# RB-134

# DIFFERENTIAL METHOD OF LAG COMPENSATION IN PHOTOCONDUCTIVE DEVICES



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The slow response time often observed in devices utilizing photoconductivity may be caused by the slow rise and decay of conductivity in the photoconductor, or by the RC time constant of the photoconductor in its associated circuit. In imaging devices, such as television camera tubes and light amplifiers, the lag is manifested by smearing of the image for moving scenes. This bulletin describes a method for reducing the effective response time of the device regardless of the source of lag. By taking the difference of the signals from two photoconductive elements having unlike transient responses, a resultant signal with a faster response than either element alone can be obtained.

Measurements have been taken on pairs of vidicons set up to view the same scene simultaneously. The lag-corrected video signal formed by the external combination of the two outputs showed improved speed of response with a moderate loss in signal. Similar results have been obtained with pairs of photoconductive cells. The method can also be applied to light amplifiers and to experimental camera tubes designed to yield a lag-corrected signal directly.

## Introduction

Devices employing photoconductive materials for transforming light energy into an electrical signal are often limited by a slow response time. Two primary sources of lag are encountered, one caused by the inherent response of the photoconductor and the other by the RC time constant of the photoconductor in the associated circuit. The photoconductive lag, caused by the delay in change of charge-carrier density with changes in light levels, varies widely from one material to another but is also affected by such factors as temperature and intensity of illumination. The capacitive lag is specified by the product of the capacitance of the photoconductor and the resistance of the measuring circuit. A high-impedance circuit, such as the scanning beam in a television camera tube, may increase the observed time lag considerably beyond that from photoconductive lag alone. Conditions imposed by the nature of the device or the properties of the photoconductor may prevent the RC product from being as small as necessary to avoid capacitive lag.

Various methods for compensating for lag in television camera tubes and other imaging devices have been under investigation. By "lag compensation" is meant any basic change in design or method of operation of the device which reduces the effective time lag to less than that expected from the characteristics of the photoconductor. Lag in imaging devices causes smearing of the image for moving scenes. Lag compensation involves some reduction in the effective sensitivity of the device but the photoconductor sensitivities are often high enough that such a compromise can be advantageous.

The differential method of lag compensation, which was first proposed many years ago by Korn[1] in attempts to improve the response of selenium cells, has apparently gone unnoticed in modern applications of photoconductivity. This bulletin describes the application of the method to imaging devices for the correction of both photoconductive and capacitive lag. Measurements of lag compensation using a pair of commercial photocells and a pair of photoconductive camera tubes have been made. The application of the method to a single camera tube or light amplifier is discussed.

## The Principle of Differential Lag Compensation

Differential lag compensation is a method of producing an improved photoconductive response by taking the difference of two signals obtained by simultaneously

[1] A. Korn and B. Glatzel, "Handbuch der Phototelegraphie und Telautographie", Otto Nemnich, Leipzig, (1911).

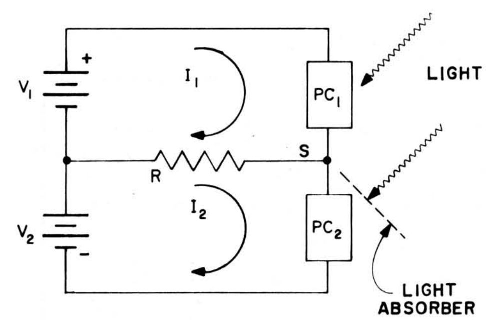



Fig. 1 - The basic circuit for differential lag compensation.

illuminating two photoconductors having unlike response times. Fig. 1 shows a simple bridge circuit in which the net current flowing through the load resistance $R$ is the difference between the currents in the two photoconductors $PC_1$ and $PC_2$. The larger signal is produced by $PC_1$ and is assumed to have a typical laggy photoconductive response to a short burst of light as shown by curve 1 in Fig. 2. Curve 2 shows the current produced by $PC_2$ to be of smaller magnitude and relatively more laggy. The total current flowing in R given by curve 3 represents the lag-compensated difference signal. Curve 4 is the same as curve 3 except that its amplitude has been plotted on a larger scale to permit direct comparison of the original uncompensated signal 1 with the final lag-corrected difference signal. Both the rise and decay times have been decreased at the expense of a moderate loss in sensitivity.

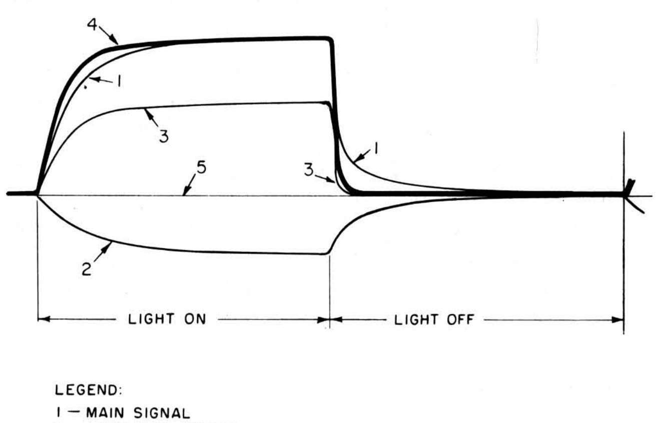



Fig. 2 - Typical improvement in response obtained by differential lag compensation.

To yield an effective improvement in response without appreciable loss in signal, the signal to be subtracted must be considerably more laggy than the original uncorrected signal. This condition is readily obtained by proper choice of photoconductors for $PC_1$ and $PC_2$ or by operating the same type of photoconductor under different voltage or light level. The improvement is most striking when photoconductor response shows an initial rapid rate of change followed by a slow change which gradually approaches a steady value. Under these conditions the slow change (which is most objectionable in television camera tube applications) can be subtracted leaving the rapid component unaffected. (See Fig. 2).

The lag-compensation method can be applied to either photoconductive or capacitive lag or to combinations of the two. The subtraction of two exponential decay curves representative of some cases of capacitive lag is discussed in Appendix I.

As the measurements in the following section show, the differential lag-compensation method does not necessarily provide optimum compensation at all light levels. If conditions are chosen to give the best possible compensation in the brightest areas of the picture, the lower light levels may show less improvement. In general, a net improvement could be readily observed in the television camera tube applications without critical adjustment of balance between the two signals.

## Measurements of Lag Compensation Using Two Photocells

The basic characteristics of differential lag compensation were studied using two commercial CdS photocells, RCA type 6694-A. The cells were connected as shown in Fig. 1, but with convenient means for adjusting the voltages. A cathode-ray oscilloscope capable of slow sweep speeds was connected across the load resistor $R$. The value of $R$ was made small compared to the static photocell resistance which is of the order of $10^9$ ohms in the dark and $10^6$ ohms in the light. The two cells were mounted side by side and illuminated by a uniform source of light interrupted by a motor-driven slotted disc. In the tests made, the lag of $PC_2$ was made relatively larger than $PC_1$ by reducing its incident light with a neutral density filter. Either cell could be used with the filter to compensate for the lag of the other, although it was desirable to select the faster cell for $PC_1$.

The typical improvement using two 6694-A cells has already been discussed in reference to Fig. 2, which was scaled from a multiple-exposed photograph of the oscilloscope. The gain-adjusted lag-corrected signal, curve 4, is shown here as a broader line and in subsequent photographs as the brightened oscilloscope trace. The rise of signal with light has been improved a moderate amount while the decay of signal when the light was removed has been improved quite markedly.

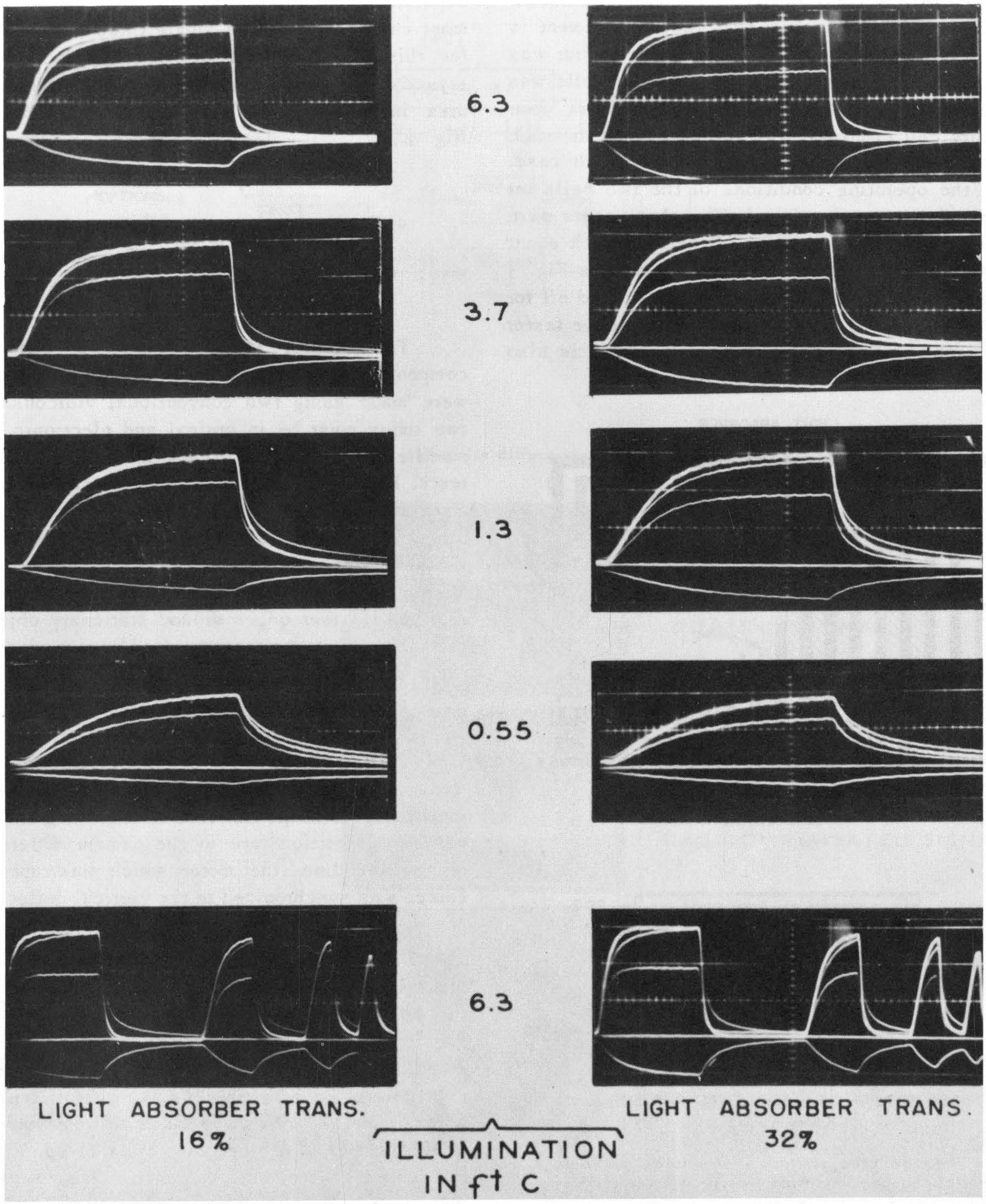
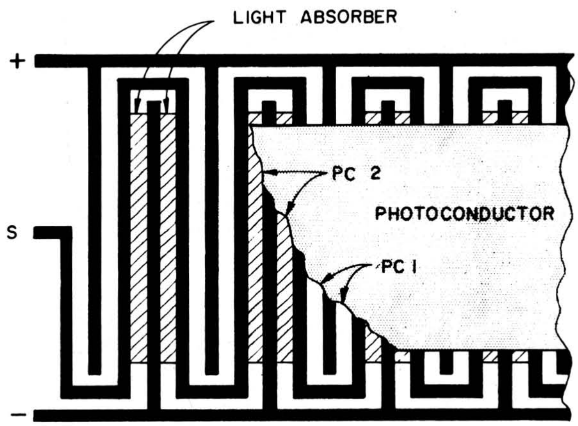


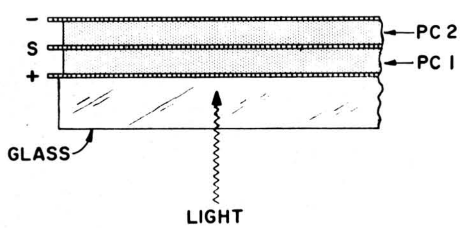

**Fig. 3 - Relative response times for differential lag compensated type 6694-A photocells under various levels of illumination and light absorber transmissions. Refer to Fig. 2 for curve identification.**

The compensated signal decays to 10 percent of peak in 10 milliseconds after the removal of light which compares with 34 milliseconds for the uncompensated cell. This advantage was obtained at the expense of using a second cell and net reduction in signal level of about 45 percent.

Fig. 3 shows a series of these photographs for various levels of illumination and two different fractions of light passed on to the auxiliary cells, 16 percent and 32 percent compared with the amount on the main cell. The cell used for the main signal was a typical type RCA 6694-A while the one used for the auxiliary signal was selected from several as having the greatest amount of lag. The photographs show that the improvement is apparent over the range of light levels tested, but was better at the higher levels. The same pair of cells was used in tests with 5 to 100 percent of light incident upon the auxiliary cell compared with the amount on the main cell, with some improvement resulting in each case. Adjusting the operating conditions of the two cells for optimum results was not critical. The above tests were made with the light-on and light-off periods each equal to 0.25 sec. The lowest pair of photographs in Fig. 3 were taken when the light was alternately on and off for 0.12, 0.06, 0.03 and 0.015 seconds. In each case faster response resulted, indicating that improvement is also independent of the time the incident light is on.




(a) THREE ELECTRODE INTERDIGITATED PHOTOCELL. (PLAN VIEW)




(b) THREE ELECTRODE LAYER-TYPE PHOTOCELL. (END VIEW)

Fig. 4 - Large area photocell structures employing differential lag compensation. (a) Plan view of three-electrode interdigitated photocell. (b) End view of three-electrode layer-type photocell.

The usefulness of the differential lag-compensation method for photocells depends upon the required application. It would be most effective in cases where the long-term rise and decay characteristics must be minimized. It would be less suitable for high-speed applications where a single conventional cell with associated circuitry to enhance the high-frequency response is adequate. If the differential method is required, the use of two separate photocells would probably be satisfactory in most cases. However, a single three-electrode photocell for this purpose could be made by incorporating two crystals in a single encapsulation or by the use of large area interdigitated or layered structures as shown in Fig. 4.

## Measurements of Lag Compensation Using Two Vidicons

To evaluate the application of differential lag compensation to image pickup devices, measurements were made using two conventional vidicons. Since the two tubes must be in optical and electronic registry, a modified three-tube color camera was used for the actual tests. Fig. 5 shows in block diagram the circuit arrangement used. The signal from each tube was amplified, the signal from the more laggy tube was inverted and the two signals combined to form a lag-compensated signal. Misregistry of the two signals would appear not only as lighter or darker edges around stationary objects in the picture but also as uncompensated laggier edges surrounding a moving object in the scene.

Two types of tests have been devised to measure and compare lag in camera tubes. The first method is similar to the one used on photocells and employs an interrupted light source and an oscilloscope to display the transient response of the video signal. Since the vertical deflection rate in the camera differs from that of the a-c line, the motor which interrupts the light source was synchronized to the vertical deflection.

The second type of test uses a motor to drive a wheel containing a white spot placed near the edge of a black background. By reflected light, the camera views the rotating spot, but because of the lag the bright spot appears as a portion of an annular ring. By photographing the picture on the television monitor with an exposure time approximately equal to one vertical period, a permanent record can be made and measurement taken of the number of degrees of arc displayed. Fig. 6 shows the data taken for both methods of measuring lag. Two commercial vidicons, type 6326, were used with two conventional preamplifiers. The two signals were combined in a two-channel matrix circuit which could add or subtract adjustable amounts of each signal.

The differential method of lag compensation has been tested with commercial one-inch vidicons containing a porous antimony tri-sulfide photoconductor as well as with experimental tubes employing the photoconductor developed by Cope[2] for use in a one-half inch vidicon.

[2] *LB-1049, A Miniature Vidicon of High Sensitivity.*

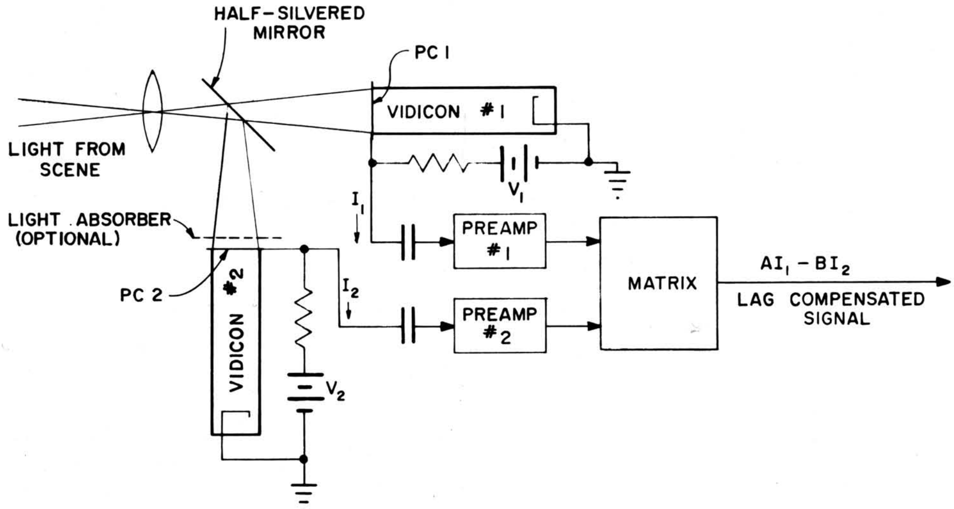



**Fig. 5 - Two-vidicon set-up for differential lag compensation.**

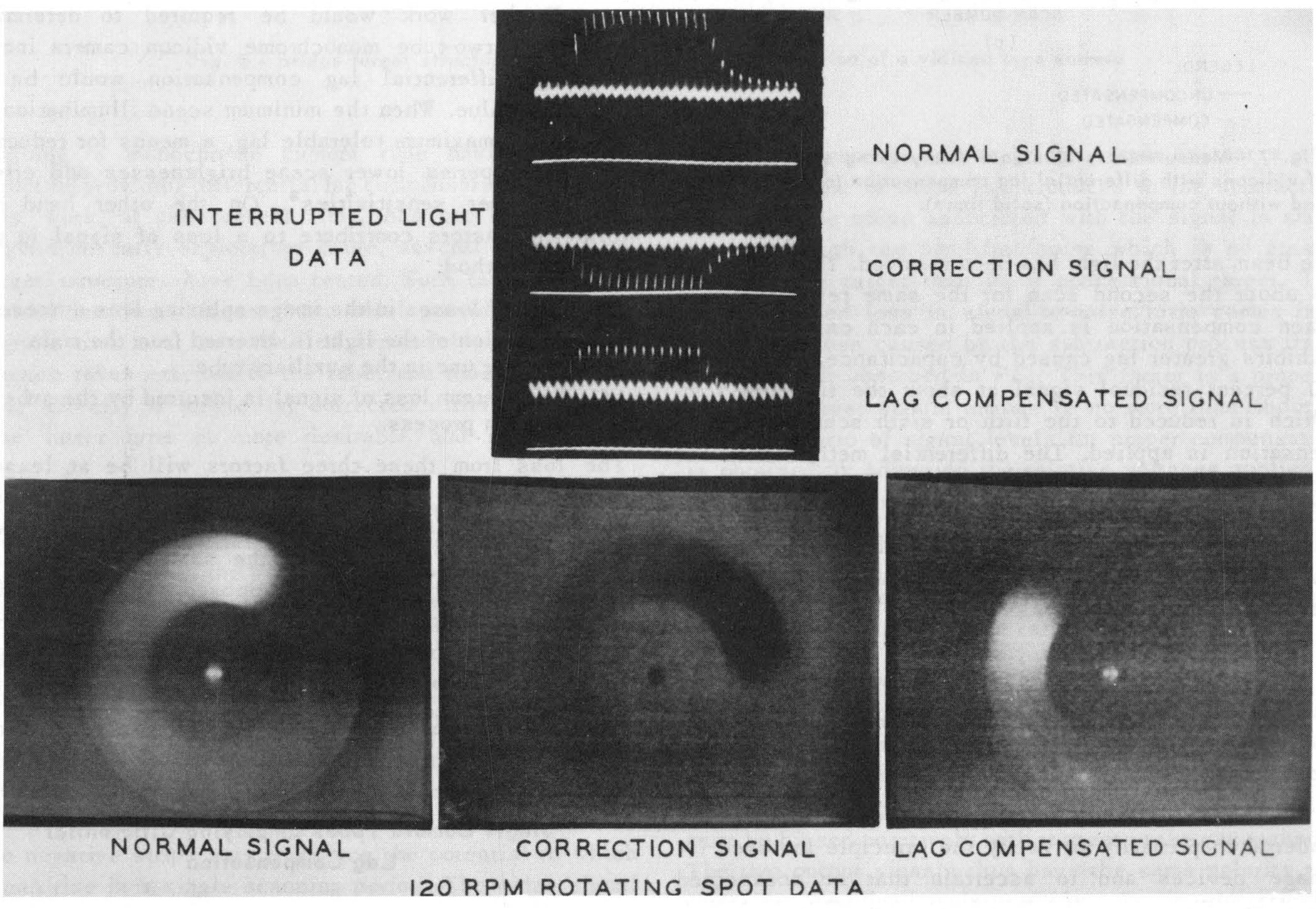



**Fig. 6 - Typical test results using two type 6326 vidicons in the arrangement of Fig. 5.**

This new photoconductor has higher sensitivity than the standard one but introduces capacitive lag when used in the one-inch target size. Fig. 7 shows the improvement obtained by the differential method of lag compensation when light is removed. Three cases with and without compensation are plotted: (a) the commercial one-inch vidicon type 6326 with the standard photoconductor, (b) the experimental photoconductor in one-half inch size, and (c) the experimental photoconductor in one-inch size. A comparison of (a) and (b) shows roughly the same amount of lag in each case when uncompensated; about 20 percent signal remains after the fourth scan by

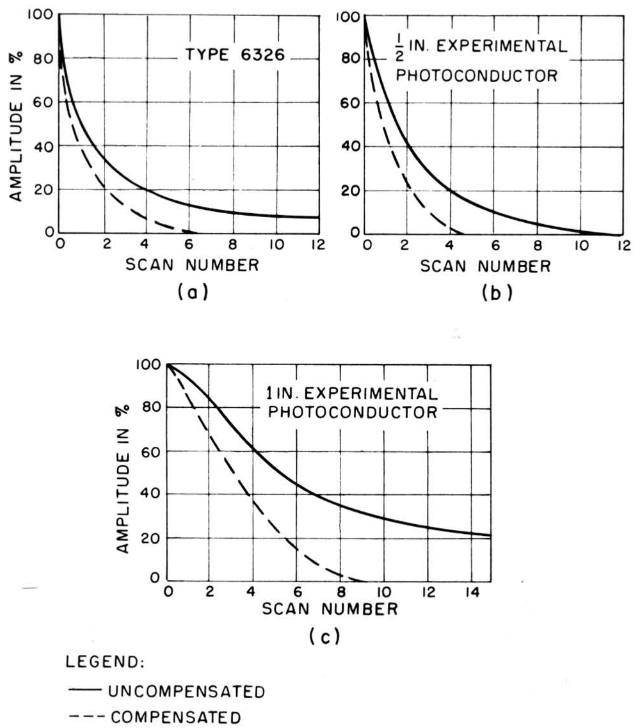



**Fig. 7 - Measurements of signal decay using several types of vidicons with differential lag compensation (dashed lines) and without compensation (solid lines).**

the beam after the light has been removed. This compares to about the second scan for the same residual signal when compensation is applied in each case. Case (c) exhibits greater lag caused by capacitance and reaches 20 percent residual signal at about the fifteenth scan which is reduced to the fifth or sixth scan when compensation is applied. The differential method does not depend on the origin of the lag, but requires that the correction signal have relatively more lag than the main signal. These measurements show that approximately the same relative improvement is obtained with camera tubes as with photocells.

## Discussion of Tests of Lag Compensation With Two Vidicons

The two-vidicon tests of lag compensation were undertaken primarily to verify the principle involved for image devices and to ascertain that no unexpected spurious effects were visible in the reproduced picture. From this standpoint the tests were successful and lent considerable encouragement that the method might be incorporated successfully into a single camera tube or light amplifier of the type discussed in the next section.

The noticable improvement in lag was achieved with little inconvenience in determining the proper proportion of signal in each channel. The increased lag in the auxiliary channel was obtained by adjusting the relative illumination on each tube, while signal gains were set for best compensation. The white trail normally left by a moving white spot could be reduced to substantially zero or made to turn black depending on the relative gains. "Burn-in" effects lasting many seconds which give an illusion of transparency to objects moving in the foreground could be greatly reduced.

It should be stressed that the differential lag-compensation method provides only an approximate correction for the low-light areas. Conversely, if the optimum correction is set for the gray areas of the scene, the bright areas would be over-corrected and give a negative after-image. A satisfactory compromise yielding a net improvement could be reached for a given scene, but the failure to "track" might require some readjustment of relative gains for widely varying scene illuminations.

Further work would be required to determine whether a two-tube monochrome vidicon camera incorporating differential lag compensation would be of practical value. When the minimum scene illumination is set by the maximum tolerable lag, a means for reducing lag would permit lower scene brightnesses and effectively higher sensitivities[3]. On the other hand the following factors contribute to a loss of signal in the two-tube method:

(1) Optical losses in the image-splitting lens system.
(2) A fraction of the light is diverted from the main tube for use in the auxiliary tube.
(3) An inherent loss of signal is incurred by the subtraction process.

The loss from these three factors will be at least a factor of two or three. At the same time the subtraction process will increase the noise by about 40 percent assuming each channel has the same gain. Although various methods have been proposed for reducing this noise and simplifying the preamplifier circuits (See Appendix II), the two-tube camera will suffer a total loss in signal-to-noise ratio of at least three or four for the same light level.

## Single Camera Tubes Employing Differential Lag Compensation

Techniques developed in the course of work on the tricolor vidicon[4] have opened up the possibility of

[3] In one qualitative test a twenty-fold increase in light level was required to reduce the lag in the uncompensated main channel to the same value as was obtained at the lower light level by compensation.

[4] *LB-1043, The Tricolor Vidicon - A Developmental Camera Tube for Color Television.*

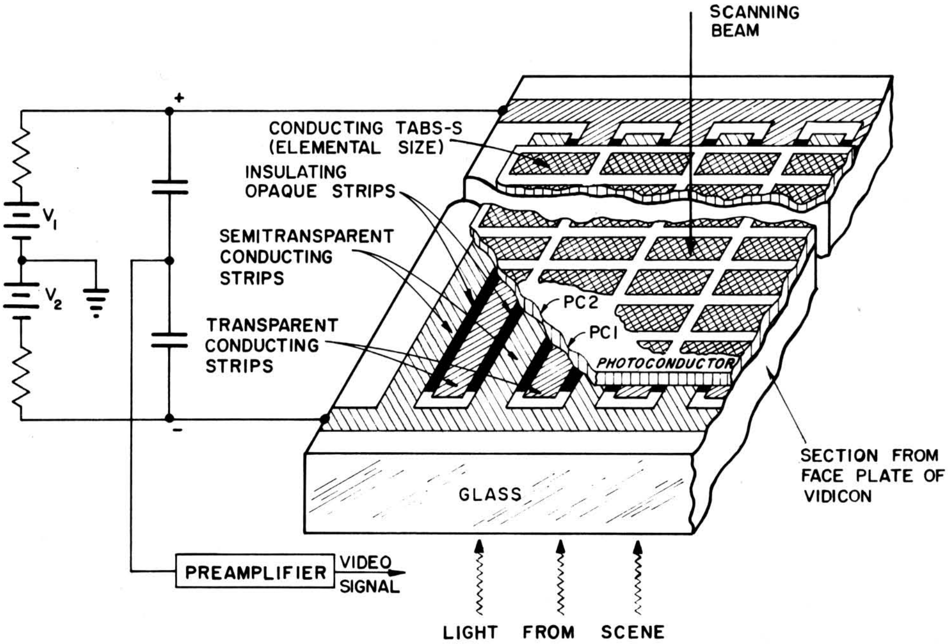



Fig. 8 - Bridge target structure for differential lag compensation of a vidicon type camera tube.

building a monochrome camera tube having a target structure providing differential lag compensation. Although this work, at the present time, has not been carried beyond an early exploratory stage, several experimental target structures have been tested. Such targets can be divided into two classes: those which provide two output signals that must be amplified separately and the difference taken external to the tube, and those which provide directly a single lag-corrected difference signal. The latter type is more desirable and is discussed first.

Fig. 8 is a form of "bridge" target whose output is proportional to the difference between the photoconductive signal generated in the part of the photoconductor labeled $PC_1$ and the part labeled $PC_2$. Each picture element of the target has the equivalent circuit shown in Fig. 1. The conducting tabs labeled $S$ (which in some versions may be replaced by a continuous semiconducting layer) assume a potential in the dark corresponding to cathode potential. When light falls on a picture element, the photoconductive current over the positive strips tends to charge the surface $S$ positively while the current over the negative strips acts to reduce the potential to which $S$ can rise in a single scanning period. The video signal generated when the beam returns $S$ to cathode potential is the lag-corrected signal representing the difference between the two currents which flowed in $PC_1$ and $PC_2$. The photoconductor $PC_2$ over the negative strips is assumed to be more laggy than $PC_1$ at all light levels, even if the identical photoconductor layer is used for both, because of the light attenuation built into the negative strips of the target.

An advantage of the bridge target is that a negligible amount of noise is introduced in the subtraction process. The noise associated with the signal is small compared with the amplifier noise which is no greater for a bridge target than for a conventional target. The only observed loss in signal-to-noise ratio comes from the signal loss caused by the subtraction process itself and the light absorbed in $PC_2$. This factor is a properly designed target should amount to no more than about 2. The best ratio of signal levels for proper compensation is obtained by adjusting the relative voltages applied to the two sets of signal strips. The addition of the negative target voltage supply represents the only modification which should be necessary in connecting a conventional vidicon camera for use with a tube having a lag-compensated bridge-type target.

Fig. 9 shows the form of a lag-compensated target mentioned earlier which provides separate output signals to be combined externally to produce the lag-compensated signal. Assuming negligible surface conductivity of the photoconductor[5], each set of strips must be biased positively with respect to the gun cathode. The two output signals thus have the same polarity and must be combined subtractively. As in the tricolor vidicon, a high capacitance exists between the different sets of strips. Therefore, amplifiers of low input impedance must be used to obtain independent signals. The

[5] If the surface of the photoconductor were appreciably more conducting than its bulk conductivity, the target structure of Fig. 9 could be operated as a bridge target as discussed for Fig. 8.

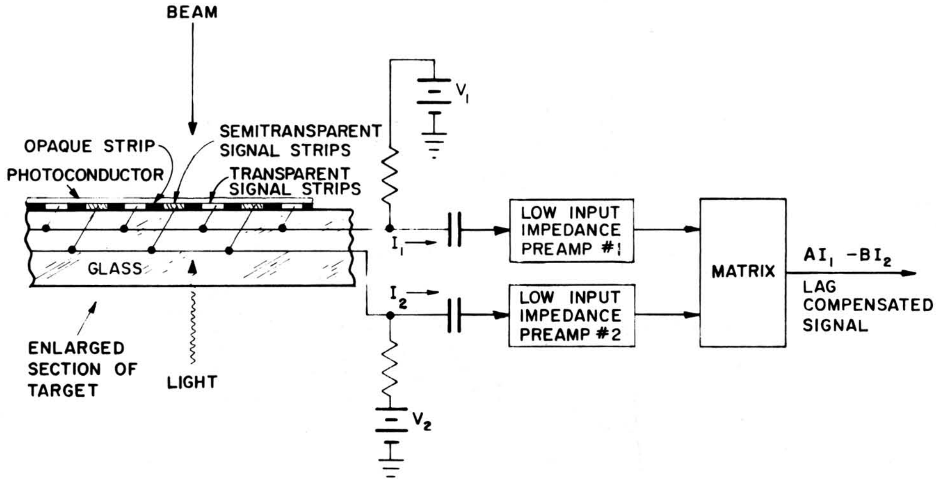



**Fig. 9 - Two-channel output target for differential lag compensated vidicon type camera tube.**

noise level in each channel caused by this added capacitance is thus considerably higher than normal (by a factor of about 6). Furthermore, the noise in the final signal is increased still more by the subtraction process since the two noise currents are 180 degrees out of phase and add directly[6]. This loss in signal-to-noise ratio appears to be too great to make this method of operation attractive.

The problem of fabricating a bridge-type target with strips sufficiently fine and uniform to produce a high quality television picture is a serious one. At least 500 strips in each set would be required for normal television standards. Breaks in continuity of the strips would also cause trouble, particularly if the voltage difference between the two sets is too high to permit connection at both ends of each strip. The evaporation techniques developed for the tricolor vidicon are capable of producing bridge targets of the required fineness, but further refinement in technique is necessary to produce targets free of defects. A tricolor lag-compensated bridge target is also a possibility but would be still more difficult to fabricate.

[6] *LB-1044, Simultaneous Signal Separation in the Tricolor Vidicon.*

### Application of Lag Compensation to Other Devices

Differential lag compensation should also be effective in display devices employing photoconductivity. For example, a light amplifier might be constructed with two groups of photoconductive elements having different speeds of response. The electroluminescent light-output elements would be so connected as to be driven by the lag-corrected difference current. The nonlinear character of the presently known electroluminescent and photoconductive powders complicates the design of the structure, however, and the feasibility of the proposal has not been evaluated.

Harold Borkan

Paul K. Weimer

## Appendix I

### Computed Lag Compensation For Exponential Decay

For an assumed exponential decay characteristic it is possible to calculate the improvement in response available by the differential method of lag compensation. If both signals decay exponentially with the same time constant no improvement in speed of response occurs when any fraction of one signal is subtracted from the other. However, if the auxiliary signal has a longer time constant than the main signal, a reduction of lag is indicated. Mathematically, the net gain adjusted resultant signal is

$$R = 1/1\text{-}x \left( e^{-t/t_o} - x\, e^{-b(t/t_o)} \right)$$

where

$t_o$ is the time constant of the main signal,
$t_o/b$ is the time constant of the auxiliary signal,
$x$ is the relative amplitude of auxiliary signal, and
$t$ is the time after the removal of light.

For an assumed value of $b$ between 0 and 1, $R$ will reach a negative maximum and asymptotically approach the axis. Fig. 10 shows the decay characteristic of compensated signals for comparison with the uncompensated signal for various values of $b$. The condition is imposed that all corrected signals may go no further than 10 percent negative which specifies the value of $x$ for each value of $b$. The assumption is made here that a 10 percent overshoot in the negative direction is the maximum amount which is tolerable.

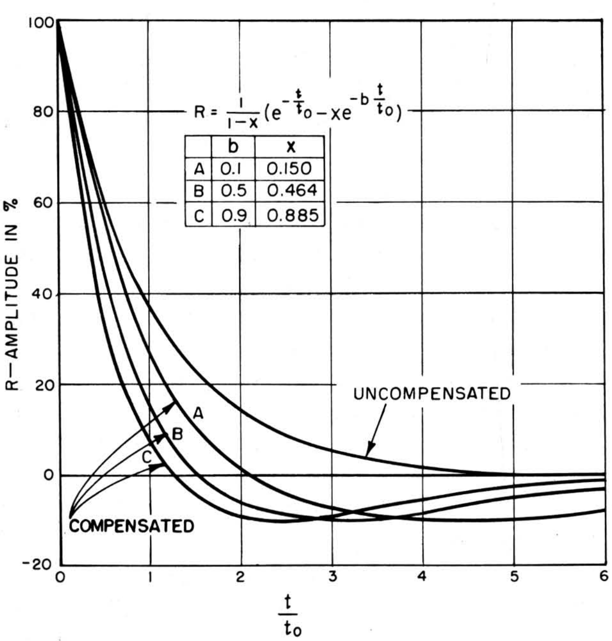



**Fig. 10 - Theoretical compensation attainable with exponential decays of signal. Parameters selected so that compensated response is tangent to R = 10%.**

Fig. 11 shows the reduction in the time for the signal to reach the positive 10 percent value and also the amount of net signal remaining which is indicative of resultant signal-to-noise ratio. The curves show that the reduction in decay does not change rapidly with $b$, but loss of signal does increase markedly as $b$ approaches unity.

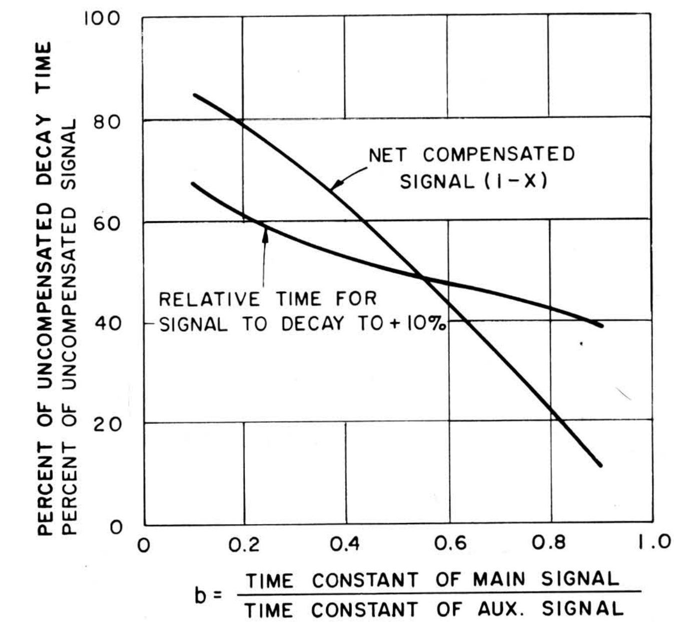



**Fig. 11 - Response time and residual signal for compensation in Fig. 10.**

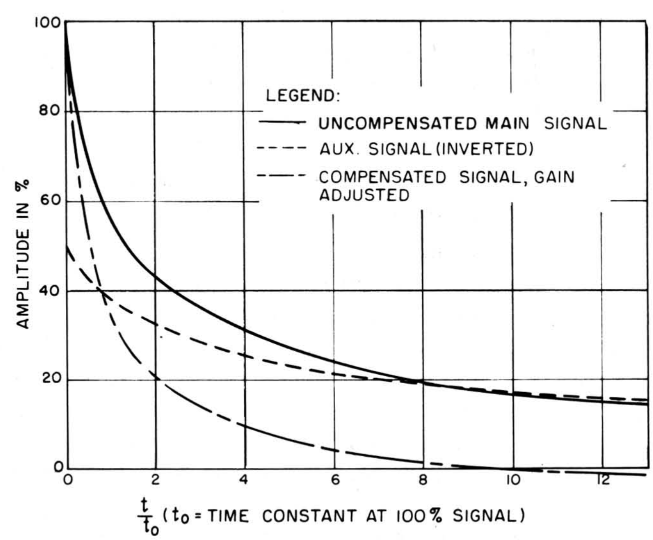



**Fig. 12 - Calculated compensation attainable for capacitance lag in a vidicon assuming that the beam resistance is inversely proportional to the signal amplitude.**

The above analysis applies to two camera tubes having only capacitive lag with the beam resistance constant. It has been observed however, that in vidicons having capacitive lag dominating, the decay is slower than exponential. This may be explained by assuming that the beam resistance and therefore the time constant increases with decreasing signal level. The relative improvement when assuming that the beam resistance varies inversely as the signal level is calculated in Fig. 12. It has been assumed that the time constant of the auxiliary signal is three times that of the main signal while the amplitude of the former is 50 percent of the latter, which is sufficient compensation to greatly reduce the long tail of decay.

Since the capacitance across the photoconductor can be readily adjusted by choice of photoconductor thickness, the conditions necessary for effective compensation of capacitive lag can be met without great difficulty. Fig. 7c is an example of compensation for capacitive lag.

## Appendix II

### Methods of Combining Video Signals For Lag Compensation

The noise associated with vidicons is primarily caused by the head amplifier stage in the preamplifier. Subtracting signals from two preamplifiers results in addition of noise. If equal amplifier gains are employed in the two channels there will be a 41 percent increase in the rms value of the noise and if the auxiliary signal is 30 percent of the main signal there will be only 70 percent net signal. The result is a reduction in signal-to-noise ratio by about 50 percent. Obviously, it is desirable to have the auxiliary tube more sensitive to reduce the the gain required of its preamplifier relative to that of the main signal. Higher target potential on the auxiliary tube is a means of achieving this greater sensitivity.

If it were possible to use a single head stage of the preamplifier to accept the two signals and yield the difference signal, improved signal-to-noise ratio would result. However, noise considerations restrict the selection of input tubes to a high $g_m$ triode and the only method of taking the difference of two signals is then to feed one signal to the grid and the other to the cathode. This method offers many disadvantages, the main one because the cathode impedance is very much smaller than the grid impedance. Since the output impedance of a vidicon is of the order of megohms, the amplifier input voltages vary as the input imoedances. If the grid resistor were reduced sufficiently to equal the cathode input impedance, added thermal agitation noise in that resistor will more than offset the advantage of a single input tube.

However, the difference circuit could be placed early in the preamplifiers and offer a reduction in the number of vacuum tubes required. A convenient form of a head-stage difference circuit offering two high input impedance points involves two triodes sharing a common cathode resistor. Signals are fed to the two control grids while the output is taken from one of the plates. If the cathode resistor is large enough, the output voltage is proportional to the difference of the two input voltages. With this arrangement only one additional triode is required over a conventional preamplifier.

If one of the vidicons is operated to yield an inverted polarity signal compared with the other vidicon, lag compensation may be obtained by addition of the two signals rather than subtraction. In this way the signals can be combined directly at the input to the amplifier without requiring separate input stages. A feasible way of doing this is to take the signal from the target of one tube and the decelerating mesh of the other. The mesh is made to act as a collector of the return beam yielding the opposite polarity signal compared with the target signal. Another method is to operate both tubes at high velocity with the target of one biased positively with respect to its collector, while the target of the other is biased negatively with respect to its collector. This latter method may also be used with the single tube structure of Fig. 9.