A VELOCITY-MODULATION TELEVISION SYSTEM.

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SUMMARY.

The paper describes a complete television system operating on the velocity-modulation principle. The theory, advantages, and limitations, of the principle are discussed, and it is shown how these limitations are overcome by the use of a further principle, that of intensification.

The practical development of the system is described in detail, particular attention being given to the transmitting end, where the most fundamental problems are encountered. The results obtained to date (with single-channel wire transmission) are specified.

The complete system is shown to be characterized by the following features:—

(*a*) Absence of synchronizing problem in the line-scanning direction.

(*b*) Simple solution of synchronizing problem in the picture-traversing direction, including automatic framing.

(*c*) Greatly relaxed modulation requirements on the receiving oscillograph.

(*d*) Increased picture-brightness for a given receiving oscillograph as compared with the intensity-modulation system.

(*e*) Favourable concentration of detail in the light portions of the picture.

(*f*) Nearly constant percentage modulation of radio transmitter.

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(1) INTRODUCTION.

The conception of the velocity-modulation principle dates back, as far as it has been possible to trace it, to Boris Rosing,* who described it in 1911. Since that date the principle appears to have fallen into oblivion, and to have been next considered by Thun,† who gave it the name *Liniensteuerung*. The first practical realization of the principle was achieved by von Ardenne‡ in 1931. The present authors were first led to consider velocity-modulation television in December, 1931. At that time they were in ignorance of the earlier publications, and had been led to the principle in a search for a means of circumventing the difficulty of satisfactorily modulating the intensity of the cathode ray. It was, however, the other advantages of the principle, which became apparent on closer consideration, and which in fact had been clearly pointed out by Thun,§ which led to the decision to proceed with the development of a complete television system on a velocity-modulation basis, a development which was actually commenced in August, 1932.

(2) THE VELOCITY-MODULATION PRINCIPLE.

The basic idea underlying the velocity-modulation principle is to obtain light-intensity variations in the received picture by varying not the instantaneous intensity of the scanning spot but its instantaneous scanning velocity, i.e. its speed of traverse over the screen, the actual light intensity of the scanning spot remaining constant. That a true impression of light and dark can be produced in this manner depends upon the phenomenon of persistence of vision. If a light-spot of constant intensity describes a repeating oscillogram, in which the instantaneous traversing speed varies from point to point, the eye will appreciate this state of affairs as such only if the movement is sufficiently slow. If the movement is so rapid that the oscillogram is completed in a period within the persistence of vision, the eye renders a totally different impression, namely that of a stationary oscillogram with variations of brightness along its length. The brightness which the eye associates with an element ds of the oscillogram is that obtained by averaging over a period of time the instantaneous flashes of light which occur as the spot passes through the element. Thus, if the actual intensity of the light-spot is constant, the apparent brightness of the element ds is proportional simply to the time taken by the spot to traverse the element; hence the apparent brightness is inversely proportional to the local instantaneous scanning velocity.

This principle, then, presents the possibility of obtain-

* See Bibliography, (1). † *Ibid.*, (2). ‡ *Ibid.*, (3). § *Ibid.*, (4).

ing light and dark in a received picture without actual modulation of the spot or ray intensity, and it is therefore ideally suited to television reception by means of the conventional cathode-ray oscillograph. Moreover, the cathode-ray oscillograph is practically the only instrument which has sufficient freedom from inertia to reproduce successfully the extremely abrupt changes of velocity* which are called for.

Consideration shows that it is fundamentally impossible to realize a velocity-modulated received picture from a uniformly scanned object; the scanning at the transmitter must also be velocity-modulated. It follows that the scanning element at the transmitter must also be a cathode ray, which means that, if a process analogous to beam scanning is to be employed at the transmitter, a cathode-ray oscillograph must serve as a source of light. This means that the picture subject-matter will, on grounds of scanning-light economy, be restricted to film material, at least so long as anything comparable with the ordinary low-voltage oscillograph is employed as scanner. In the opinion of the authors, this restriction does not constitute a drawback to the system, as the same restriction is forced upon a television service of any sort from quite other considerations; but it is of technical interest to point out that direct subject transmission is not considered to be outside the bounds of possibility. The present paper is, however, exclusively concerned with the problem of transmitting from film subject-matter, a low-voltage oscillograph serving as scanner.

In essence, then, the immediate problem becomes this: To make the spot of an oscillograph illuminate a cinema film point by point (through a lens), the light transmitted through the film falling on to a photo-cell, and to cause the output from the photo-cell to react back on the scanning oscillograph in such a manner as to control the instantaneous scanning speed. In the case of transmission from a positive picture, increased light on the photo-cell must bring about a decrease of scanning velocity. The path of the spot must, so to speak, be mapped out beforehand into a suitable line *raster*,† which is of such a size and shape as to allow the real image of the spot to explore the whole of one picture; and the photo-cell output must determine only the instantaneous speed of the scanning spot and not its position or intensity. It then comes about that a copy of the picture appears on the screen of the transmitting tube itself; for wherever the real image of the spot falls on an opaque portion of the film the spot itself is speeded up and so gives the appearance of darkness on the transmitter.

The appearance of the picture on the transmitter is a feature of fundamental importance; for since this picture has come about solely by means of the voltages applied to the deflector plates of the oscillograph, the same picture will result on any similar oscillograph to which these voltages are faithfully transmitted.‡ The transmission problem is reduced, in fact, to that of tying the X and Y plates of the receiving oscillograph in parallel with the corresponding plates of the transmitter. If this is done, the question of synchronization does not arise; the synchronism of the system is, in fact, *implicit*. This feature is one of the most important advantages offered by the principle.

* See Bibliography, (3).
† This word, imported from the German, is used to mean a scanning field or grating.
‡ See Bibliography, (5).

The tying together of the X and Y plates of the receiver and transmitter requires, however, fundamentally two communication channels. Von Ardenne* has attempted to transmit these two channels of intelligence, namely the line and picture deflector voltages, over a single physical channel, by making use of a frequency discrimination between them. The solution adopted by the authors differs fundamentally from this, and depends on converting the intelligence to a single channel by sacrificing the feature of implicit synchronism in the picture-traversing direction, whilst retaining it in the line-scanning direction. This state of affairs may be expressed by saying that the synchronism is implicit in the line-scanning direction and explicit in the picture-traversing direction. The picture synchronism, though explicit, is made absolutely solid by means of a signal impressed on the line scanning, so that in effect the system still operates as though the synchronism were wholly implicit.

The principle, as so far described, is seen to offer two advantages: (*a*) Absence of synchronizing problem, at least in the line-scanning direction. (*b*) Absence of intensity modulation of the cathode ray. In addition to these there are two other features to be noted in comparison with the intensity-modulation principle: (*c*) Increased picture brightness for a given receiving oscillograph. (*d*) Concentration of detail in the light portions of the picture.

The last two features, which have been particularly stressed by Thun,† result from the fact that the scanning is relatively slow in the lighter portions of the picture; both the light and the scanning time which are not wanted in the dark places are made use of in the lighter portions.

(3) THE INTENSIFICATION PRINCIPLE.

The last of the above features shows as an advantage only so long as the contrast ratio of the picture is kept low; but as soon as a high contrast-ratio is attempted, the sacrifice of detail in the dark places in favour of the light becomes objectionable, since the detail in the dark is inadequate; further, as is shown later on [see (4·146)], it becomes impossible to obtain a satisfactory transition, more particularly from dark to light, without the use of an unduly widened frequency-band. There are, in addition, very serious practical difficulties in the way of obtaining faithful tone reproduction by pure velocity-modulation [see (4·31)]. The authors were therefore led to consider the possibility of transmitting a velocity-modulated picture at low contrast-level, and superposing intensity modulation upon it at the receiving end. This system proves to be a remarkably advantageous combination of the two principles, since both kinds of modulation work at their best only when called upon to operate over a relatively restricted range. Indeed the intensity-modulation requirements are so far relaxed by the presence of velocity modulation that the ordinary type of gas-focused oscillograph tube, which shows very poor modulation characteristics, is reasonably satisfactory.

* See Bibliography, (3).
† *Ibid.*, (4).

It might perhaps be supposed that the lowering of the velocity-modulation contrast-level would seriously reduce the advantage of increased picture brightness which is such a valuable characteristic of the pure velocity-modulation principle. This supposition is not realized, the advantage of increased picture brightness being retained almost intact. For, as regards conservation of scanning time, the extremely high scanning velocities which contribute the black picture portions in a pure velocity-modulation picture conserve very little more scanning time for the light picture portions than do the only moderately high scanning velocities characteristic of the intensification system. As regards spot brightness, the spot is at its full brightness in the light portions of the picture, and, since the spot is dimmed only in the dark places, the intensification process involves only the abstraction of light from the places where its presence is detrimental.

In practice the comparison of intensified and unintensified pictures is very emphatically in favour of the former. It is, in fact, the opinion of the authors that only with the addition of intensification does the velocity-modulation principle become a practical proposition.

(4) DEVELOPMENT OF THE SYSTEM.

The development falls into the following three main categories, which, however, cannot be entirely separated:—

The television transmitter [see (4·1) below], that is to say the apparatus for providing a satisfactory picture on the transmitting oscillograph.

The transmission link [see (4·2) below]. This includes all of the apparatus joining up the television transmitter and television receiver, namely, the input to the radio transmitter, the radio transmitter itself, the ether channel, and the radio receiver. For experimental purposes the physical transmission link has been a single wire-line. The complete link for the case of radio transmission will be discussed only in general terms in the present paper.

The television receiver [see (4·3) below], that is to say the apparatus for reproducing the picture which is on the transmitter tube, when provided with a single-channel signal from a suitable part of the transmitting circuit, and also apparatus for intensifying the received velocity-modulated picture.

Of the above items, the one which is most fundamental and which presents the most outstanding difficulty is the first; it has indeed absorbed more than 75 per cent of the development effort, and inevitably occupies a somewhat similar proportion of the present paper.

(4·1) THE TRANSMITTER.

(4·11) *Preliminary Calculations.*

It was arbitrarily decided to aim at a picture frequency of 25 cycles per sec., with a detail corresponding to $120 \times 160 (= 19\,200)$ picture points. This mode of expression refers to standard cinema picture-shape (3×4), with 120-line horizontal scanning or 160-line vertical scanning. According to the usual calculation, this calls for a frequency band of $(19\,200 \times 25 \times \frac{1}{2})$ cycles per sec., or 240 kilocycles per sec. (The authors do not regard the basis of this calculation as entirely satisfactory, but consider that it gives at least the minimum frequency-band required in the case of intensity modulation, and that it provides a rough estimate in the present case.)

Taking $0 \cdot 5$ mm as the diameter of the scanning spot, the smallest allowable size for the picture on the transmitter is then $6 \cdot 0 \times 8 \cdot 0$ cm, whilst the picture should preferably be larger in order to avoid the necessity of considering the "aperture" effect, or finite size of the scanning spot.

The amount of light (in lumens) falling on the photo-cell is easily shown to be

$$\frac{1}{16}F\frac{1}{N^2}\cdot\frac{1}{(1+M)^2}\eta_1\eta_2$$

where F is the total light flux of the scanning spot (lumens), N is the "f number" of the lens, M is the linear magnification ratio of the screen picture to film picture, η_1 is the transmission coefficient of the film at any particular picture point, and η_2 is the transmission coefficient of the lens.

From this it is seen that the useful light diminishes very rapidly with the magnification ratio; it was therefore proposed to work with the above-mentioned minimum size of screen picture, giving a magnification ratio of $3 \cdot 6 : 1$ approximately.

The requirement as to signal strength from the photo-cell is simply that the signal voltage across the photo-cell output resistance should be large compared with the total noise-voltage equivalently expressed. Previous experience* had shown that this noise might be expected to be principally constituted by the thermal-agitation noise (Johnson noise†) in the photo-cell anode resistance. Taking this, for reasons which appear later, as 1 megohm, we find that the r.m.s. noise voltage corresponding to a frequency band of 240 kilocycles per sec. is 62 μV. In this calculation the capacitance across the 1-megohm photo-cell anode resistance is neglected, because the amplifier has to be so compensated as to make this capacitance appear zero over the frequency band concerned. One may therefore specify provisionally that the photo-cell voltage corresponding to full film-transparency should be of the order of 1 mV, that is to say the photo-cell current should be 1 millimicroampere.

Measurement with hard potassium photo-cells and a calcium-tungstate oscillograph (Cossor Type C) showed that such a current could be obtained with a gun voltage of the order of 2 000 volts and a lens of aperture $f/1 \cdot 9$. (Unfortunately so easy a solution was not realized in practice on account of the after-glow of the calcium-tungstate screen, which, as is shown later, has the effect of reducing the signal strength more than 8 times. In consequence of this it proved necessary to increase both the gun voltage and the lens aperture, and even to reduce somewhat the magnification ratio.)

The above calculations led to the conclusion that the "size" of the picture on the transmitter would, expressed in terms of deflector voltages, be 380×285, whence it was estimated that a d.c. supply voltage of 500 volts would be required for the time-base circuits.

* See Bibliography, (6). † *Ibid.*, (7).

(4·12) *Basic Transmitting Circuit.*

Fig. 1 shows a purely schematic version of the transmitting circuit (for a stationary picture) by which velocity-modulated scanning, and the appearance of the picture on the transmitter, is brought about.*

The screen-grid valve V_1, condenser C_1, and gas-discharge triode or thyratron V_2, constitute a time-base circuit, the valve V_1 forming the " constant current " charging element, in view of its being operated with the plate voltage well above that of the screen, that is to say in the saturated part of its anode-current/anode-voltage characteristic. The instantaneous charging current is determined from instant to instant by the voltage on the grid of V_1, which voltage is actually the output of the photo-cell amplifier. The bias on the grid of the thyratron V_2 determines, at least nominally, the voltage amplitude of the time-base sweep. The cathode of V_2 is connected to one of the X deflector plates (P_{X1}) of the oscillograph, the opposite plate (P_{X2}) being taken to a biasing potentiometer for the purpose of shifting the picture. The arrangement thus constitutes a time base which provides a scanning sweep whose speed is modulated by the instantaneous amount of light falling on the photo-cell, and a rapid fly-back on the occasion of each discharge of the thyratron. This fly-back is so rapid as to be invisible, so that it is not necessary to quench the spot on the fly-back in order to obtain a correct picture.

The type of scanning described above has been termed " constant-voltage scanning," in contradistinction to an alternative arrangement which was first contemplated and used,† called " constant-time scanning." In the former case the scanning lines are allowed to take their own time, which will vary from line to line according to the amount of light or dark encountered by the scanning spot, the lines being all of the same " voltage length." In the latter case the lines are all caused to take the same time; this is done by providing a locking arrangement which holds the spot at a point beyond the boundary of the picture until the thyratron V_2 is fired by a timed pulse on its grid. This latter arrangement has been found uneconomical in scanning time, and has been abandoned.

Coming now to the picture-traversing circuit, the screen-grid valve V_7, condenser C_7, and thyratron V_8, constitute the traversing time-base. It will be appreciated that, unless constant-time scanning is used in the line-scanning circuit, it is not satisfactory for the traversing time-base sweep to be uniform; for, if this were the case, the scanning lines would not be straight, and the pitch would be opened out in the bright portions of the picture. Two alternatives present themselves: either (*a*) the traversing velocity may be modulated along with that of the line scanning, in such a way that the two velocities hold a constant ratio; or (*b*) the scanning line may be moved on in a stepwise manner between consecutive lines, the magnitude of the step being fixed and independent of the time taken by the line. Either of these arrangements has the effect of reducing the 2-dimensional scanning raster to a single degree of freedom. The latter alternative, which may be termed a " ratchet " arrangement, is adopted in the present case.

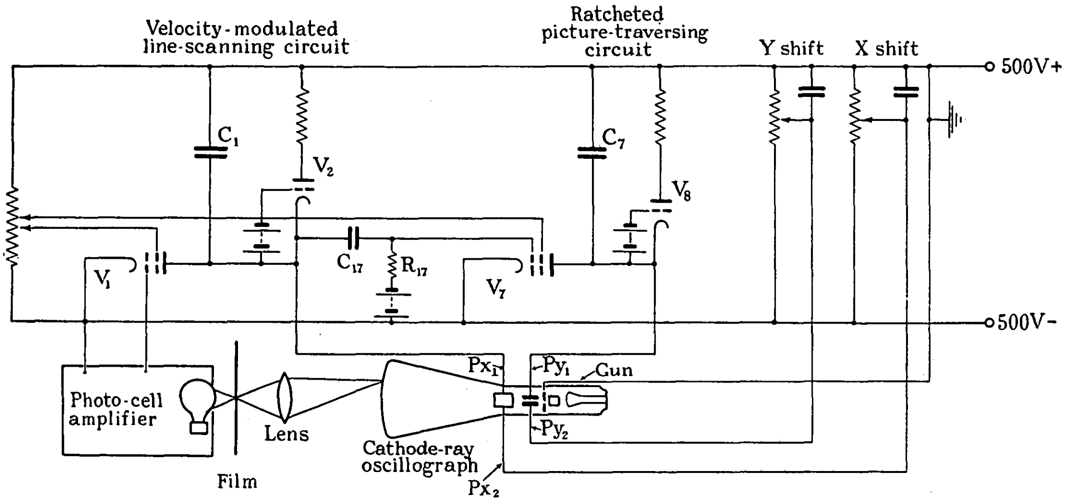

Fig. 1.

In Fig. 1 the ratcheting effect is obtained thus. The condenser C_{17} and resistance R_{17} form a species of differentiating circuit, and the high rate of change of voltage corresponding to the discharge of V_2 causes a pulse of voltage to appear across the resistance R_{17}; the bias on the grid of V_7 is such as to cause the anode current to be completely cut off except on the occasion of the pulse. As all the pulses are similar, and as V_7 is operated on the saturated part of its anode-current/anode-voltage characteristic, it follows that equal increments of charge are fed into condenser C_7 at every line fly-back, and so the requisite ratchet motion is obtained.

In the simplified schematic arrangement here discussed, the picture traverse is, like the line scanning, on a constant-voltage basis, the picture discharge occurring, in its own time, whenever the voltage across the condenser C_7 reaches a certain value, preset by the grid-bias voltage on the thyratron V_8. In practice this

* See Bibliography, (5). † *Ibid.*, (5).

arrangement is departed from, and the picture-traversing is made to proceed on a constant-time basis, in a manner which will be made clear in the description of the complete transmitter.

It is now convenient to consider the wave-form of the scanning deflector voltage which characterizes the above

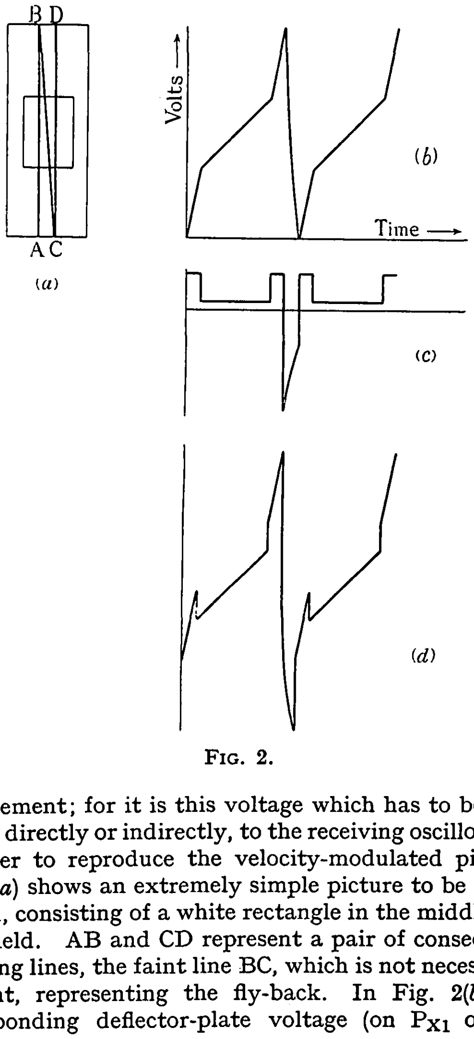

FIG. 2.

arrangement; for it is this voltage which has to be conveyed, directly or indirectly, to the receiving oscillograph in order to reproduce the velocity-modulated picture. Fig. 2(*a*) shows an extremely simple picture to be transmitted, consisting of a white rectangle in the middle of a dark field. AB and CD represent a pair of consecutive scanning lines, the faint line BC, which is not necessarily straight, representing the fly-back. In Fig. 2(*b*) the corresponding deflector-plate voltage (on P_{X1} of the transmitter) is plotted against time, whilst underneath this curve its time derivative is plotted to the same scale (Fig. 2*c*). The voltage corresponding to the scanning line AB rises steeply at first whilst the spot scans rapidly over the dark field, then more slowly as the spot moves over the white rectangle, and again steeply as the spot moves over the dark field; then follows a rapid fall of voltage corresponding to the line fly-back; in this portion of the curve the transparency variations of the film produce no effect, as the discharge valve takes control. The derived curve (Fig. 2*c*) is very much like the curve which would correspond to the transmission of the same picture in the intensity-modulation manner, except that the time scale is stretched in the light and compressed in the dark portions of the picture.

(4·13) *Practical Transmitting Circuit.*

The practical transmitting circuit shown in Fig. 3 differs from that of Fig. 1 in many points of both detail and principle; of these differences the following may be listed in advance. (1) Addition of timer circuit, providing pulses of picture frequency (25 cycles per sec.). (2) Provision of facilities ("chasing circuit") for transmission of moving pictures from a uniformly running film. (3) Substitution of thyratron V_2 of Fig. 1 by a pair of hard valves, V_2 and V_3 (Fig. 3). (4) Improved ratchet mechanism involving the ratchet driver valve V_4 (Fig. 3). (5) Picture-synchronizing signal impressed via "locking valve V_5" on scanning circuit in the form of a temporary cessation of scanning at the end of the last line. (6) Inclusion of resistances R and R′ in series with the condenser C_1. (7) Provision of output valve V_6 with condenser-resistance potentiometer input and 500-ohm output for transmission of signal to line or radio transmitter.

The last three features are concerned more strictly with the transmission-link and receiver aspects of the case, and, except for item (5), which plays a fundamental role in the transmitting circuit, can be left out of consideration here.

The valve V_1, which belongs electrically to the scanning panel, is located physically in the photo-cell amplifier, in order to save wiring capacitance on the grid side.

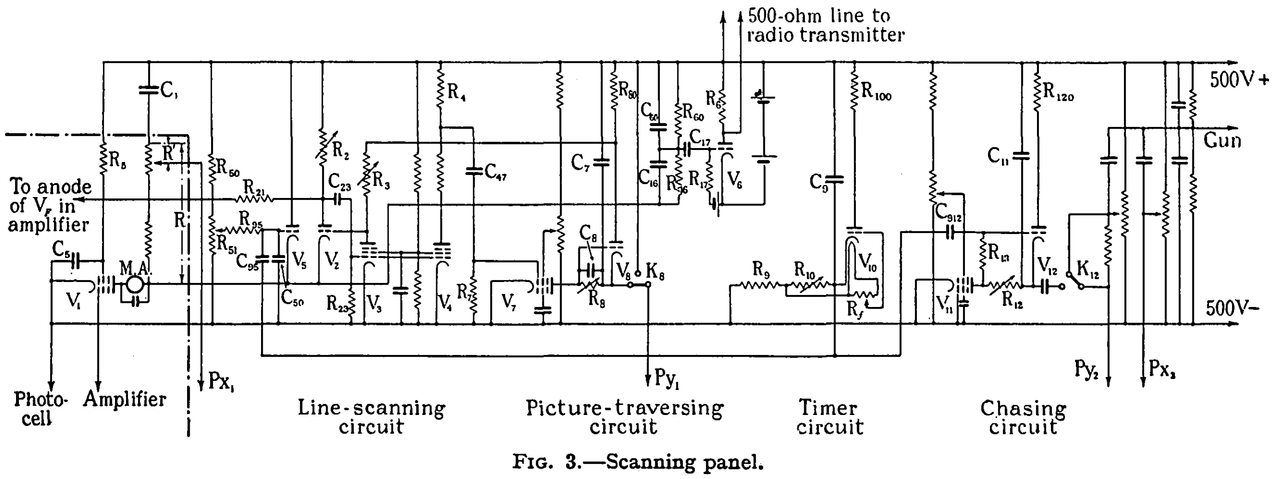

FIG. 3.—Scanning panel.

Whilst V_1 has to show fundamentally the saturated characteristic of a screen-grid valve, it is in practice found necessary to make it a screened pentode; the essential reason for this will appear later. The particular pentodes used were found incidentally to show a better saturated characteristic than the tetrodes, and pentodes were therefore adopted for all the "constant-current charging valves," namely V_1, V_7, and V_{11}.

The substitution of the hard valves V_2 and V_3 for the thyratron V_2 of Fig. 1 was an extremely important step.* The necessity for it arises from the fact that when the scanning lines are allowed to take their own time, this time can vary over a relatively wide range. With such varying frequencies, it was not possible to make a thyratron which would fire at a constant voltage amplitude; indeed at the higher frequencies corresponding to a succession of dark scanning lines the behaviour of the thyratrons was found to be completely erratic.

In the case of the hard-valve circuit the operation is as follows. During the charging of the condenser C_1, the valve V_2 takes no anode current owing to its being biased beyond cut-off by the drop in the resistance R_3 in the plate circuit of V_3. As the charging continues, the voltage across V_2 rises until a point is reached where anode current commences to flow; this causes a voltage drop over the resistance R_2, which is fed through condenser C_{23} on to the grid of the valve V_3. This reduces the current in R_3; hence the grid voltage of V_2 rises, the anode current increases, and the action is cumulative. At the end of the discharge the current in R_2 drops, the cumulative action is reversed, and the circuit resets itself for the next charging stroke.

This circuit has been found to be entirely free of the defect in the thyratron circuit, and has, in the opinion of the authors, proved superior to it in every way.

The anode of the valve V_3 makes a large excursion in voltage in the positive direction on the occasion of every fly-back. It is therefore tempting to use this voltage for the ratchet drive on the grid of V_7, instead of using the differentiating circuit of Fig. 1. As, however, the rise of the anode voltage of V_3 is checked by the grid current of V_2 during the discharge, it is preferable to use a separate ratchet driver valve V_4, whose grid and screen are paralleled to those of V_3, but whose anode is free of the load of the grid of V_2. This anode is taken to positive H.T. via a resistance R_4, and drives the grid of the ratchet valve V_7 via the condenser C_{47}; the resistance R_7 biases back the grid until it takes only a small excursion into grid current on each line fly-back; this bias is sufficient to hold the anode current of V_7 completely cut off during the actual scanning lines.

The neon thyratron V_8, which serves as discharger for the ratcheted picture traverse, is biased by the voltage drop over resistance R_8 in the anode circuit of V_7. This anode current being pulsatory, it is necessary to provide a condenser C_8 to hold up the bias between pulses. Herein lies the essence of the picture-synchronizing process, in that the time-constant C_8R_8 is made only long enough to hold up for one scanning line of maximum length, and any delay impressed on the scanning longer than this period causes the thyratron V_8 to discharge.

Such a delay is impressed every $\frac{1}{25}$ sec. by means of the timer circuit. This consists of the resistances R_9, R_{10}, condenser C_9, and thyratron V_{10}, which constitute a simple (non-linear) time base. The circuit is adjusted to pulse at 25 cycles per sec., being synchronized on to the 50-cycle mains by means of the potentiometer R_f across its heater.

As a shunt path to the discharge valve V_2 there is placed a similar valve V_5, which acts as a "locker." The grid of this valve is biased by the potentiometer R_{51} to a potential lower than that of the grid of V_2, so that V_5 passes no anode current within the excursion of cathode voltage corresponding to the picture lines. The timer pulse is fed on to the grid of V_5 via the condenser potentiometer $C_{95}C_{50}$, and is such as to make the grid of V_5 more positive than that of V_2. In this condition V_5 robs V_2 of anode current, and the scanning is held up. After the timer pulse, the grid voltage of V_5 falls back to its more negative value on account of the collapse of the time-constant circuit $C_{50}R_{95}$, and only when the grid voltage of V_5 falls below that of V_2 does the line discharge occur. The time-interval allowed for the scanning stop is adjusted by the setting of the potentiometer R_{51}, and is arranged to be rather longer than the longest possible line time. The time-constant circuit C_8R_8 is adjusted to collapse far enough within this period to ensure discharge of V_8.

What now are the advantages of this extraordinarily indirect method of timing the picture-traverse discharge? Primarily the advantage is at the receiver. Since the latter receives its intelligence in the form of the line-scanning voltage, it is necessary that this voltage should carry the picture-synchronizing signal. There is also the subsidiary advantage that this particular form of signal places the picture fly-back line at the boundary of the picture, where it can be masked off.

The circuit so far described is all that is necessary for the handling of a stationary picture. For dealing with moving pictures it is naturally desired to scan a uniformly running film rather than the intermittently moving film of cinematograph practice, since the latter would involve a loss of scanning time of the order of 25 per cent. To provide this facility, a fourth time-base circuit, termed the "chasing circuit," is added. The film is run uniformly through the gate at exactly 25 frames per sec., this being ensured by the use of a synchronous driving motor; the film is "phased" by means of a take-up roller so that the picture-change point coincides with the timer pulse, the latter being synchronized off the same mains as the driving motor. The chasing circuit superposes a linear saw-tooth motion on to the whole of the scanning, of such direction and magnitude as exactly to neutralize the motion of the film. The fly-back of this motion, which constitutes the frame change, is synchronized from the timer discharge by means of the condenser C_{912}. (In a previous arrangement the functions of timing and chasing were combined in a single time-base circuit.)

This particular form of chasing compares favourably with the procedure, known in intensity-modulation systems, of collapsing the scanning to a single line and allowing the film motion to provide the traverse, since by means of the new method it becomes unnecessary to transmit the blank bars between successive frames,

* See Bibliography, (8).

which in modern film practice represent some 16 per cent of the gross picture. Not only this, but if the scanning is set to cover a net picture, whilst the chasing is set to cover a gross picture, the scanning field cannot collapse to a single line, but only to a narrow rectangle; in this way screen burning or fatigue, which might occur with the excessively high bombardment intensity corresponding to a single-line scanning field, is avoided.

The keys K_8 and K_{12} are used in conjunction with the chasing in the following way. To set up the chasing, K_8 is thrown up, which suppresses the traversing motion, and K_{12} is thrown down. The chasing velocity is then adjusted, by means of the screen voltage of V_{11}, until exactly one gross picture is covered. The two keys are then reversed and the traversing pitch is adjusted by means of the screen voltage of V_7 until one net picture is covered. Finally, K_{12} is again thrown down when the film is set in motion.

When the chasing is put on to the transmitter tube the picture naturally becomes unintelligible; therefore a separate tube, termed the monitor tube, is paralleled on to the P_{X1} and P_{Y1} plates of the transmitter, but is provided with separate shift potentiometers for its P_{X2} and P_{Y2} plates. The monitor tube therefore receives the line-scanning and picture-traversing motions, but not the chasing motion; it thus provides a properly intelligible picture for both stationary and moving films.

The resistances R_{80}, R_{100}, and R_{120}, are limiting resistances in the thyratron anode circuits, but one of these, R_{80}, performs a second function. The resistance R_3 in the anode of V_3 is taken to H.T. positive via the resistance R_{80}. This ensures that the line discharge cannot take place during the picture discharge.

The resistance R_{21} between the anode of V_2 and that of V_F in the amplifier causes a negative pulse to be applied to the grid of V_1 during the line fly-back. This pulse is sufficient to suppress the anode current of V_1, and so ensure a constant fly-back time; this is very necessary in order to secure a uniform pitch in the picture traverse.

The feed resistance R_s and "decoupling" condenser C_s for the screen of V_1 constitute an important feature. Since the light portions of the picture are scanned at a lower speed than the dark, it follows that with a constant picture time a generally dark picture will be over-completed and a generally light picture under-completed; that is to say, the height of the picture will continually be varying. The screen feed arrangement to V_1 constitutes what may be called an "automatic monitor" which takes care of this point. As the working screen voltage is only a small fraction of the 500-volt H.T., the conditions amount to feeding the screen of V_1 at constant current; this causes the mean anode current V_1 to hold likewise a substantially constant value, which is the condition required for maintaining a constant picture height.

(4·14) *Photo-Cell Amplifier.*

The design of the photo-cell amplifier, which has proved one of the most difficult problems in the development, has to meet the following requirements. (1) Voltage gain of the order of 5 000 times. (2) Effectively level frequency-characteristic from 25 to 240 000 cycles per sec. (3) A minimum of phase distortion. (4) Minimum phase-delay. (5) Total valve and resistance noise to be a minimum. (6) Low level of microphonic noise. (7) Freedom from instability of all kinds. (8) Freedom from pick-up, e.g. of the scanning voltages. (9) Preferably should run off mains.

The fulfilment of requirements (2), (3), and (4), calls for compensation for the stray capacitance across the photo-cell, and compensation for the stray capacitances across the anode resistances of the amplifying valves, all of these stray capacitances themselves being kept at a minimum. Unfortunately this is not all the compensation necessary; there is further required compensation for the after-glow of the fluorescent material of the scanning oscillograph.

This after-glow effect, whose manifestation was a most serious blow to the development, made itself evident in the following way. It was found that whilst good picture definition could be obtained at low scanning speeds, the definition fell away rapidly as the scanning speed was increased, although the frequency characteristic of the amplifier itself was more than adequate. To explain this effect, the theory of a screen after-glow was proposed hypothetically, and was found to fit the facts. Recently von Ardenne* has obtained very direct evidence of the screen after-glow, and has also made measurements which agree in order but not in detail with those of the authors.

The theory of the screen after-glow and its compensation forms part of a detailed discussion of the amplifier, which will now be given.†

(4·141) *Theory of Screen After-glow.*—The fluorescent light of a material under electron bombardment is generally regarded as being due to the return to normal energy-level of atoms or atomic complexes after excitation to higher energy-levels by the electron bombardment. In these circumstances the response can hardly be absolutely instantaneous, although the after-glow time may be extremely short, e.g. a small fraction of a microsecond. In the absence of a clear picture of the detailed mechanism of fluorescence, one may make the physically probable hypothesis that the light response dF to an infinitely short bombardment by a charge dq at voltage V is given by

$$dF = k dq e^{-\frac{t}{T}}$$

where dF is the instantaneous light flux at time t after the bombardment, k is a constant depending on the gun voltage V, and T is the time-constant of the fluorescent material. What then is the response to a current I (at voltage V) suddenly applied? Reckoning t from the moment of application, clearly this response is given by

$$F = \int_0^t k \, . \, dq \, . \, e^{-\frac{t'}{T}}$$
$$= \int_0^t kIe^{-\frac{t'}{T}}dt$$
$$= kIT[1 - e^{-t/T}] = k'I[1 - e^{-t/T}]$$

Thus we see that the assumption of an after-glow of the

* See Bibliography, (9)

† This portion of the paper unfortunately constitutes a digression from the main argument, and Sections (4·141) to (4·15) may well be omitted on a first reading.

kind specified leads to the conclusion that the response to a suddenly applied bombardment is also not instantaneous.

Now apply the theory to the case of an infinitely small scanning spot traversing the screen at velocity u. It covers an element ds of its course in a time ds/u; the ray current being I, the element is stimulated to give a light response $kI(ds/u)e^{-t'/T}$, t' being now measured from the time the spot crosses the element ds. The total light being emitted from the screen is given by

$$\int_0^\infty kI\frac{ds}{u}e^{-\frac{t'}{T}}$$

In this integral, the value of t' to be associated with each element ds is the " time ago " at which that element was scanned, the zero of time being taken at the ray point. This integral may be written

$$\int_0^\infty kIe^{-\frac{t'}{T}}dt' = kTI = k'I$$

Next consider the case of an infinitely small scanning spot traversing the screen and throwing an image on to the film with transparency η, and suppose that this changes abruptly from value η_1 to value η_2. The light on the photo-cell at time t after the transition is

$$\begin{aligned}\eta_1\int_t^\infty kI\frac{ds}{u}e^{-\frac{t'}{T}} &+ \eta_2\int_0^t kI\frac{ds}{u}e^{-\frac{t'}{T}}\\ &= \eta_1 kI\int_t^\infty e^{-\frac{t'}{T}}dt' + \eta_2 kI\int_0^t e^{-\frac{t'}{T}}dt'\\ &= kIT\left[\eta_1 e^{-t/T} + \eta_2(1 - e^{-t/T})\right]\\ &= k'I\left[\eta_1 e^{-t/T} + \eta_2(1 - e^{-t/T})\right]\end{aligned}$$

This, however, is an expression of very well-known form; operating on it with $(1 + TD)$, we get

$$k'I\left[\eta_1 e^{-\frac{t}{T}} - \eta_1 e^{-\frac{t}{T}} + \eta_2 - \eta_2 e^{-\frac{t}{T}} + \eta_2 e^{-\frac{t}{T}}\right] = k'I\eta_2$$

This is just what we should get by making T tend to zero in the other expression, that is to say if the after-glow was infinitely short.

It follows that the compensation required for the after-glow is the very simple operator $(1 + TD)$.

The graphical expression of this matter may be seen in Fig. 9. The discontinuous curve (0) represents the transition in the ideal case of no after-glow, the continuous curve (1) the case of a finite after-glow of time-constant T. Operating on the latter with $(1 + TD)$ converts it to the former.

Physically one may regard the after-glow as causing the scanning spot to be not punctiform, but elongated, the brightness dying away from the head in an exponential fashion. The after-glow thus introduces a kind of " aperture " effect in spite of the punctiform section of the ray head; but it is an aperture effect which allows much more simple compensation than a finite length of constant brilliance. Moreover, it is to be noted that the speed of the spot does not come into the question, the argument holding equally for constant-speed or velocity-modulated scanning. The aperture effect proper can hardly be compensated when the scanning velocity is variable.

(4·142) *High-frequency Compensating Circuits.*—The form of operator required for after-glow compensation

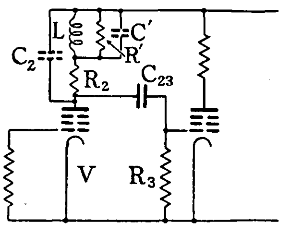

Fig. 4.

will be recognized to be identical with that required for compensating the photo-cell circuit, and also for each of the anode circuits of the coupling valves. We therefore require compensations of one mathematical form only, that is to say such as to give the operation $(1 + TD)$ or, in terms of frequency characteristic, $(1 + jpT)$. Circuits for this form of compensation are well known. The authors have used two varieties, shown in Figs. 4 and 5. In Fig. 4, so long as it is permissible to neglect the stray capacitances C' and C_2 and the damping

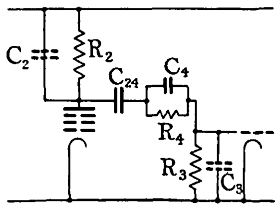

Fig. 5.

resistance R' (which is put in to prevent the circuit peaking at the resonance frequency of the circuit LC′), and to regard the valve impedance and the resistance R_3 as infinite, the gain of the valve may be written in the form

$$mR_2\left(1 + jp\frac{L}{R_2}\right)$$

an expression which shows the required type of operating factor. When, however, the stray capacitances and damping resistance are taken into account, the expression for the gain takes the more complicated form

$$mR_2\frac{1 + jp\left(\frac{L}{R_2} + \frac{L}{R'}\right) - p^2LC'}{1 + jp\left(C_2R_2 + \frac{L}{R'}\right) - p^2L\left[C' + C_2\left(1 + \frac{R_2}{R'}\right)\right] - jp^3LC'C_2R_2}$$

This circuit has not been found very suitable for compensating long time-constant effects, such as the photo-cell resistance time-constant (17 microseconds) and the after-glow time-constant (6 microseconds), because the appearance of the higher-order terms necessitates working with very low values of R_2. This means not only low gain, but also that trouble is encountered when it comes to running the amplifier off the mains, because of the finite impedance of the decoupling condensers; further, it is not suitable for providing a continuously variable compensation, since the only conveniently variable quantity is R_2, and alteration to this at the same time varies the gain. The circuit is, however, intrinsically suitable for compensating the individual capacitances in the amplifying stages.

The circuit of Fig. 5* has been found much more convenient for the compensation of the photo-cell circuit and after-glow time-constants. In this circuit R_3 is no longer a high resistance but is of the same order as R_2. The expression for the gain, from the point of view of the grid of the second valve, works out to

$$mR_2\frac{R_3}{R_s}\frac{1+jpT_4}{\left\{1+jp\left(\frac{R_2+R_3}{R_s}T_4+\frac{R_4+R_3}{R_s}T_2+\frac{R_4+R_2}{R_s}T_3\right)-p^2\left[\left(\frac{R_3}{R_s}T_2+\frac{R_2}{R_s}T_3\right)T_4+\frac{R_4}{R_s}T_2T_3\right]\right\}}$$

where $R_s = R_4 + R_2 + R_3$, $\quad T_4 = C_4R_4$,
$T_2 = C_2R_2$, $\quad T_3 = C_3R_3$,

and the capacitance of the coupling condenser C_{24} is taken as infinite.

If the time-constants T_2 and T_3 are neglected, this expression simplifies to

$$mR_2\frac{R_3}{R_s}\frac{1 + jpT_4}{1 + jp\dfrac{R_2 + R_3}{R_s}T_4}$$

Provided, then, that the fraction $(R_2 + R_3)/R_s$ is kept small, the expression shows the required compensating operator with time-constant T_4. The advantage of this circuit is that the capacitance C_4, can be made the variable quantity, so that the compensation can be varied without simultaneously varying the gain.

There is one other form of compensating arrangement, consisting of a species of feed-back circuit, which was originally used for compensating the photo-cell input capacitance directly.† This is illustrated in Fig. 6, which shows the first three stages of the amplifier as viewed in the alternating-current sense. The voltage from the plate of the second amplifying valve is fed through a very small variable condenser C′ back to the grid of the first valve. If the stray capacitances C_2 and C_3 are neglected, the theory of the circuit becomes very simple; the effective capacitance across R_1 becomes $[C_1 - (\mu_1\mu_2 - 1)C']$, where μ_1 and μ_2 are the voltage gains of the first two stages. Thus the effective capacitance can be reduced to zero or to a negative quantity.

When, however, the stray capacitances are taken into account, the expression for the behaviour of the circuit becomes very much more complicated, and takes the form

$$v_3 = \frac{\mu_1\mu_2 + T_3''D + T_2T_3D^2}{\left\{1 + (T_1' + T_2 + T_3 - \mu_1\mu_2T_1'')D + (T_2T_3' + T_3'T_1' + T_1'T_2 - T_1''T_3)D^2 + (T_1'T_2T_3' - T_1''T_2T_3')D^3\right\}}R_1 i$$

where

$T_1' = (C_1 + C')R_1$, $\quad T_1'' = C'R_1$,
$T_2 = C_2R_2$, $\quad T_3 = C_3R_3$,
$T_3' = (C_3 + C')R_3$, $\quad T_3'' = C'R_3$,

and i is the photo-cell current.

If all the time-constants except those containing R_1 are neglected, the expression becomes

$$v_3 = \frac{\mu_1\mu_2}{1 + (T_1' - \mu_1\mu_2T_1'')D}R_1 i$$
$$= \frac{\mu_1\mu_2}{1 + [(C_1 + C')R_1 - \mu_1\mu_2C_1'R_1]D}R_1 i$$
$$= \frac{\mu_1\mu_2}{1 + [C_1 - (\mu_1\mu_2 - 1)C']R_1D}R_1 i$$

which agrees with the simple theory given above.

From the more complicated expression it follows that as the effective capacitance across R_1 is reduced by an increase of C', the circuit goes into oscillation at the zero point; the frequency of this oscillation is of the order

$$\frac{1}{2\pi\sqrt{[T_1(T_2 + T_3)]}}$$

Even before the zero capacitance is reached, a selective amplification of frequencies in this region sets in. Hence the circuit cannot be employed to reduce the photo-cell circuit capacitance indefinitely, but it might conceivably be used in conjunction with one of the other compensating circuits in a later stage. It must be pointed out,

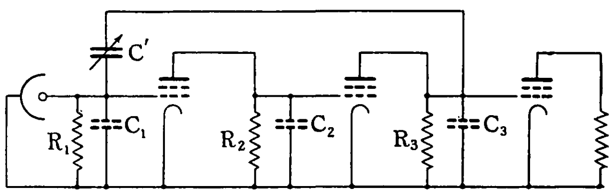

FIG. 6.

however, that the circuit suffers from a further drawback, namely that any noise generated in the plate circuit of the first valve becomes exaggerated by reason of its being fed back on to the grid.

(4·143) *Signal/Noise Ratio.*—The consideration of signal/noise ratio is of fundamental importance in the design of the amplifier; in particular, it dominates the choice of the photo-cell anode resistance, which in its turn determines the value of the time-constant of the photo-cell compensating stage.

For the thermal e.m.f. in the photo-cell anode-resistance we take Johnson's formula‡ in the form

$$E = J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}f_b^{\frac{1}{2}}$$

* See Bibliography, (10). † *Ibid.*, (10) and (11). ‡ *Ibid.*, (7).

where E is the r.m.s. noise voltage in microvolts, θ the absolute temperature, R_1 the anode resistance (ohms), f_b the frequency band (cycles per sec.), and J the Johnson constant (equal to $7 \cdot 4 \times 10^{-6}$ with the above units).

For the e.m.f. corresponding to the small frequency-band f to $f + df$ we have then,

$$dE = J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df$$

The corresponding potential difference appearing across R_1 is less than this owing to the loading effect of the shunt (stray) capacitance C_1, and is given by

$$dV = J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{\sqrt{(1 + 4\pi^2f^2C_1^2R_1^2)}}$$

The corresponding voltage on the plate of the first amplifying valve is

$$J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{\sqrt{(1 + 4\pi^2f^2C_1^2R_1^2)}} \cdot mZ_2$$

where m is the mutual conductance of the valve, and Z_2 the (modulus of the) plate-facing impedance. On the plate of the first valve after the compensating circuit, this voltage appears as $J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}dfmZ_2\mu'$, where μ' is the effective amplification at low frequency between the plate of the first valve and that of the first valve after the compensation.

For the shot noise on the first anode we may assume* an expression

$$V' = KZ_2f_b^{\frac{1}{2}}$$

where K is the appropriate shot constant.

Thus

$$dV' = KZ_2\tfrac{1}{2}f^{-\frac{1}{2}}df$$

This appears on the plate of the first valve after the compensation as

$$KZ_2\tfrac{1}{2}f^{-\frac{1}{2}}df\mu'\sqrt{(1 + 4\pi^2f^2C_1^2R_1^2)}$$

The signal voltage at this plate is $R_1imZ_2\mu'$

Hence we find that

$$\frac{\text{Component of Johnson voltage}}{\text{Signal voltage}} = J\theta^{\frac{1}{2}}R_1^{-\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{i}$$

and $$\frac{\text{Component of shot voltage}}{\text{Signal voltage}}$$

$$= KR_1^{-1}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{mi}\sqrt{(1 + 4\pi^2f^2C_1^2R_1^2)}$$

$$= K\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{mi}\sqrt{\left(\frac{1}{R_1^2} + 4\pi^2f^2C_1^2\right)}$$

The conclusion from this result is that R_1 should be as high as possible, from consideration of both Johnson noise and shot noise. In the case of the former, the improvement is progressive as R_1 is increased, the noise-component/signal ratio being proportional to $R_1^{-\frac{1}{2}}$. In the case of the shot noise, the improvement is progressive at the low-frequency end of the scale, but not at the more important high-frequency end, where the noise-component/signal ratio saturates to the value $K\pi f^{\frac{1}{2}}dfC_1(1/mi)$. This last expression reveals the very important fact that relative shot noise can only be reduced by reduction of the stray capacitance C_1.

In formulating the amplifier design it was considered undesirable to make special low grid-capacitance valves, and the lowest value of total stray capacitance that could be obtained was 17 $\mu\mu$F. Further, it did not appear to be convenient to compensate for a time-constant of more than about 20 microseconds. Hence the value of R_1 was settled at 1 megohm. In the future it is hoped to halve this capacitance and at least to double the value of R_1, which should result in a very considerable improvement in the signal/noise ratio.

(4·144) *Photo-cell Amplifier Circuit.*—Actually three amplifiers were built in the course of the development. The first, a 4-stage d.c. coupled amplifier, had to be abandoned on account of the intrinsic troubles associated with this type of coupling. The next was a 4-stage a.c. amplifier, battery-driven. With this amplifier the presence of screen after-glow was revealed, which necessitated the addition of two more stages. This amplifier, though by no means physically suited to the purpose, was used for trying out experimentally the various forms of compensating circuits, and was, moreover, gradually converted to mains operation. It provided the information necessary for the design of the final amplifier, whose circuit is shown in Fig. 7.

This amplifier consists of six stages, each of the amplifying valves (V_A, V_B, . . . V_F) being provided with a partner valve (V_A', V_B', . . . V_F') operating in paraphase. The object of these apparently idle valves is threefold: (*a*) To secure low-frequency stability by balancing out the alternating currents in the decoupling condensers; (*b*) To avoid non-calculable low-frequency distortion due to the above currents; and (*c*) To reduce the amount of shielding required to secure high-frequency stability.

To avoid unnecessary stray capacitances such as would be introduced by the Miller effect with triodes, it was an obvious step to use screen-grid valves throughout To avoid the necessity for separate voltage supplies to the screens, a further step was to make these valves screened pentodes; this permits the screens to be fed from the same decoupling condensers as the anodes, the latter actually operating at a potential below that of the screens owing to the drop in the anode load resistances. The paraphasing arrangement may be described with reference to the first amplifying stage, which is typical (and is therefore the only one fully designated in the diagram). The load resistance R_2, of about 5 000 ohms, is low compared with the plate impedance; the voltage gain is therefore mR_2, where m is the mutual conductance of the valve. This being known, the paraphasing resistance R_p is calculated, such that $mR_p = 1$. The voltage across R_p is fed through condenser C_p on to the grid of the partner valve. In order that the balanced condition shall hold at the low end of the frequency range, the coupling time-constant C_pR_1' is made considerably longer than the time-constant C_2R_3, which itself is long compared with the picture period. Although ideally the valves V_A and V_A' should be matched to close limits, it has not proved necessary in practice to go to very much trouble in the matter of selection.

* See Bibliography, (12).

With regard to the elimination of mains hum, no serious difficulty was encountered in connection with the H.T. A normal rectifier with two stages of smoothing suffices for all except the first stage, for which a further stage of smoothing (L_SC_S) is added. Heater hum was more troublesome, and was overcome by running the first five stages on direct current obtained from a rectifier.

Only two high-frequency compensating stages appear in the amplifier, namely between V_C and V_D and between V_D and V_E. These are of the type shown in Fig. 5 and discussed in Section (4·142), and are for photo-cell-capacitance and after-glow compensation respectively. The frequency range of the amplifier could be appreciably raised by adding compensation for the other stray capacitances in the amplifier, but this step is not justifiable with the present limitations of input signal strength, since any extension of the frequency band brings up the relative noise-level.

The potentiometer R_v in the anode circuit of V_E provides a calibrated gain control.

The valve V_1 belongs, as has been explained above, more properly to the scanning panel, but is located in the amplifier box in order to minimize the stray capacitance on its grid side. V_1 is also provided with a partner valve V_1', which, however, is not a paraphase valve. It serves, in fact, a variety of experimental functions, of which the most important is to simulate on the monitor tube the effect of receiver intensification.

It will be noticed that the valves V_1 and V_1' operate without any grid bias other than that set up by grid current over the grid resistances R_g and R_g'. By this artifice a very peculiar effect is introduced, namely that the d.c. component of the light signal, which is cut out by the condenser-coupled amplifying stages, is, in a manner of speaking, "faked in." This effect depends on two conditions, first that the light on the photo-cell should go to zero at least once in every picture, a condition which is easily secured by means of a barrier, and secondly that the valve V_1 should show an extremely rapid rise of grid current at the "grid current starting point." In these circumstances the grid bias always adjusts itself so that the extreme of signal corresponding to dead black is just sufficient to run the valve into the beginning of grid current; hence the grid voltage corresponding to dead black is a closely fixed quantity (near to zero), so that, in effect, the d.c. component comes through.

The key K_1 provides for transmission from positive pictures (up) or negative pictures (down); K_2 performs a similar function from the point of view of V_1'. By means of these keys it is further possible to obtain intensity-modulated pictures on the monitor tube for purposes of comparison. The setting for this is simply K_1 to neutral, and K_2 up or down according as the subject is a positive or a negative.

The keys K_3 and K_4, which are ganged together, are used for checking the noise-level of the amplifier. When the keys are closed, the screen of V_1 takes a fixed voltage, C_1 is short-circuited, and V_1 itself functions as a valve voltmeter.

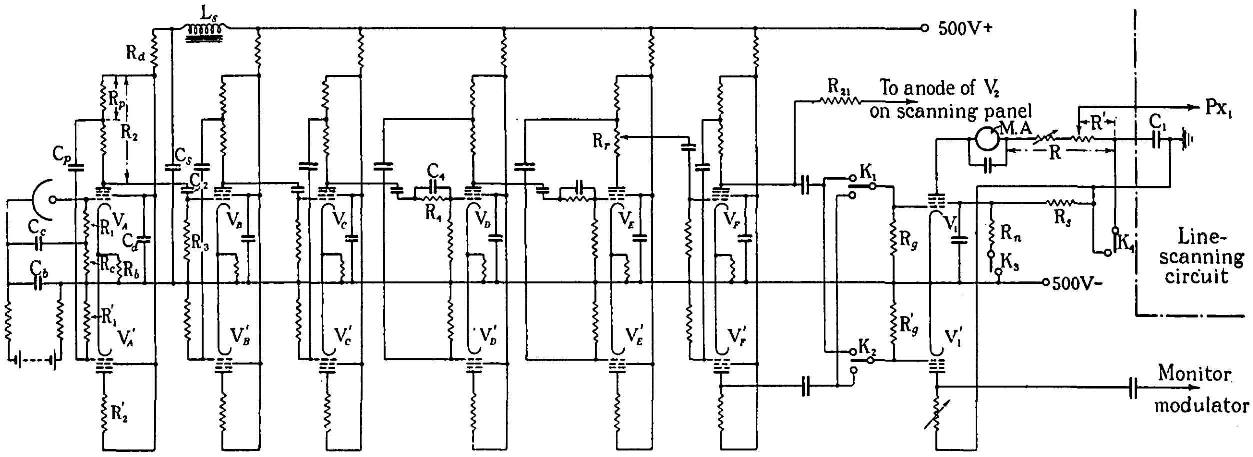

FIG. 7.—Photo-cell amplifier.

(4·145) *Frequency Characteristics of Amplifier.*—Fig. 8 shows the amplitude and phase characteristics of the amplifier. These curves are obtained by calculation only, the apparatus for direct experimental verification being still under construction; experiments other than direct measurement, however, indicate that these characteristics are substantially realized in practice.

Considering first the high-frequency end, the compensating circuits are set for a 17-microsecond time-constant for the photo-cell, and a 6-microsecond time-constant for the after-glow. The four uncompensated amplifier stages have each a time-constant of 0·159 microsecond, and the two compensating circuits contribute residual time-constants of 0·343 and 0·075 microsecond and 0·205 and 0·075 microsecond respectively, these residual time-constants being obtained by arithmetically factorizing the denominators in the expressions given in Section (4·142).

From these time-constants the characteristics are easily calculated, and are shown in curves A of Fig. 8. Curves A are the effective overall characteristics, taking into account the presence and compensation of the after-glow. The characteristics as viewed from the point of view of the amplifier *per se*, that is to say from the point of view of the photo-cell current, differ from the above on account of the after-glow compensation; these characteristics, i.e. those of the amplifier proper, are shown in curves B.

Curve B of the amplitude characteristic shows how very seriously the after-glow effect increases the noise/signal ratio. Not only is the noise amplitude raised nearly eightfold at the maximum, but high-frequency components of noise which are outside the signal range come through at very high amplitudes. It has not so far been found possible to include a filter to cut out this high-frequency noise, on account of phase and time-delay considerations.

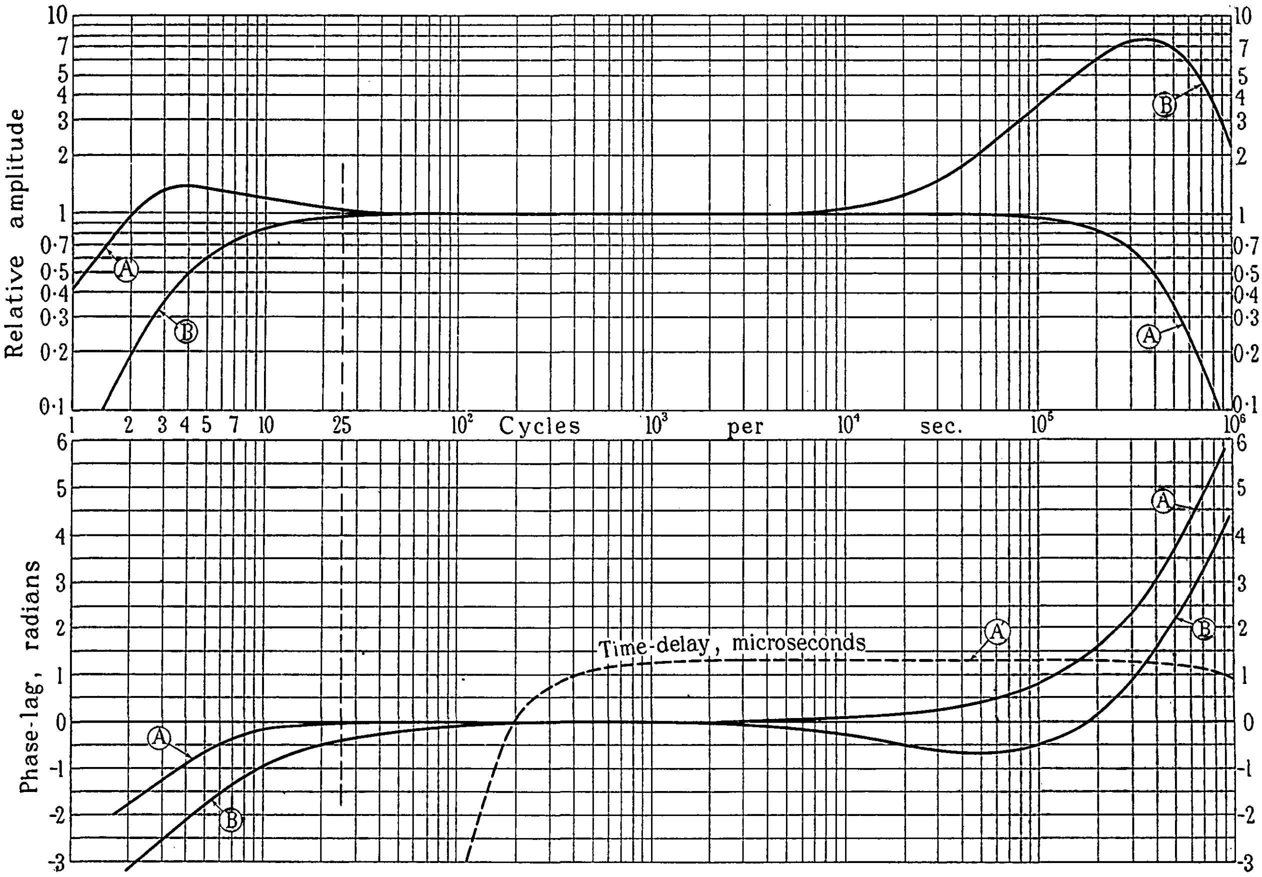

FIG. 8.

At the low-frequency end, all of the shunt capacitances are neglected, together with the effect of the high-frequency compensating circuits; the impedance of the decoupling condensers is taken to be zero, in view of the balancing effect of the paraphase valves. The only effect to be considered is then the transmission over the transfer circuits C_2, R_3, etc. As R_3 (3 megohms) is very high compared with R_2 (5 000 ohms), the fraction of the voltage passed on is

$$\frac{1}{1+\dfrac{1}{jpC_2R_3}} \quad \text{or} \quad \frac{1}{1+\dfrac{1}{jpT'}}$$

where T' is written for C_2R_3.

The six coupling circuits were originally given time-constants of $0 \cdot 3$ sec. each; this, however, gave too slow a low-frequency cut-off, which led to decoupling troubles. For this reason, the last two time-constants were reduced to $0 \cdot 03$ sec. and $0 \cdot 06$ sec. respectively. Curves B show the characteristics corresponding to this condition, namely four coupling circuits at $0 \cdot 3$, one at $0 \cdot 06$, and one at $0 \cdot 03$ sec.

The " d.c. faking effect " referred to in Section ($4 \cdot 144$) plays a certain role at the low-frequency end which actually allows the amplifier to operate successfully with a relatively poor low-frequency characteristic. It was decided, however, to make the low-frequency characteristic as good as possible, independently of the " fake," and accordingly a compensating circuit was added to correct the above curves. This consists of a low-frequency compensating circuit at the photo-cell input, namely the compensating condenser C_c and isolating feed resistance R_c (see Fig. 7). The operating factor of this compensation is easily found to be

$$\frac{1+\dfrac{1}{jpC_cR_1}+\dfrac{1}{jpC_cR_c}}{1+\dfrac{1}{jpC_cR_c}}$$

or

$$\frac{1+\dfrac{1}{jpT_c}+\dfrac{R_1}{R_c}\cdot\dfrac{1}{jpT_c}}{1+\dfrac{R_1}{R_c}\cdot\dfrac{1}{jpT_c}}, \quad \text{where } T_c = C_cR_1.$$

Thus, provided R_c is high compared with R_1, the circuit gives compensation for a single time-constant T_c.

In the present case, this is made equal to the equivalent coupling time-constant of the whole amplifier, 0·0158 sec. Curves A show the low-frequency characteristics after this compensation has been included.

Owing to the logarithmic frequency-scale, the linearity of phase displacement with frequency is not apparent. To show this, the curve A′ has been added, which gives the time-delay, i.e. the ratio of phase lag to angular frequency. This is seen to stay remarkably constant over the high-frequency end of the working range. At the low-frequency end the value of the time-delay changes rather abruptly to a time-advance, as is to be expected. The constant value of the time-delay in the high-frequency region is actually 1·33 microseconds.

(4·146) *Effect of Finite Time-delay.*—The above time-delay of 1·33 microseconds is too long, and needs to be improved by compensation of the individual anode circuits as soon as the signal/noise ratio is sufficiently improved. This time-delay implies that a certain

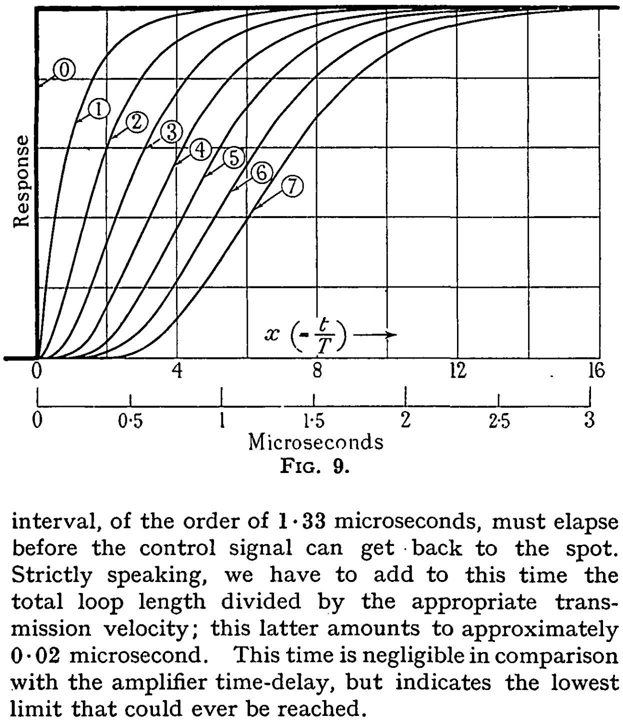

FIG. 9.

interval, of the order of 1·33 microseconds, must elapse before the control signal can get back to the spot. Strictly speaking, we have to add to this time the total loop length divided by the appropriate transmission velocity; this latter amounts to approximately 0·02 microsecond. This time is negligible in comparison with the amplifier time-delay, but indicates the lowest limit that could ever be reached.

On the basis of 25-cycle pictures and 19 200 picture points, the average picture-point time is 2·08 microseconds. Supposing that the scanning speed in the dark places is 4 times the average speed, the shortest picture-point time is 0·52 microsecond. Hence the total time-delay ought to be reduced to a quantity smaller than this. If intensification is not used, the maximum scanning speed must amount to much more than 4 times the average, in which case the effect of the time-delay becomes aggravated.

(4·147) *Transient Aspect of Amplifier.*—Although the amplitude and phase characteristics contain implicitly the whole information as to the behaviour of the amplifier, it is not entirely an easy matter to deduce from them the response of the amplifier to a transient. The authors have found it useful to keep the latter point of view closely in mind, and to facilitate this an attempt was made to calculate directly the response to a transient of the Heaviside type, namely an input voltage which is 0 for $t < 0$ and equal to a constant v_0 for $t \geqslant 0$. This calculation falls into two sections; first the response during the first few microseconds of the transient, during which time the long time-constant coupling circuits play no part, the response being determined by the short time-constants of the anode circuits and compensating circuits; secondly the response during the following few hundredths of a second, the short time-constant effects having settled down to a stationary condition, the response being now determined only by the long time-

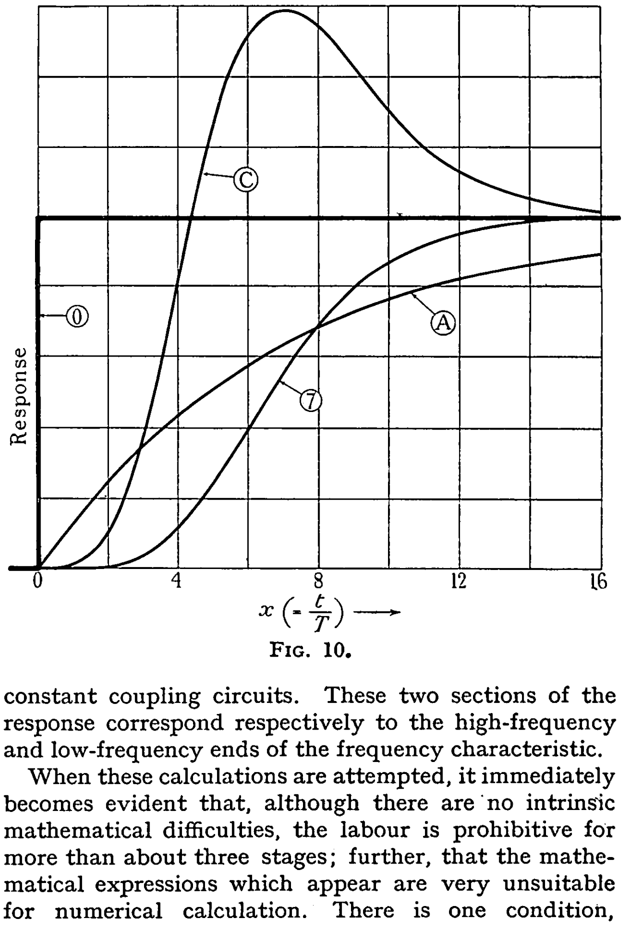

FIG. 10.

constant coupling circuits. These two sections of the response correspond respectively to the high-frequency and low-frequency ends of the frequency characteristic.

When these calculations are attempted, it immediately becomes evident that, although there are no intrinsic mathematical difficulties, the labour is prohibitive for more than about three stages; further, that the mathematical expressions which appear are very unsuitable for numerical calculation. There is one condition, however, in which both the mathematics and the arithmetic become very much simplified, and that is when all the circuits have the same time-constant. Because of the intrinsic interest of these two cases, namely equal shunt time-constants T and equal coupling time-constants T', the following results are given.

(*a*) High-frequency end:

If there are n equivalent circuits each of time-constant T, the solution is

$$v_n = v_0 \left[1 - e^{-x} E_n(x) \right]$$

where x is written for t/T, and $E_n(x)$ means the first n terms of the expansion of e^x, namely

$$1 + x + \frac{x^2}{2!} + \ldots + \frac{x^{n-1}}{(n-1)!}$$

This peculiarly simple result is worked out as far as the case of 7 equivalent circuits, and is exhibited in Figs. 9 and 10. Fig. 9 shows a family of 8 curves (numbered 0 to 7); the discontinuous curve 0 is the transient itself, and curves 1, 2, . . . 7, show how it appears after 1, 2, . . . 7, stages of " distortion " with time-constant T. If the photo-cell amplifier is regarded as equivalent to 7 stages each of 0·19 microsecond time-constant, the appropriate time scale for this particular case may be drawn in the diagram. Fig. 10 shows the transient and a specimen curve (7) together with a comparative curve (A) giving the response of a single stage with 7 times the time-constant. Curve C in the diagram shows the effect of endeavouring to compensate curve 7 with the compensation appropriate to curve A. The hump which appears in curve C shows up in a television picture as exaggeration of the contrast at the transitions, or " harsh boundaries."

(b) Low-frequency end:

The result is given for purposes of record, the application to the present photo-cell amplifier being hindered by the inequality of the coupling time-constants. For n coupling circuits, each of time-constant T', the solution is expressed in the inductive form

$$v_n = v_0 e^{-x} f_n(x),$$

where x is written for t/T', and

$$f_n(x) = f_{n-1}(x) - \int f_{n-1}(x)dx$$
$$\vdots$$
and $$f_1(x) = 1$$

This inductive formula leads to the following:—

$$v_1 = v_0 e^{-x}$$
$$v_2 = v_0 e^{-x}(1 - x)$$
$$v_3 = v_0 e^{-x}(1 - 2x + \tfrac{1}{2}x^2)$$
$$\vdots$$
$$v_6 = v_0 e^{-x}(1 - 5x + 5x^2 - \tfrac{5}{3}x^3 + \tfrac{5}{24}x^4 - \tfrac{1}{120}x^5)$$

Fig. 11 shows a plot of certain of these results. Curve 0 is the transient itself; curve 1 is the response after a single coupling circuit of time-constant T'; and curve 6 is the response after six such circuits. Curve A is the response of a single coupling circuit of time-constant $T'/6$, which is seen to coincide with curve 6 over a sufficiently short time-interval, but not over a long time-interval.

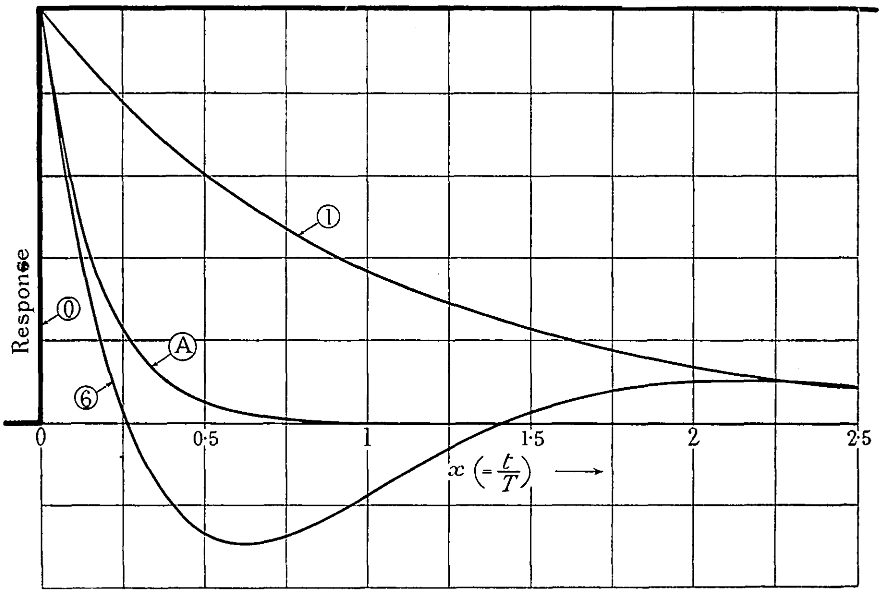

FIG. 11.

(4·15) *After-glow and Aperture Measurements.*

The measurement of after-glow times of a few microseconds is not intrinsically an easy matter, but the authors have found a simple solution to the problem in making the television transmitter serve as its own measuring apparatus. For this measurement the key K_1 of the amplifier was set to the neutral position so as to provide uniform line-scanning, K_2 was thrown to the up position, and the voltage on the anode of V_1' was examined on an oscillograph. The latter was actually the monitor tube, the normal paralleling of its X plate to that of the transmitter being left unaltered, so as to provide directly a synchronized time-base motion Instead of a picture, a barrier was inserted in the film gate so as to mask off sharply one-half of each of the scanning lines.

With an infinitely small scanning spot, the signal on the photo-cell is thus simply a repetition of curve 0 of Fig. 9. In the case of a finite circular scanning spot this " transient " is modified to the form of curve 0 of Fig. 12. At normal scanning speeds the output of the amplifier does not show exactly this wave-form, but departs from it in the same way as, for instance, curve 7 departs from curve 0 in Fig. 9. If, however, the scanning speed is progressively reduced, the output wave-form closes down to the shape of curve 0 in Fig. 12, this curve expressing simply the "aperture effect." At sufficiently low scanning speeds this statement remains true even when the after-glow compensation is removed by setting to zero the condenser C_4 in the second compensating circuit. Then if the scanning speed is raised, the output wave-form on the oscillograph is seen to change to the form of curve 1 in Fig. 12. Curve 1 can now be brought back to coincide with curve 0 by increasing the value of capacitance C_4. This condenser value is then measured, and the product C_4R_4 gives the time-constant of the after-glow. This process is only applicable provided the time-constant to be measured is reasonably long compared with the time-constant of the whole amplifier, as the method requires it to be possible to select a scanning speed at which the after-

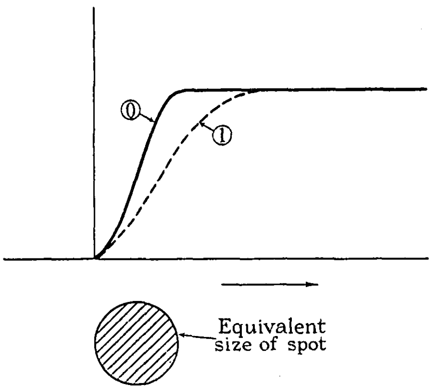

FIG. 12.

glow effect is shown up whilst the amplifier characteristic remains substantially perfect.

Whilst the above experiment is extremely instructive, it is in practice possible to perform almost the same measurement on an actual television picture. The scanning is first slowed down, only a fraction of the picture being covered; and the optical focus of the transmitter tube, and electrical focus of transmitter and monitor, are set to optimum. The satisfactory definition of the picture in this condition indicates that the aperture effect is not troublesome. Then the scanning is speeded up and the second compensating circuit is adjusted to give optimum picture definition without harsh boundaries. The time-constant C_4R_4 of the second compensating circuit is then the time-constant of the after-glow. As the scanning speed is raised still higher, the definition again begins to fall away owing to the high-frequency droop of the amplifier.

(4·2) THE TRANSMISSION LINK.

A satisfactory velocity-modulated picture having been achieved on the transmitter tube, and, indeed, an enlarged and intensified version of it having been produced on the monitor tube, the next problem is to select a point in the transmitting circuit from which to take the transmission signal. According to the ideas of Thun, and also originally to those of the authors, the signal to be transmitted was essentially the voltage on the line-scanning deflector plate (P_{X1}) of the transmitter. When R and R' (in Fig. 3) are made equal to zero, this voltage is the same as that on the anode of V_1. The condenser-resistance potentiometer $C_{16}\,C_{60}\,R_{16}\,R_{60}$ provides a faithful copy of the anode voltage of V_1 at a convenient level (about 2 volts swing). This voltage is stepped down to a low impedance by means of the valve V_6 and passed out on to a 500-ohm line. This line would ultimately lead to the input of the radio transmitter, but in the present case it leads directly to the receiver.

There exists, however, a serious disadvantage in deriving the transmission-signal voltage directly from the line-scanning voltage, a disadvantage which was first explicitly pointed out by von Ardenne. Although the radio transmitter may be modulated to a high percentage, the modulation corresponding to a single picture point is only a small fraction of this percentage; hence the picture detail is liable to serious disturbances from interfering voltages. To overcome this disadvantage, von Ardenne has proposed to treat as the transmission signal not the voltage on the anode of V_1, but the voltage on the grid of this valve. This means, however, that the implicit synchronism which is such an attractive property of the velocity-modulation principle, is sacrificed. Investigations made by the authors* have shown, however, that by reason of the fact that the voltage transmitted according to this proposal is still in the nature of a scanning voltage, the synchronization problem allows of an extremely simple solution; but that the proposal itself is accompanied by the following very serious practical difficulty. The proposal contemplates a receiving circuit very closely analogous to that at the transmitter, and comprises the equivalent of the time-base circuit $V_1\,C_1\,V_2$; to the grid of V_1 is to be fed an exact copy of the corresponding voltage at the transmitter; the successful operation of the system therefore requires not only an extremely accurate copy of the potential on the grid of V_1, but also that the anode-current/grid-voltage characteristics of the two valves should be accurately matched over the whole of their working range. Departure from these conditions results in very serious picture-distortion.

The solution adopted by the authors, and which is free of these difficulties, may best be introduced by expressing the above disadvantage in a rather different form. The voltage across the condenser C_1 is obtained from the signal on the grid of V_1 by a species of integration process, which means that the higher-frequency components of the signal are relatively attenuated. This does not imply distortion, but merely that with progressive reduction of the field strength at the receiver the higher-frequency components are the first to drop below the noise-level. To overcome this disadvantage the signal voltage is made to consist of two components directly superposed, namely a voltage proportional to the displacement, and a voltage proportional to the velocity, of the scanning spot.

The introduction of the resistance R in Fig. 3 provides on the anode of V_1 exactly such a voltage. Referring back to Fig. 2, the wave-form (*b*) is the displacement voltage; the wave-form (*c*) is proportional to its derivative,

* See Bibliography, (13).

and is in fact the voltage across the resistance R; the wave-form (*d*), which is the superposition of these two wave-forms, represents the transmitted signal. At the receiving end these two voltage components may be separated out and led to perform their proper functions of spot displacement and intensification respectively. This separation, which is only possible in view of the fact that the one component is proportional to the time derivative of the other, is effected by a circuit which is shown schematically in Fig. 13. In this circuit V is a high-impedance valve whose anode faces a resistance R_0, which latter is shunted to earth via condenser C and a small resistance R″. If R″ is made vanishingly small, and if the time-constant CR_0 in Fig. 13 is made equal to the time-constant C_1R in Fig. 3, then it comes about that when a voltage wave corresponding to Fig. 2(*d*) is applied to the grid of the valve V, a voltage corresponding to that of Fig. 2(*b*) appears on the anode whilst a voltage proportional to that of Fig. 2(*c*) appears across R″. By choice of the time-constant C_1R at the transmitter, the relative amplitudes of the displacement and the velocity components can be set to any desired value.

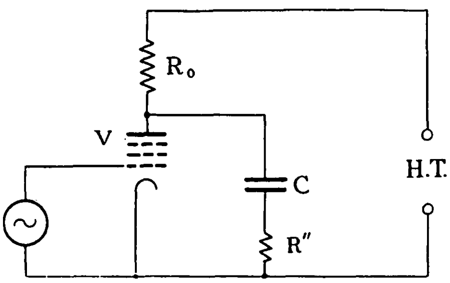

FIG. 13.

The feature of this form of signal voltage is that it contains a component which is not attenuated with frequency.

To establish that the circuit of Fig. 13 actually does separate out correctly the two superposed components, we have only to note that the impedance facing the plate of the valve V is

$$R_0\frac{1 + jpCR''}{1 + jpC(R_0 + R'')}$$

which becomes, when $R'' \to 0$,

$$R_0\frac{1}{1 + jpCR_0}$$

This is the correct form of operator for reproducing the scanning voltage from the compound signal. The more accurate expression, taking into account the finite value of R'', shows that the operator should more strictly be taken as

$$\frac{1}{1 + jpC(R_0 + R'')}$$

whilst in addition the operator $(1 + jpCR'')$ appears in the numerator. This can be made to compensate the high-frequency loss of the previous stage, although in practice both the latter and its compensating factor are of rather small account. If v is written for the voltage across R_0, the voltage across R″ is easily found to be

$$R''\frac{1}{1 + jpCR''}\cdot\frac{dv}{dt}$$

Thus the finite value of R'' introduces a small high-frequency droop into the intensification voltage, which may, if desired, be compensated in a later stage.

The peculiar advantages of this compound form of transmission signal accrue at the receiver. At the transmitting end the advantage is with the simpler arrangement on the lines of that devised by Thun, as will be seen from considering the modulation conditions on the radio transmitter. In the case of a signal such as that of Fig. 2(*b*) we have the unique advantage of absolutely constant percentage modulation for the radio transmitter, because the extremes of signal correspond simply to the lateral boundaries of the picture, which do not vary. With a signal such as that of Fig. 2(*d*), a variable component is added to the modulation; but in practice this variation is relatively small because the upper extremity corresponds to the full picture displacement, plus a component corresponding always to " black." This is because the spot has always to overrun to a small extent the boundary of the picture proper and pass behind a barrier. Thus the only variations in this component are those due to the functioning of the automatic monitor on the screen of V_1. At the lower extremity, which corresponds to the end of the fly-back, conditions are always the same. The modulation conditions in the present case can therefore be described as nearly, but not quite, constant percentage modulation.

A further complication is introduced at the transmitter when the resistance R is introduced for the purpose of yielding the compound signal. In the simpler case of $R = 0$, the several stray capacitances from the anode of V_1 to earth come directly in parallel with the condenser C_1, and so simply constitute part of the charging condenser of the time base. When the resistance R is introduced, these stray capacitances are no longer in parallel with C_1', and part of the time-base charging current is diverted from the condenser branch proper. This effect, which by appropriate design can be kept small but not negligible, can be compensated by the inclusion of the resistance R′, such that

$$(C_1 + C')R' = C'R,$$

C' being the total stray capacitance from the anode of V_1 to earth.

(4·3) THE TELEVISION RECEIVER.

This section is concerned only with the television part of the receiver, and not with the radio portion; the television portion is, however, designed to work from a low level of signal voltage such as could easily be obtained from a detector.

The receiver comprises in principle a separating circuit such as that of Fig. 13, for separating out the displacement and velocity components of the signal, a line-scanning amplifier for the displacement voltage, giving a sufficient voltage output for providing the horizontal scanning, a ratcheted time-base for the picture-traversing, and an amplifier for the velocity-component voltage for intensification.

For the type of oscillograph contemplated, the picture size is approximately 440 × 330 volts. The 330-volt swing is the sweep of the ratcheted time-base, whilst the 440-volt swing is the output of the line-scanning amplifier. In order to avoid having to provide an inconveniently high H.T. voltage for so large a voltage swing, a paraphase drive for the P_X deflector plates suggests itself. This reduces the voltage swing per anode to 220 volts, and a 500-volt H.T. supply is adequate for both this and the 330-volt time-base sweep. The paraphase arrangement of the line-scanning amplifier is also an advantage from the point of view of avoiding low-frequency distortion, which latter has and low resistances R and R′ to earth. The time-constants $(C + C_s)R_2$ and $(C' + C_s)R_2'$ are each made equal to the time-constant C_1R at the transmitter, C_s being the stray capacitance in each case. Herein lies an incidental but extremely important advantage of the compound form of signal, for the resistances R_2 and R_2' can be made relatively high, e.g. from 30 000 to 50 000 ohms, which could not be done in the case of the simple displacement signal on account of frequency-characteristic droop; in the present case, frequency-characteristic droop is actually required and has to be encouraged by increasing the stray capacitances several-fold with the condensers C and C′. Because of this high output-resistance the gain of the output valves is high, the grid swing is small, and the valve characteristics

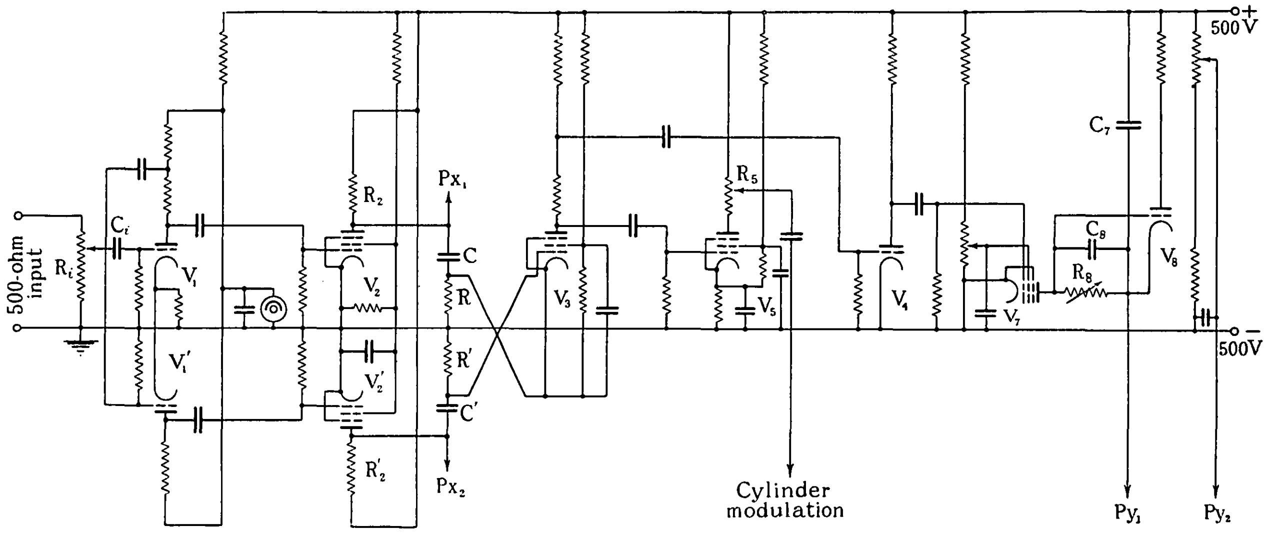

FIG. 14.—Receiver.

necessarily to be kept down to a very low level in order to avoid misshaping of the picture.

(4·31) *Circuit Arrangements.*

In the practical receiver, whose circuit is shown in Fig. 14, the separating stage is combined with the paraphase output stage of the line-scanning amplifier. The input, which is fed straight from the wire-line on to a 500-ohm potentiometer R_i, is tapped off at a suitable level and passed via a blocking condenser C_i on to the grid of valve V_1. The latter drives its paraphase partner V_1' in the same manner as that described for the photocell amplifier at the transmitter. The anodes of V_1 and V_1' are fed from a common decoupling circuit, the condenser of the latter being shunted by a neon stabilizer tube for the purpose of smoothing out mains fluctuations on this stage. The anode of V_1 supplies a small-scale copy of the compound voltage on the anode of V_1 at the transmitter, whilst V_1' supplies a similar copy in opposite phase. These two anodes drive the grids of the paraphase output valves, the latter being screened pentodes. The anodes of these pentodes are connected directly to the P_{X1} and P_{X2} deflector plates of the receiving oscillograph and face the equal resistances R_2 and R_2'; the latter are shunted by equal condensers C and C′ do not depart seriously from linearity; such distortion as does occur is cancelled out by the paraphase arrangement.

Across the resistances R and R′ appears a voltage proportional to the instantaneous scanning velocity. This is passed through two amplifying stages V_3 and V_5, and provides the intensification voltage which is taken on to the Wehnelt cylinder of the oscillograph. The valve V_3 also drives a further valve V_4, which acts as ratchet driver for the picture-traversing circuit. The latter consists of components strictly analogous to the picture-traversing circuit at the transmitter, namely the ratcheted charging valve V_7, the time-base condenser C_7, and the discharge thyratron V_8; the latter is biased by the time-constant circuit C_8R_8, which is again wholly analogous to that at the transmitter, the time-constant being adjusted so as to allow V_8 to fire within the delay interval in the scanning sent out by the transmitter.

The controls at the receiver are extremely simple. The input potentiometer R_i is adjusted to give the required picture breadth, and the screen voltage of the valve V_7 is then set to give the required picture depth, which it does by varying the pitch of the raster. There is no synchronizing adjustment because the values of R_8 and C_8 will be fixed. The remaining controls are " intensification volume control," namely the potentiometer R_5, and oscillograph focusing, namely the cylinder-biasing potentiometer.

The above adjustments can of course only be made while the signal is actually being transmitted. It might be supposed that if the transmission were cut off, the spot on the receiving oscillograph would come to rest and so possibly damage the screen. This in practice is not the case, because as soon as the transmission is cut off, the ratchet driver V_4 ceases to pulse, and the grid of V_7 rapidly slides to zero voltage and causes a traversing movement to start up on its own account, thus preventing the screen from being damaged.

A further feature of importance is that the valves V_2 and V_2' are given no applied grid bias, but are allowed to find their own bias by means of grid current. This arrangement provides a d.c. faking effect similar to that described for V_1 at the transmitter. Such a d.c. fake is necessary, because in its absence the line-scanning waveform would tend to set itself with its " centre of gravity " in a fixed location, the moving of this centre of gravity being tantamount to the transmission of direct current; such a movement is necessary if the lateral boundaries of a moving picture are to stay in a fixed position. By operating without an applied grid bias, matters adjust themselves so that the two extremes of signal correspond to the respective starting-points of grid current on the two valves. That is to say, definite anode voltages on the valves V_2 and V_2 are associated with the boundaries; and since there is d.c. transmission between these anodes and the deflector plates, the picture boundaries remain stationary.

(4·32) *Shape of Intensification Curve.*

In order to decide on the proper shape of intensification curve, it is necessary to revert to the transmitter and consider the shape of the V_1 charging-current characteristic. It will be recalled that matters are so arranged at the transmitter that, in the case of transmission from a positive, the condition of no light on the photo-cell corresponds very closely to zero grid voltage on V_1, whilst increasing light on the photo-cell causes the grid voltage to become negative. In these circumstances, and assuming that the amplification is linear up to the grid of V_1, that is to say assuming no *amplitude* distortion, it follows that the ideal theoretical shape for the V_1 anode-current/grid-voltage characteristic is the rectangular hyperbola $i = k/(-v_g)$, curve A of Fig. 15.

Such a curve, giving an infinite current at zero grid voltage, cannot of course be obtained in practice; and even if an approximation to it, namely a curve with a very steep rise of anode current in the region of zero grid voltage, could be obtained, the correspondingly high scanning velocities would be objectionable, on the grounds stated in Section (4·146). In the low-current region of the curves, however, the hyperbolic shape can be approximately realized by the now common " variable μ " type of characteristic. Such a characteristic is shown in curve B of Fig. 15. In order to obtain faithful tone reproduction, the difference between curves A and B has to be made good by intensification.

In Fig. 15, the ordinate in the positive direction is primarily a scale of V_1 charging current (i), and the abscissa in the negative direction is a scale of V_1 grid voltage. The ordinate, however, can equally well be regarded as a scale of instantaneous scanning velocity (u). If we now make the abscissa in the positive direction a scale of relative spot-intensity (at the receiver), the top right-hand quadrant is suitable for drawing-in the intensification curve. This is done in curve C of the diagram. Over the range of velocity in which curves A and B coincide, the intensification is not required to function; the spot remains at full intensity as indicated by the value 1 in curve C. For velocities which are less than that corresponding to the hyperbolic curve, the

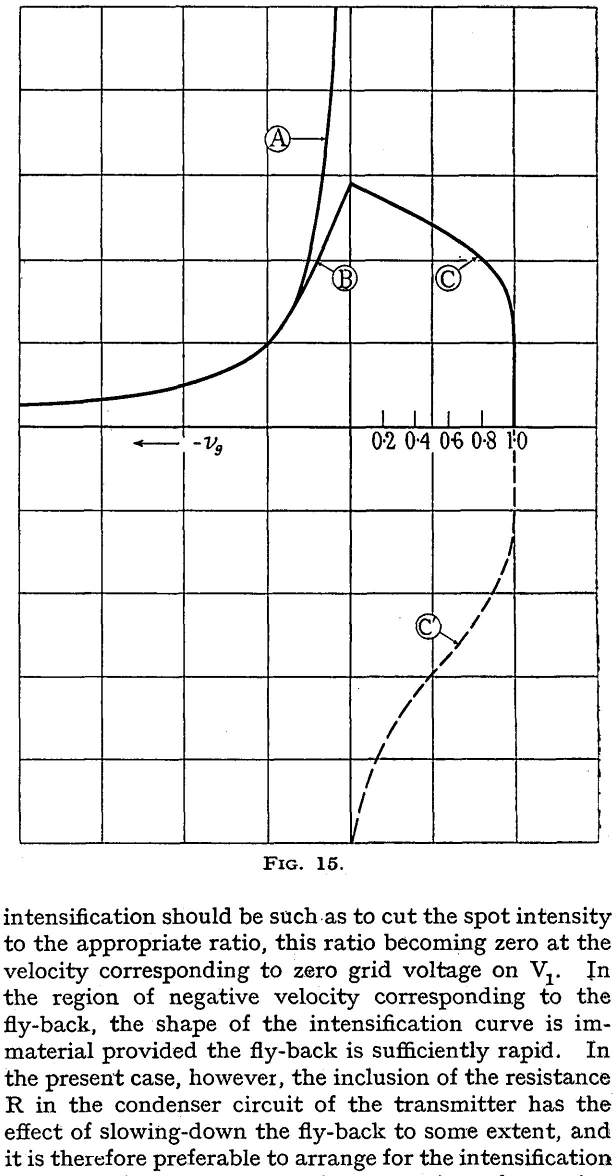

FIG. 15.

intensification should be such as to cut the spot intensity to the appropriate ratio, this ratio becoming zero at the velocity corresponding to zero grid voltage on V_1. In the region of negative velocity corresponding to the fly-back, the shape of the intensification curve is immaterial provided the fly-back is sufficiently rapid. In the present case, however, the inclusion of the resistance R in the condenser circuit of the transmitter has the effect of slowing-down the fly-back to some extent, and it is therefore preferable to arrange for the intensification curve to show a cut-away in the region of negative velocity, as indicated by the dotted curve C'.

The detailed shape of this intensification curve appears, on experiment, to be of academic rather than of practical importance, as satisfactory pictures are obtained in spite of serious departures from the theoretical shape. The general form, however, should be preserved, namely that

FIG. 16.—Reproduction of photograph (December, 1933).

FIG. 17.—Reproduction of photograph (December, 1933).

[NOTE.—The above photographs should be viewed at a distance of 4–5 ft.]

the intensification should not function in the brightest portions of the picture, and that the curve should cut away for extremes of scanning velocity, both positive and negative. In the present receiver, this state of affairs is approached by working the valve V_5 (see Fig. 14) well down the bend of its characteristic, relying on the modulation curve of the oscillograph to give a partial cut-away for negative velocities.

(5) RESULTS AND PROSPECTS.

Specimens of results to date (December, 1933) are shown in the photographs, reproduced in Figs. 16 and 17 (see Plate facing page 80), of pictures of about 120 lines. The photographs are intended to convey some idea of the available detail, but they give an unfavourable representation of results. In the first place a picture viewed on the tube appears, partly on psychological grounds, much more acceptable than a photographic reproduction. Secondly the addition of motion, and to a less extent the addition of sound, make a very surprising difference to the " intelligence " carried by the picture. In order to convey a more representative indication of results, a cinema film is being prepared, photographed frame by frame off the receiving tube, which provides a short demonstration of moving subject matter.

The number of lines that can be used, at present limited to about 140, is determined by two factors: (*a*) the signal/noise ratio in the photo-cell amplifier, and (*b*) the size of the scanning spot on the film. These two effects are closely linked together, for the size of the scanning spot on the film can always be reduced by increasing the magnification ratio of screen picture-size to film picture-size; this, however, entails a loss of light, so that the limit is eventually again determined by signal/noise ratio.

When the noise of the amplifier has been reduced to its theoretical minimum, there remain two possibilities for improvement; first by improving the photo-cell sensitivity, and secondly by improving the transmitter tube itself. The latter possibility is extremely promising and will without doubt shortly be put into effect in the form of reduced after-glow, increased light value, and possibly reduced size of scanning spot. That such improvements are possible will scarcely be doubted when it is recalled that the results so far obtained have been with a transmitter tube which is simply the standard " measuring " type of oscillograph* without any modification whatever.

From the point of view of the transmitter-tube possibilities, there seems to be no doubt that the number of scanning lines could be raised to at least 150–200, at which latter value the theoretical detail approaches that of the home cinema; in the opinion of the authors the entertainment values become comparable at a considerably lower number of lines, say 100–150.

The present basis of operation at the transmitter appears to limit the picture subject-matter to film material. As previously mentioned, this restriction is not considered to be of much significance, because a television service is subjected to the same limitation on account of the following considerations. (*a*) Owing to the large frequency band the service must necessarily be on ultra-short waves, i.e. below 9 metres; this means a short transmission range, and so a moderately large number of local transmitters. The subject matter must therefore be in a form which can be easily sent about from place to place. (*b*) Topical events must constitute an important item of an entertainment television service, and only a negligibly small proportion of these can be " brought into the studio." Direct television transmission from the site, even if it were technically possible, would hardly be of much value on account of considerations of " time of day."

In spite of the above arguments there is a rooted inclination to demand the television of direct subject matter, and it is therefore desirable to consider what are the possibilities of modifying the velocity-modulation transmitter to handle such material. Although the construction of a " giant " oscillograph for direct subject illumination is not inconceivable, a more promising line of approach appears to be offered by a reversion to a process analagous to the " floodlight " system, in which a real image of the flood-lit subject is scanned. Methods of achieving this process on a cathode-ray scanning basis have been indicated by Farnsworth* and by Zworykin,† and either of these seems to be basically suitable for application to the velocity-modulation principle.

At the receiving end, the oscillograph tube is again the dominating consideration. Whilst the system has been developed in terms of the present type of " measuring " tube, and whilst acceptable results are so obtained, it is the fact that these tubes are in many respects unsuitable. Very considerable improvements may be looked for with the development, now in hand, of a " hard vacuum " oscillograph for the receiver. It is in expectation of this development that no measures have been taken to circumvent the origin distortion effect,‡ which is an objectionable feature of the present tubes. The new tube, moreover, must be indirectly heated and must show better modulation characteristics than the average tube of the present type.

As regards screen size, the authors regard a 9-in. diameter screen as a satisfactory compromise between what is desirable and what is practical, and tubes of this size have already been made. The electrode structure required for the wide-angle deviation in these tubes has presented a certain amount of difficulty, but this matter is in abeyance pending the hard-vacuum tube development.

For still larger picture size, and when cost is not a ruling factor, the possibility of optical projection from a relatively small fluorescent screen may be considered.

As regards screen materials, a wide range has been examined, and a mixture evolved which gives a satisfactorily white-light response. Other materials which are now coming to hand, however, indicate that it will be possible to effect a substantial increase in the luminous efficiency.

In conclusion, it is thought that the results obtained to date indicate that the system has reached a practical footing, and that the fact of this having been achieved in a relatively short time, and with standard but ill-suited oscillographs, is a vindication of the fundamental merits

* See Bibliography, (14).

* See Bibliography, (15). † *Ibid.*, (16). ‡ *Ibid.*, (17).

of the system. The completion of the above-mentioned tube developments may be expected to effect a substantial improvement on the results at present obtainable.

(6) ACKNOWLEDGMENTS.

The authors wish to acknowledge their indebtedness to Mr. W. R. Bullimore, managing director of Messrs. A. C. Cossor, Ltd., who sanctioned both the work and its publication, and whose keen personal interest in the development has been a standing encouragement. They also wish to acknowledge the assistance of their various colleagues in the Cossor company, but especially that of Mr. W. H. Stevens, who personally constructed the major part of the experimental apparatus.

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