pictures. Its sensitivity is such that a colour camera using "Plumbicon" tubes can easily pick up a normal scene where the illumination is 1500 lux (150 foot-candles): the normalized signal-to-noise ratio in the luminance signal is then 42 dB. Acceptable pictures can still be obtained at 200 to 250 lux.