Optics and Photography in the Flying Spot Store

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The flying spot store is a semipermanent binary information storage system in which a cathode ray tube display is imaged on photographic emulsion by parallel optical channels. One section of the lens system provides the cathode ray tube with spot-positioning information for a closed-loop servo; the remainder of the channels are used for storage of the desired information. This paper discusses some of the optical and photographic problems to be considered in the construction of a flying spot store.

I. INTRODUCTION

The experimental electronic switching system uses as its large, semipermanent memory a flying spot store which has been developed to meet the needs of the system.* The flying spot store holds the telephone translation records and the operational program. Because it is desirable to handle this information on a word-organized basis, many parallel optical channels are desired.

Stores of several capacities and configurations have been proposed.[3] Discussion in this paper will be limited to the optical and photographic problems of an initial laboratory model flying spot store assembled to show the feasibility of the switching system at as early a date as possible,[2] and to bench tests of an optical configuration proposed for a store of approximately two million bits capacity. In each instance, reference is made to optical channels containing the stored information and to the optics of the closed-loop beam positioning servo.

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* The system was described in a paper[1] in a previous issue of this publication. The flying spot store[2] has been described in a previous issue and system considerations[3] of the flying spot store are discussed elsewhere in this issue. These articles provide pertinent background for this paper.

II. SYSTEM CONSIDERATIONS

2.1 *Flux Distribution*

Fig. 1 shows the physical nature of a single channel. An optical channel consists of an objective lens, a photographic plate, a condenser lens and a photomultiplier tube. Ref. 2 points out the limits of the physical parameters involved in the realization of a flying spot store. The maximum flux per unit area which can be obtained from the phosphor screen on the cathode ray tube is the limiting physical parameter. The cathode ray tube characteristics which also influence optical system performance include light scattering within the phosphor, which affects the distribution of light within the spot; halo; defocusing of the spot with deflection; and local variations of light output with beam position, due to defects in the phosphor. The cathode ray tube face plate is one of the optical elements of the system.

The radiant flux required at the photocathode of the photomultiplier can, within the limitations of phosphor efficiency and aging characteristics, be achieved even for very high speed systems with lenses of relatively high *f* number. The lens aperture and focal length and the system magnification ratio may be selected to give as little as 1/45,000 of the 1500 microwatts total flux from a typical spot operated at the phosphor loading limit of a P-16 screen and yet operate at an output circuit bandwidth of 10 mc.

At the image plane, flux distribution within the spot is important. The flux density of the spot focused at the image plane must be sufficiently high to produce a relatively dense spot for an exposure time of a few

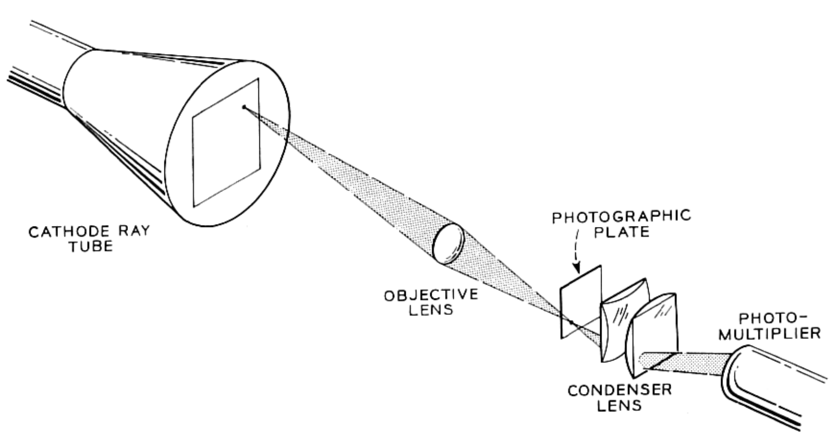

Fig. 1 — Single information channel of a flying spot store.

hundred microseconds. Flux levels which meet the signal-to-noise requirements of the photomultiplier will produce such spots in emulsions which are characterized by the spectroscopic types readily available. These are generally high-contrast, blue sensitive emulsions of medium to low granularity.

2.2 *Information Channels Organization*

In a multiple-channel store one or more bits from each word may be stored in each information storage area of the photographic plate. In general, the number of channels may be made equal to or greater than the word length, so that a single beam positioning yields a readout of the entire word. The total storage capacity is seen to be equal to the number of spots on the cathode ray tube raster times the number of channels viewing the raster. The maximum number of channels depends on the maximum off-axis angle at which the objective lens may be used and the limit of the flux level required at the photocathode. The off-axis angle and the distance from lens to cathode ray tube screen fix the size of the lens board. The number of lenses which may be placed in this area is a function of the diameter of the lens barrel and the magnification ratio of the system. Because the image areas may not overlap, the magnification ratio is usually less than 1 and decreases with increasing numbers of channels. Magnification may be selected such that both adjacent lens barrels and condenser systems have suitable mounting space. For a given flux level at the photocathode, the number of spots on the phosphor-loading-limited cathode ray tube will have to be decreased with increasing numbers of channels, since the spot size must be increased to provide more flux with the increasing f number of the objective lens. The general problem, then, is to ascertain the required number of addresses for the system application and predicate as large a spot size as feasible within the limitations of the cathode ray tube raster. Following this, a lens must be sought with an adequate field angle to allow enough parallel channels for the length of the word required by the system.

The exposure of the photographic plates containing the stored information is carried out by the store itself, under control of an external exposure unit. A shuttering system, normally open, is used to close off all image areas except the one to be written. The information to be stored is organized image area by image area and read to the store from magnetic tape. When a complete plate has been written, it is removed, processed and reinserted in the store. Optical variations between lenses in quadrants otherwise symmetrical preclude exchange of plates between quadrants or between parallel stores.

2.3 *Optical Channels of the Closed-Loop Beam-Positioning Servo*

The optical channels of the closed-loop beam-positioning servo provide the spatial division of the cathode ray tube raster area by means of code plates fixed in the image plane. Code plates are required for both the x and y coordinates, so that readout from the photomultipliers of these channels gives a spot's address on the raster in both coordinates in parallel binary words.

Beam positioning is accomplished by comparing the position readout of the servo channels with the desired address and deriving therefrom an error signal, which is used to deflect the beam to the desired position.

With these aspects of the system in hand, the individual characteristics of the optical and photographic elements of the system may be analyzed with respect to their contribution to system performance.

III. OPTICAL DISCRIMINATION RATIO

3.1 *Definition*

The measure of success of the optical system in performing its function in the flying spot store can be determined from a single parameter, the optical discrimination ratio, which is defined as follows:

$$\rho = \frac{S_{(1,\min)} - S_{(0,\max)}}{S_{(0,\max)}},$$

where ρ is the optical discrimination ratio, $S_{1,\min}$ is the relative amplitude of the minimum "1" in the channel, and $S_{0,\max}$ is the relative amplitude of the maximum "0" in the channel.

All elements in the optical path — cathode ray tube, objective lens, photographic plate, condenser lens and photomultiplier — may be evaluated with respect to the effect they have upon the discrimination ratio.

3.2 *Experimental Approach*

Photography may be discussed in terms of many different parameters, but the most fundamental difference for the flying spot store application is whether one uses opaque spots on a clear background (negative) or clear spots on an opaque background (positive). A negative plate and a positive plate, as used in one information channel of the laboratory model of the flying spot store, are shown in Fig. 2.

It has been verified by experiment that it is very desirable to use a positive plate instead of a negative plate in the image plane. The positive

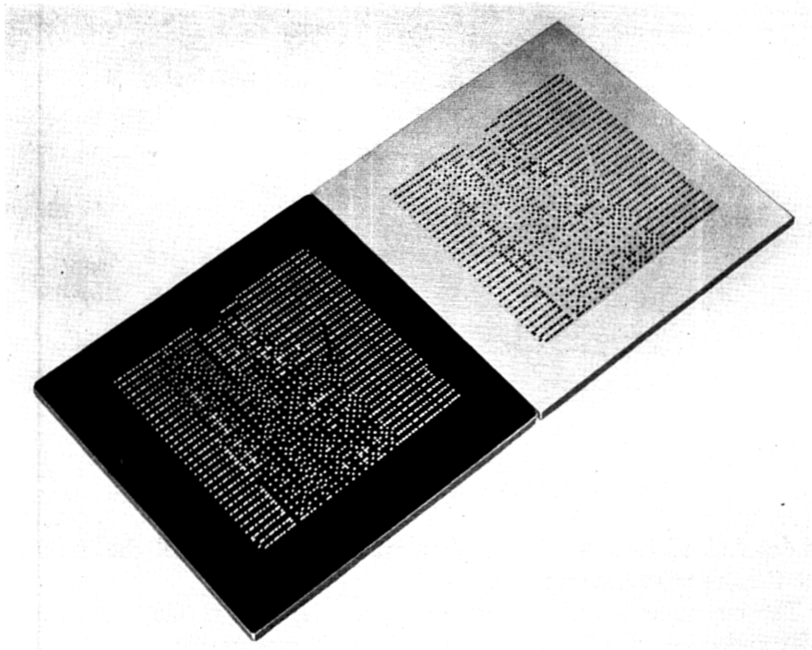

Fig. 2 — Positive and negative information storage plates.

plate gives an appreciable gain in the discrimination ratio of the optical system. Since this gain is often a factor of two or more, it is necessary to restrict the photographic emulsions to those which can be readily and reliably reversed in processing. This requirement, together with the speed requirement, reduces the possible emulsions to a very small number. Fig. 3 shows the basic quantities of the optical discrimination ratio for either negative or positive plates.

The following experimental procedure describes the method of measuring the optical discrimination ratio for positive plates. (The procedure applies equally for negative plates.)

A lens or array of lenses is set up together with the other optical elements of a flying spot store, and arrays of spots are written on a photographic plate. These spots are written in two ways: first, as isolated clear spots on the emulsion (1's) surrounded by dark spots (0's); second, as arrays of boxes in which a 0 is surrounded by 1's, as shown in Fig. 4. After the arrays are written, the photographic plate is removed, processed, reinserted in its original position and read out with the same experimental setup. The minimum 1 ($S_{1,\min}$) and the maximum 0 ($S_{0,\max}$),

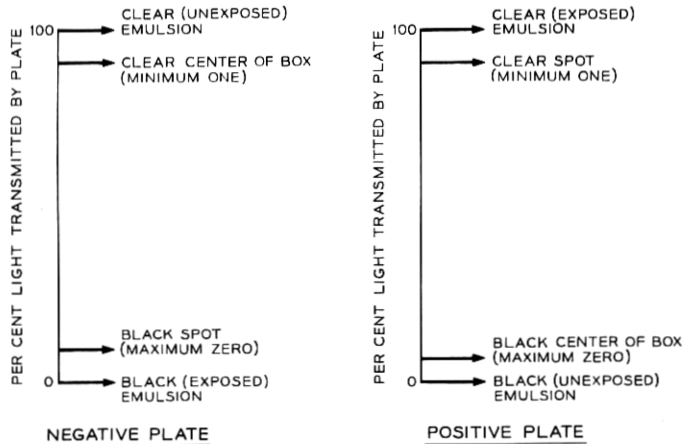

Fig. 3 — Definition of optical discrimination ratio.

as determined by the relative photomultiplier response of the channel, are then used to determine ρ.

The instrumentation for such tests must be very stable both electrically and mechanically, and also must permit measurements to be made at considerable distances off the system axis. Since conventional lens benches did not prove satisfactory, a standard machine shop surface plate was used to mount the various parts of the system, as shown in Fig. 5. This type of bench, together with the usual box parallels, straight edges, milling machine cross slides and rotary motions ordinarily found

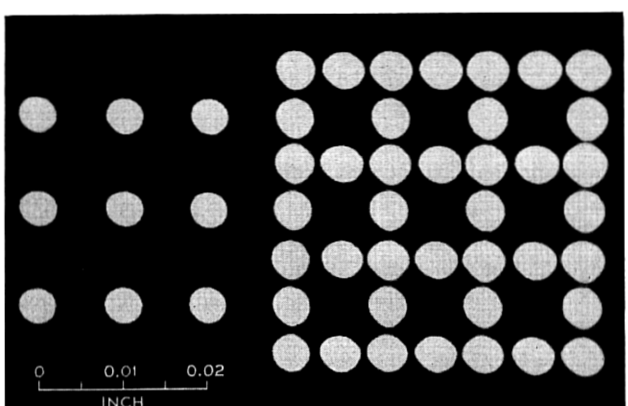

Fig. 4 — Enlargement of an array used to determine optical discrimination ratio.

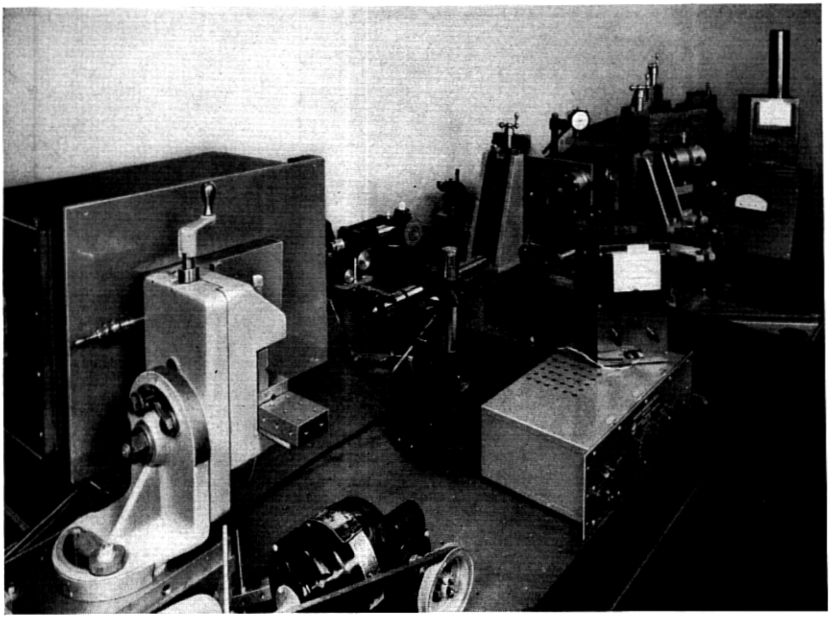

Fig. 5 — Typical experimental setup for optical measurements.

in a machine shop, has supplied the rigidity and versatility necessary in three-dimensional optical measurements.

While specific test results are inevitably a function of the many variables of the system, optical discrimination ratios of 10 to 1 or better may be achieved using a 6-inch $f/8$ lens corrected for field angles to 25° imaging 0.018-inch cathode ray tube spots on 0.021-inch centers at 4 to 1 reduction.

IV. DISCRIMINATION RATIO AS A FUNCTION OF RESOLUTION

4.1 *Cathode Ray Tube Resolution*

The maximum cathode ray tube resolution is determined by the light intensity distribution in the spot achieved by the tube. It has been experimentally verified that shrinking-raster methods of measuring spot size may be in error by as much as a factor of two when compared with results based on energy considerations. The intensity distribution of light within the spot is essentially Gaussian:

$$I = I_0 e^{-(r^2/2\sigma^2)}.$$

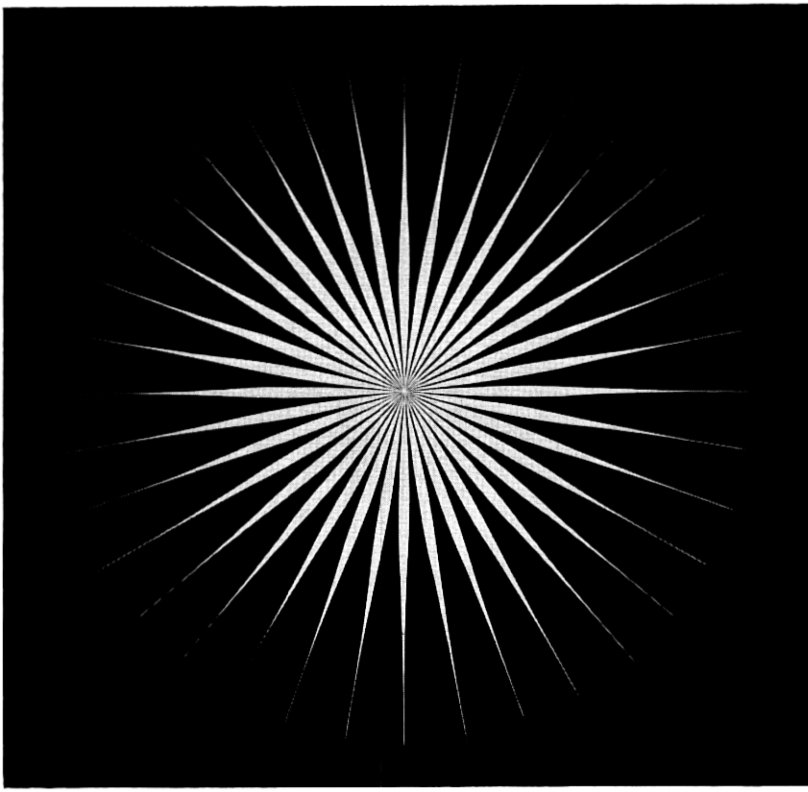

Fig. 6 — Reticle used to simulate intensity distribution of cathode ray tube spot.

A square whose side is 4σ will contain 90 per cent of the energy of the spot. A mechanical simulation of the light source for initial test work was produced by making a reticle in the shape of a "Gaussian star," (Fig. 6) which, when imaged through a microscope, gives a light spot whose intensity distribution is Gaussian. Suitable filters effectively simulate the desired spectral region. A cathode ray tube, as characterized in Ref. 2, with a 256 × 256 array of 0.018-inch spots on 0.021-inch centers would present an object plane 5.4 inches on a side and could be contained on a 10-inch tube. In the laboratory model store, a 3-inch raster of 64 × 64 spots is used on a 7-inch tube. Clearly, as the limiting resolution of the cathode ray tube is approached, the problems of deflection defocusing, phosphor aging, phosphor blemishes and uniformity of the phosphor screen become more and more important. If the cathode ray tube spot varies with time in any of the parameters mentioned above, the value of $S_{1,\min}$ will also vary and tend to be smaller. If the apparent position of the spot on the tube face varies for any reason, both $S_{1,\min}$ will be decreased and $S_{0,\max}$ will be increased, with a resultant decrease in ρ, the discrimination ratio.

4.2 *Lens Resolution*

The objective lenses used in a flying spot store image the spots from the flat face of the cathode ray tube onto the photographic plate. The phosphor screen of the cathode ray tube must either be planar or approaching planar quality or the objective lens must have a small aperture so that the depth of focus and field curvature characteristic of the lens can absorb the deviation. In general, this would be possible only with low-resolution systems working close to system axis, such as the laboratory model which employs a cathode ray tube face plate with a 30-inch radius of curvature. The 10-inch tube with a 256 × 256 array will require a flat faceplate.

The objective lens must be designed to have very little curvature of field. The Petzval lens of the laboratory model, which exhibits excellent resolution characteristics on axis, also had satisfactory curvature of field at its aperture of $f/13$. In later flying spot store designs, a lower f-number lens was required and, for this problem, the curvature of field of the Petzval design is much too great, and, therefore, a six-element, double-Gauss type of objective lens was used. While the influence of several aberrations may be eliminated by writing and reading through the same optical channel, any aberrations which cause images of adjacent spots on the cathode ray tube to overlap must be reduced below that point. Chromatic aberration corrections are a function of the spectral emission characteristic of the phosphor. For example, P-16 phosphor emits energy over a relatively narrow spectral range, while P-24 phosphor covers a much broader spectral region. Therefore, the chromatic correction for a lens is smaller with P-16 phosphor than with the use of P-24 phosphor.

4.3 *Experimental Measurements on Lens Resolution*

The resolution of the various lenses that have been tested has been determined by two different means.

4.3.1 *Measurement of Contrast*

The contrast of the lens is measured by determining its sine wave response, using the technique described by W. Herriott[4] and D. R.

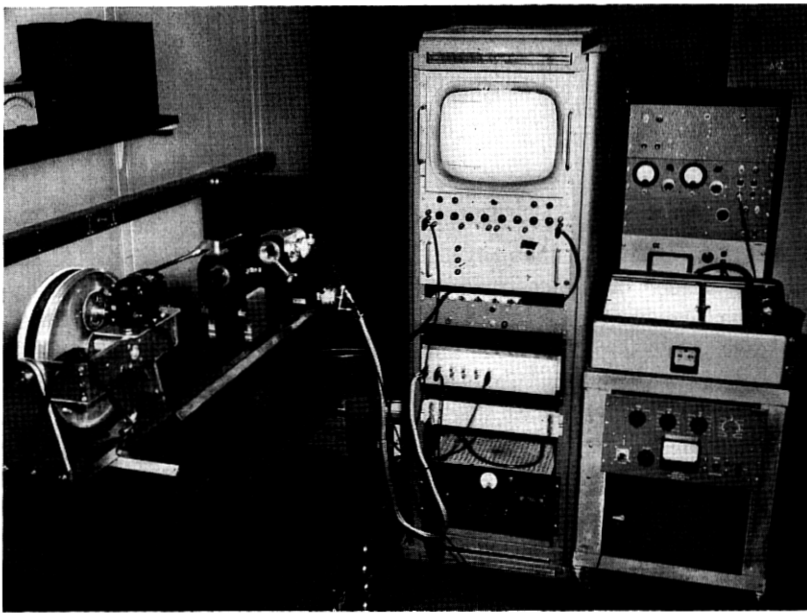

Fig. 7 — Equipment for measuring sine wave response of lenses.

Herriott.[5] This method has the advantage of speed in routine testing and permits both inspection and determination of the precise conjugates which optimize the operation of each particular lens in the flying spot store. The lens bench equipment used in measuring the sine wave response is shown in Fig. 7.

The contrast of the image of a sinusoidal target as a function of target spacing through focus on a lens sample is shown in Fig. 8.

4.3.2 *Measurement of the "System" Conditions*

This method involves the use of the image analyzer shown in Fig. 9. This instrument, designed by D. R. Herriott, consists of a microscope that images the spot on a square aperture of variable size. Behind the aperture is mounted a photomultiplier tube. A beam-dividing prism and eyepiece allow visual observation of the spot. Measuring spot size in either the image or object plane consists of determining the aperture size which contains 90 per cent of the light, which may be considered a measurement of spot size as defined above. If the aperture is set at an opening small compared to the spot size, the image analyzer or the spot may be traversed to measure the intensity distribution of the spot or,

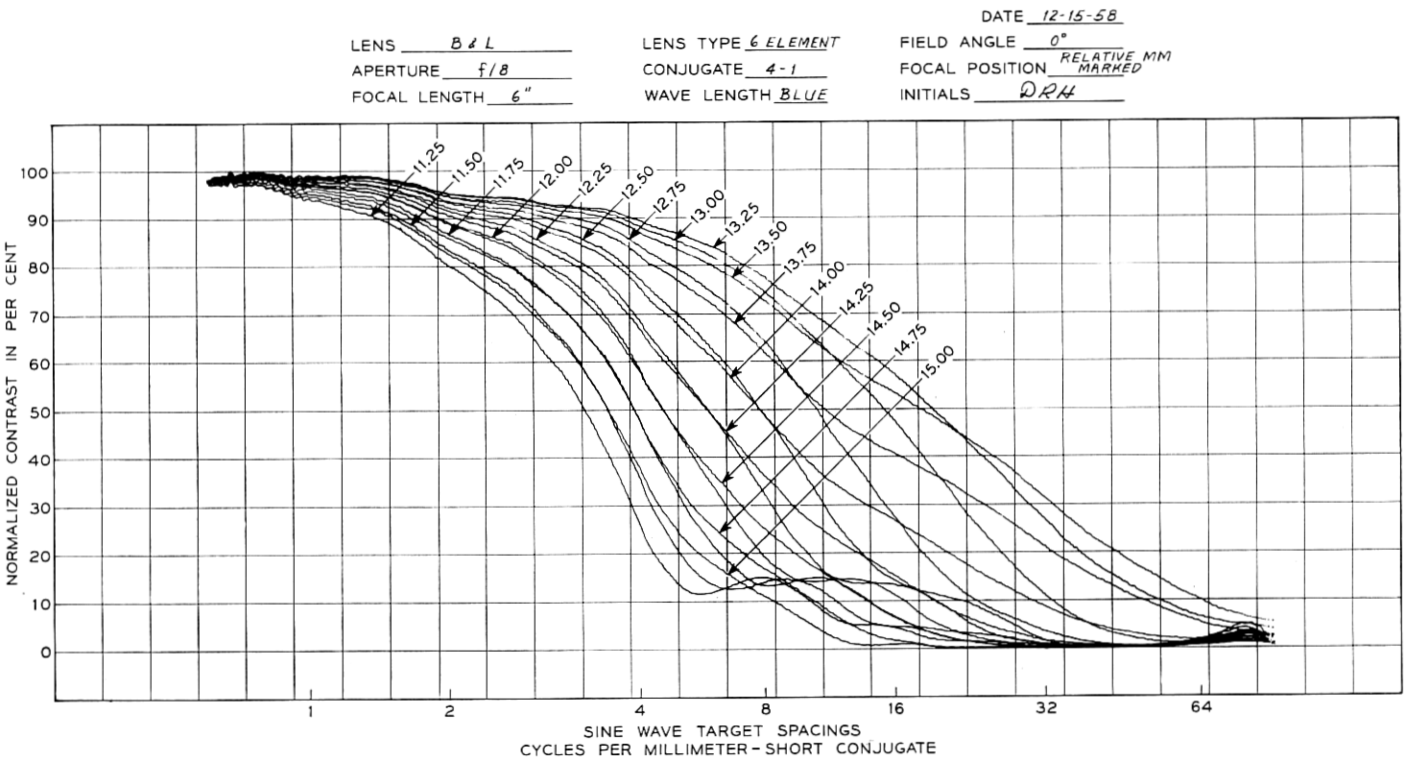

Fig. 8 — Sine wave response of a sample lens measured on a photoelectric lens bench.

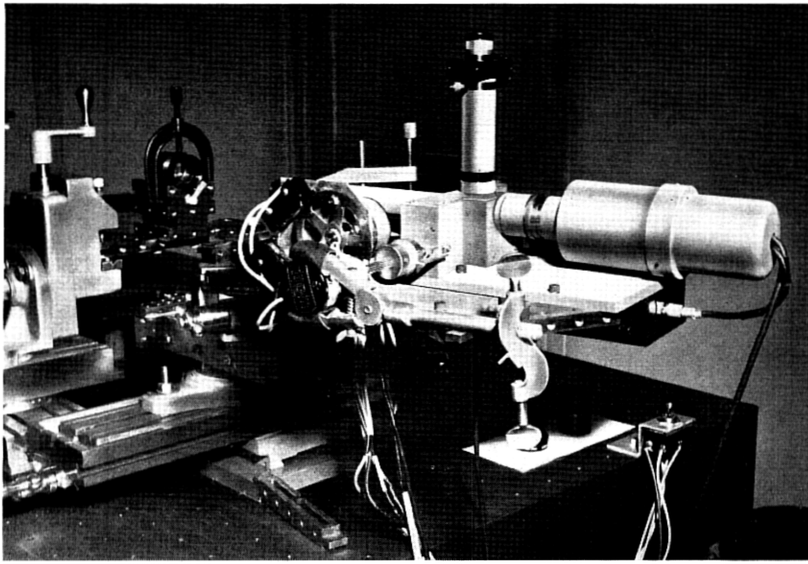

Fig. 9 — Image analyzer.

of course, the square aperture can be replaced by a slit and the intensity distribution measured in that way.

In operation, the square aperture is centered on the image by both the visual observation provided and by maximizing of the electrical output at a suitable aperture. The electrical signal is then recorded as the aperture is driven through its range of opening. Such a recording is shown in Fig. 10. The percentage of light incident upon various-sized squares is meaningful, in a system sense, since the square array used on the cathode ray tube assigns a square area to each bit of information. If the image quality of the lens is such that this percentage of incident light is relatively low for a square whose side is the spot spacing, then the remaining light must fall on adjacent areas, and the discrimination ratio will be reduced. Experience has shown that a 6-inch $f/8$ lens corrected for a 25° field angle, as characterized in Ref. 2, may be expected to yield 90 per cent of the energy from a cathode ray tube spot into a square whose size is the spot spacing at the image plane.

4.4 *Photographic Emulsion*

The resolution used in the flying spot stores now under investigation does not approach the resolution of the currently available photographic

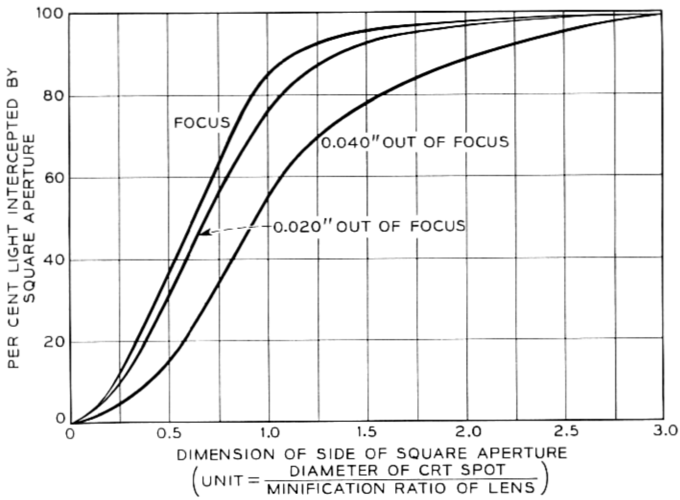

Fig. 10 — Percentage of light incident upon a square aperture for a 6-inch $f/8$ lens and a 0.015-inch diameter cathode ray tube spot.

emulsions; therefore, the granularity of emulsion is not a limiting factor. However, care must be taken to avoid dust particles or emulsion blemishes which would affect readout of the store. With the resolutions now being considered, neither dust nor blemishes poses a serious problem.

V. UNIFORMITY OF ILLUMINATION

After a flying spot store has been designed so that the cathode ray tube supplies enough light and the photomultipliers receive enough, it is still necessary to provide the same flux level through the various channels and uniform flux over the field of each individual channel.

5.1 *Uniformity as Influenced by the Objective Lens*

The problem of uniformity of illumination from channel to channel must be considered at the image plane, where the radiant flux varies as $\cos^4\theta$, and in the photomultiplier output. Both variations may be corrected to within ± 10 per cent by making the lens stop diameter a function of the position of the lens relative to the system axis. To make the light more uniform over the field of a particular lens, a front stop or "vignetting blade" is used to partially compensate for the $\cos^4\theta$ and vignetting effects. Operating uniformity to ± 10 per cent can be achieved by these methods. Fig. 11 shows the effect of adding vignetting blades.

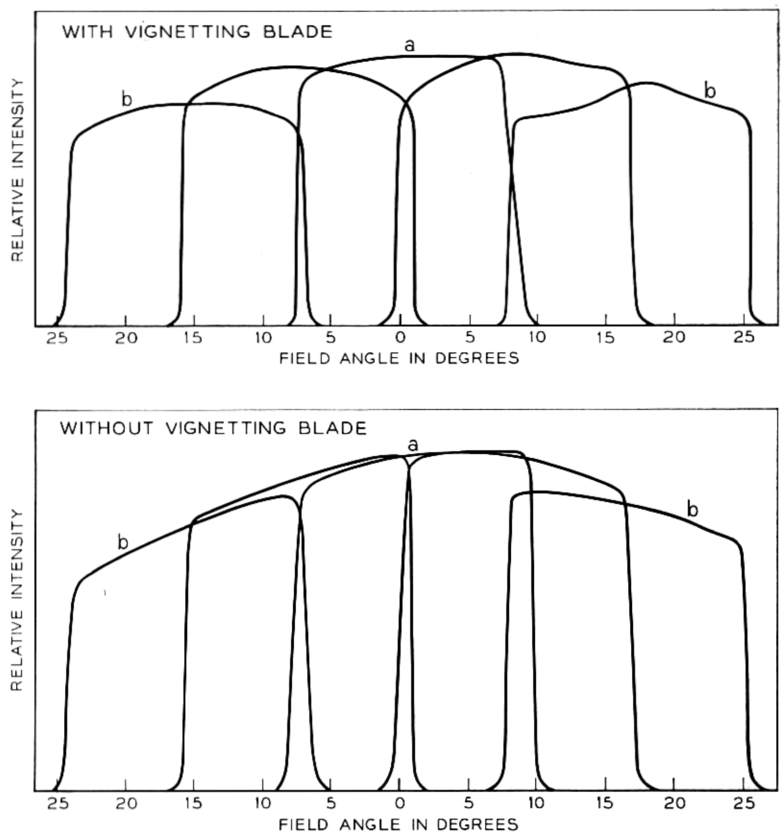

Fig. 11 — Uniformity of illumination across the field of the information channel lenses, showing illumination across the field of the lens on (a) the system axis and (b) the outside of the lens array.

5.2 *Uniformity as Influenced by the Condenser Lens*

The condenser lens in each optical channel is mounted at an angle to the photographic plate such that its optical axis passes through the center of its objective lens stop. This type of mounting allows the condenser system to operate on axis. The requirements that must be met by the condenser are that it shall image the objective lens stop and pass the intercepted light with a minimum loss to the photomultiplier. Since the light intercepted for any given address on the cathode ray tube lies in a rather small cone, which may pass through any zone of the condensing lens, the condenser must be corrected for spherical aberration to prevent the image from moving too greatly on the photomultiplier tube face.

Even rather small motions of the image are important, since the photocathodes of the photomultiplier tubes may be quite nonuniform in response, as shown in Fig. 12, and the resultant variation in photomultiplier tube output reduces the discrimination ratio as defined above.

In practical systems, it is necessary to provide adequate mounting space between channels for the lens, photographic plates and condensers. Because the condenser is mounted at an angle so as to be working on axis, it must be spaced some distance behind the photographic plate and therefore must be of larger aperture. The selection of magnification should be made to give just adequate mounting space for both the lens and condenser. This usually provides enough space between adjacent image areas for mounting parts. As the speed of the objective lens is increased, the angle of the cone of light passing through a point of the photographic material likewise increases, requiring larger condenser apertures.

VI. THE OPTICS OF THE SERVO SYSTEM

The spot of light on the cathode ray tube is positioned to a given address in the raster by means of a servo system.

6.1 *The Laboratory Model Servo Optics*

In the laboratory model, a cylinder lens forms a line of light which is focused on a code plate. This code plate is made so that the complete x

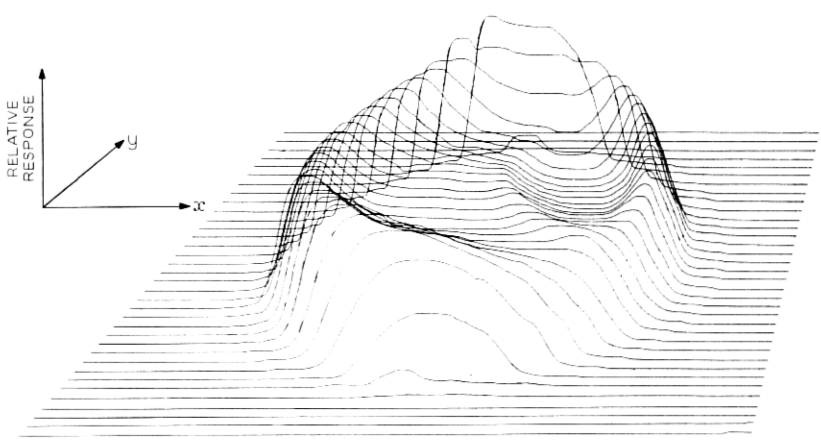

Fig. 12 — Sensitivity variation over photocathode on typical photomultiplier.

address of the cathode ray tube spot is given directly in the binary or Gray code. Another cylinder lens and code plate oriented at a 90° angle to the first gives the y address. Individual Lucite light pipes gather the light for each address bit from behind the code plate and conduct it to the photomultiplier tube. A unique cylinder lens system based on the Petzval design was used in the laboratory model. The line of light formed by the servo lens is about four inches long, and there is a considerable variation in intensity along this line, in spite of a front rectangular stop used to control the intensity distribution along the line. As in the case of the spherical Petzval, the curvature of field of the cylinder lens is quite severe and, over a flat image plane, this results in a 4-to-1 line-width variation. Although the lens performance is undesirable, the flying spot store has been operated very successfully.

6.2 *Spherical Lens Servo Optics*

When systems with many channels are considered, the use of a spherical lens encoder requiring one lens per address bit is preferred. Fig. 13 shows a sample lens assembly for a single channel. For example, a 256 x 256 array would require 16 servo channels ($2^8 = 256$) to read out the x and y coordinates of a cathode ray tube spot in binary form.

The cathode ray tube spot is positioned reproducibly to within $\frac{1}{10}$ spot diameter by an analog method which assures that the image of the cathode ray tube spot in the servo channel lies half on and half off the controlling reference edge. The analog part of the servo response, as seen

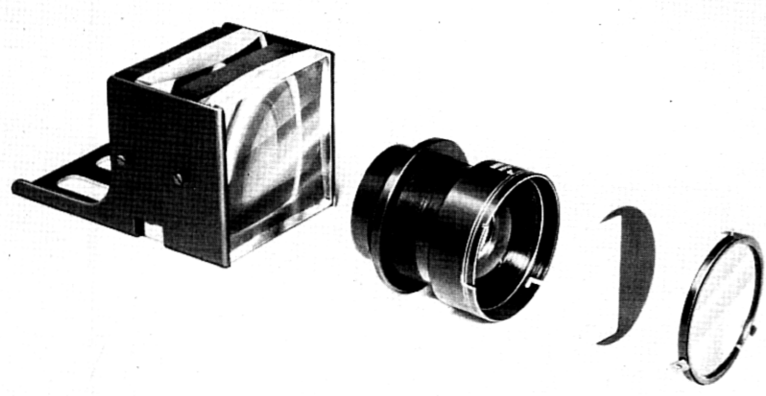

Fig. 13 — Sample lens assembly.

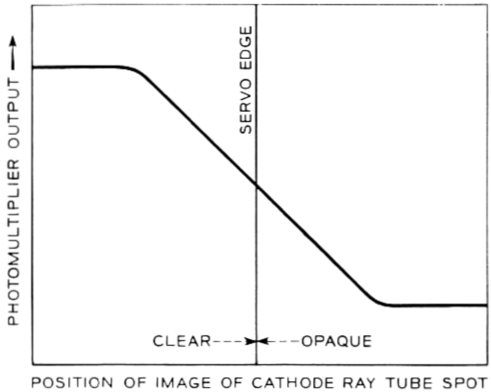

Fig. 14 — Optical crossover characteristic of servo system.

by the photomultiplier tube, should be of the form shown in Fig. 14. This curve is referred to as the optical crossover characteristic of the servo. If the slope of the crossover is greater, the spot is more accurately positioned but the positioning operation must be slower. If the slope is less, the positioning accuracy is decreased and the servoing speed may be increased.

Since the shape of this curve is important to the operation of the flying spot store, it must be controlled as accurately as possible. In the experimental electronic switching system, the crossover characteristic was controlled by defocusing the cylinder lens. In the spherical servo system, the same effect is produced and lens distortion eliminated as a problem by choosing a lens with an appreciable longitudinal chromatic aberration, and then photographing the servo code plates through the lens in red light, for which it is focused, and reading back with the blue-violet light produced by P-16 phosphor. Code plates produced for such a system are shown in Fig. 15. Another method of controlling crossover consists of using a combination of a weak cylinder lens and a spherical lens to produce a short line of light. This line is oriented at a slight angle to the positioning edge so that, when the image of the spot crosses the edge, the crossover characteristic is produced. By shaping the stop of the lens and rotating the cylinder lens, it is possible to control the crossover quite closely. Fig. 16 shows an oscillogram obtained on a test bench and indicates the excellent control that can be achieved. The oscillogram shows the crossover obtained for a 0.005-inch spot as imaged from a cathode ray tube and swept across alternate opaque and clear 0.010-inch bars.

The accuracy with which the spot is positioned on the cathode ray

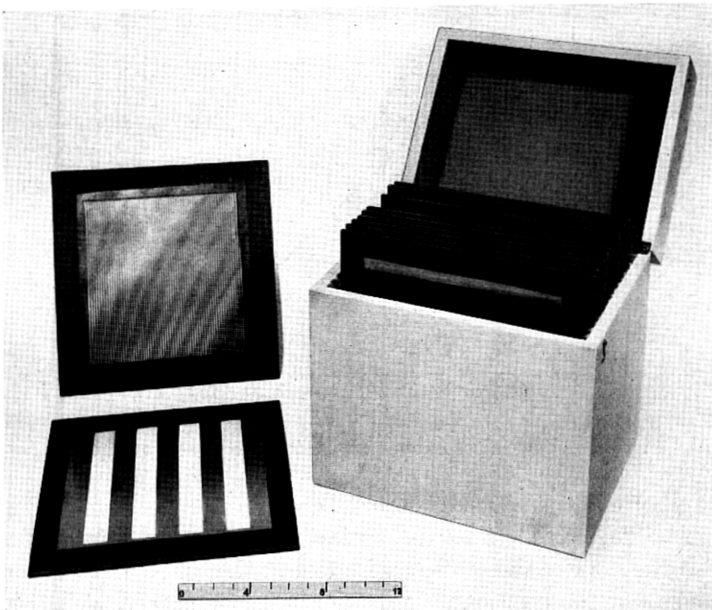

Fig. 15 — A set of master code plates for an optical beam encoder.

tube has a direct effect upon the optical discrimination ratio. If, for readout, the image of the spot is not centered exactly upon a clear spot in the emulsion, then the value of $S_{1,\min}$ is reduced and, for an opaque area, $S_{0,\max}$ is similarly increased. The servo system will misposition the cathode ray tube spot if the light level in a servo channel varies with time. For this reason, it is important to control the radiant flux produced by the cathode ray tube as the phosphor ages.

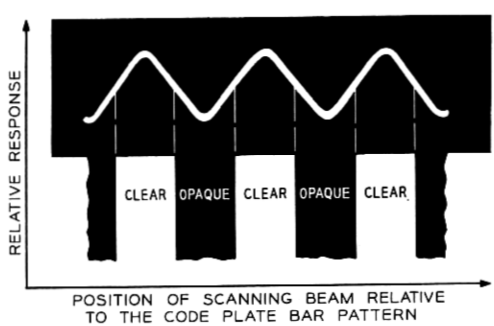

Fig. 16 — Oscillogram of the crossover characteristic of an optical beam encoder.

VII. TOLERANCES AND DEFECTS

The major problem encountered in the construction of a flying spot store is that of distributing the mechanical, optical and electrical tolerances so that an optimum design is achieved.

For the laboratory experimental switching system, the spot spacing is so large, 0.048 inch, that the written spot may be "burned in" to a large size relative to the 4σ spot. Conventional reversal processing gives clean, clear spots and blacks with a density of 2.0 or more. Under these conditions, optical discrimination ratios of 50 can be maintained.

A more difficult problem arises with higher resolution systems. A schematic drawing of this type of flying spot store is given in Fig. 17 to show the servo system and a typical information channel.

The servo channels are arranged in the form of a cross having its center on the axis of the system. The horizontal row of lenses controls the vertical position of the cathode ray tube spot and the vertical row, the hori-

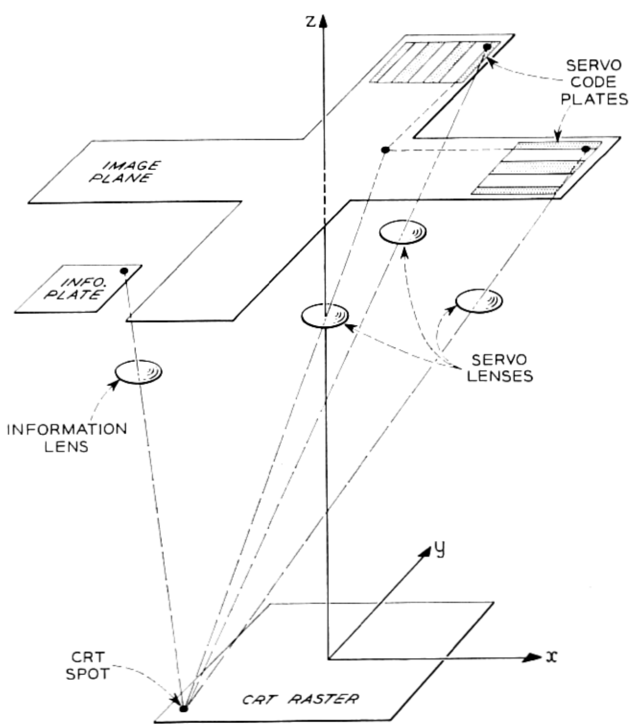

Fig. 17 — Optics of servo system.

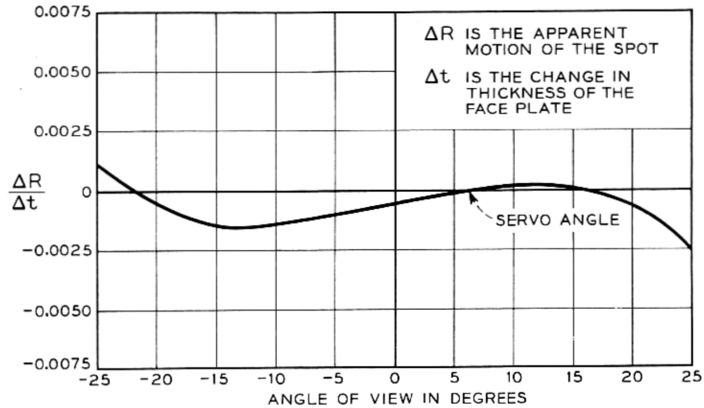

Fig. 18 — Motion of the servo-locked image in an information channel due to the change in the face plate thickness when the cathode ray tube is replaced.

zontal position of the spot. This type of geometric arrangement relaxes the mechanical tolerances for initial positioning of the cathode ray tube.

When a cathode ray tube must be replaced in the flying spot store, it is very desirable that the information in the store can be read without re-exposure of the plates. With the servo system shown in Fig. 17, and the present tolerances of cathode ray tube face plates, it is expected that a tube may be replaced without serious difficulty. Fig. 18, for example, shows a curve for the amount of spot motion, in the image plane, when the face-plate thickness of a cathode ray tube varies from tube to tube and the spot is locked to give a servo address.

The effect of the movement of the image of the readout cathode ray tube spot relative to the written spot is shown in Fig. 19. The amount of movement permitted by the system will be determined by the cathode ray tube spot size, the intensity distribution and spacing, the imaging quality of the lens, the exposure time, the emulsion speed and contrast and the photographic processing methods.

Other elements in the optical system which influence the optical discrimination ratio are defects in the cathode ray tube phosphor and in the photographic plate. The optical discrimination ratio will be reduced if the cathode ray tube phosphor has blemishes which cause the servo system to crowd spots together, or if the aging of the phosphor is so severe that the radiant flux cannot be held constant by the intensity monitor. Any blemishes or dust particles on the photographic plate which block clear areas or produce unwanted clear areas will also reduce the discrimination ratio.

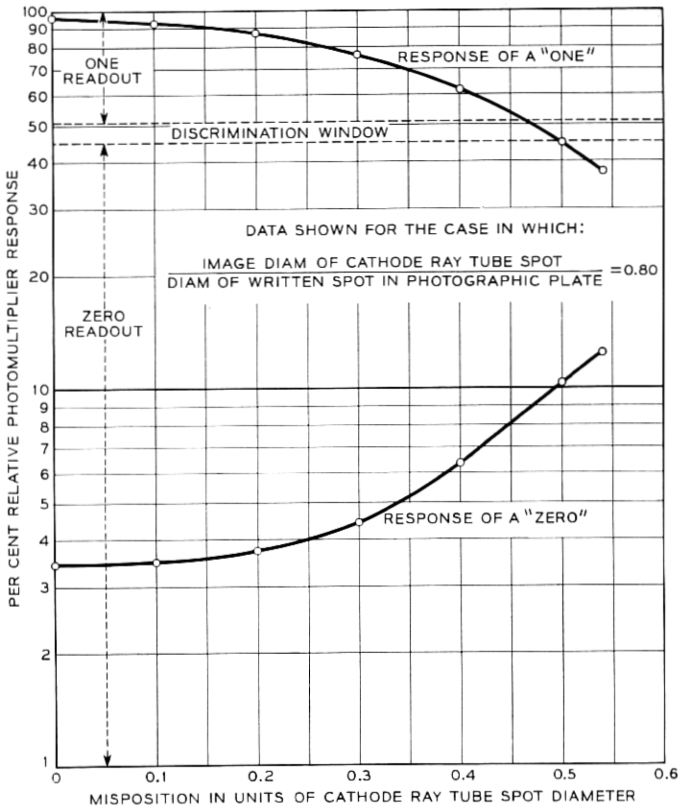

Fig. 19 — Effect of mispositioning of readout spot relative to the written spot for a typical information channel using a positive plate.

Experience with carefully made phosphors and standard photographic materials shows that, in both cases, adequate quality may be obtained to meet system requirements.

VIII. CONCLUSIONS

An experimental laboratory model flying spot store has been built and operated, and the feasibility of a multiplexed optical-photographic permanent memory has been demonstrated. Laboratory experiments on other possible optical systems have extended the art to demonstrate the feasibility of multichannel systems using a spherical lens optical beam encoder for servo control of the cathode ray tube spot. Studies of tolerances on this system indicate satisfactory margins for reliable operation can be achieved.

IX. ACKNOWLEDGMENTS

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