NASA TECHNICAL NOTE

NASA TN D-3360

NASA TN D-3360

AN EXPERIMENTAL DETERMINATION OF TELEVISION CAPABILITIES FOR MAKING NAVIGATIONAL MEASUREMENTS

by Frank A. Pauli and Daniel M. Hegarty

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1966

NASA TN D-3360

AN EXPERIMENTAL DETERMINATION OF TELEVISION CAPABILITIES FOR MAKING NAVIGATIONAL MEASUREMENTS

By Frank A. Pauli and Daniel M. Hegarty

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $0.55

AN EXPERIMENTAL DETERMINATION OF TELEVISION CAPABILITIES FOR MAKING NAVIGATIONAL MEASUREMENTS

By Frank A. Pauli and Daniel M. Hegarty
Ames Research Center

SUMMARY

The capability of a closed-circuit television system for making accurate spacecraft navigation measurements has been investigated. An image orthicon type camera tube was operated at 525 scan lines and 30 frames per second (not interlaced), and the system had a bandwidth of 10 megahertz (MHz).

Maximum resolution and minimum perceptible contrast were measured and the accuracy of angular measurement was determined over a range of background lighting from 0.034 to 343 candela per square meter (0.01 to 100 foot lamberts). Television operating conditions and adjustments were found to have a large effect on the relative distance between images on the monitor screen; for maximum accuracy, therefore, it was necessary to obtain an angular calibration from the field of view when a measurement was taken. An additional calibration technique for correcting position distortion over the field of view decreased the error by a factor of 7.

Maximum horizontal resolution was found to be 850 TV lines, corresponding to a distance of 0.0032 cm on the photocathode. The minimum perceptible contrast for a 0.020 cm spot on the photocathode was 5 percent; this contrast increased considerably for smaller spots. The use of both angular and positional correction calibration procedures yielded a maximum error of 0.27 percent in the measurement of the angular separation between two objects about 12-1/2° apart.

In general, such measured television characteristics can then be combined with those of an optical system to determine an overall capability of the combined system.

INTRODUCTION

Optical systems provide an attractive on-board sighting or navigation capability for manned spacecraft. They are also potentially useful for earth-based tracking of a vehicle on or near the moon. Television systems, in particular, can aid the human eye in a tracking or sighting task and can be used for monitoring some remote or dangerous location. A television system with suitable optics can display objects of lower contrast and can resolve more detail than the unaided eye. A target can be located accurately when the television presents it in a field that contains accurately known reference points, such as stars or salient points on the surface of a planet. Television-optical systems have not been used extensively in spacecraft partially because not enough quantitative information is available to determine their ability to make precise measurements.

This investigation was undertaken to study the measuring precision of television-optical systems. In general, overall system capability can be determined from the transfer characteristics of the optical system combined with the pertinent basic characteristics of the television system. Also, a trade-off can be made between the optical field of view and the detail to be seen, the larger the field of view the less detail that can be seen for a given diameter lens.

To locate objects by television, the contrast of the objects must exceed the minimum perceptible contrast, and adjacent objects must be resolvable. An experimental technique was devised for measuring the minimum perceptible contrast and the resolution limit of television systems. A calibration technique was used for determining the accuracy of measuring the angles between lines of sight to targets, as displayed on a visual monitor. All system capabilities were measured over a wide range of laboratory-controlled background lighting levels.

Since the techniques and instrumentation for measuring resolution, minimum perceptible contrast, and accuracy differ substantially, they will be discussed individually in separate sections.

EXPERIMENTAL EQUIPMENT

Television System

A General Electric 4TE5B1 closed-circuit television system of high resolution (fig. 1) was modified for these tests. It consisted of four main units: the image orthicon camera, the control unit, the monitor, and the power supply. Auxiliary equipment included a crosshatch generator and a pulse integration unit.

The system was especially designed to provide a choice of sweep frequencies. The best operation for a simulated spacecraft guidance scene was judged by subjectively analyzing the picture obtained for different combinations of sweep frequencies. The best operation was attained with 525 scan lines per frame, at 30 frames per second, not interlaced. This combination was used for all tests. Bandwidth was 10 MHz, or about 2-1/2 times that of home television sets.

An 8092a General Electric image orthicon field mesh tube (ref. 1) was used in the camera because of its flat field, high resolution, and low image retention. The original high voltage power supply section was replaced with an externally regulated high voltage supply. The camera lenses were a Summerex f/1.5, with a focal length of 85 mm, and an Astro-Berlin f/1.8, with a focal length of 150 mm. Transmission, exact focal length, and size of Airy disk were measured for each lens.

All controls had digital readout dials so that settings could be repeated. The aperture correction was set somewhat above normal to permit optimum observation of detail even though the setting caused a somewhat noisy picture.

The monitor faceplate was marked to show the corners and the true center of each edge of the reference raster. Linearity was adjusted by visually judging the best overall effect obtained from a pattern of squares.

Standard procedure was followed in setting up the system. The only camera controls adjusted during the test were the fine beam, target, brightness, and contrast. These took care of changes in object brightness. Sometimes the monitor brightness was changed slightly for better viewing, especially if the room lighting changed appreciably.

Photometer

The background brightness and the contrast of various targets were measured with a photometer which measured brightness (luminance) over the range from 3.43×10^{9} to 3.43×10^{-6} cd/m^2 (10^{9} to 10^{-6} ft-L) with an error of less than 5 percent of the reading. The investigation, however, was concerned primarily with small targets in the lower brightness ranges. A field of 6 minutes of arc with full-scale sensitivity of 0.343 cd/m^2 and also a 2 minute of arc field with a full-scale sensitivity of 3.43 cd/m^2 were used. The photometer could also be used as an illumination meter. This permitted the brightness of a source smaller than the field of measurement to be calculated if the illumination was measured in the dark.

Other Equipment

Figure 2 shows the arrangement of the equipment which also included a slide projector, three controllable diffused light sources, another projector for controlling background lighting, an 8- by 8-foot metal screen painted flat white, and a 70 mm camera for photographing the monitor. Accurate film readout equipment was used for measuring target locations on the film.

Data were taken in two ways, by photography and by direct viewing. The camera was placed far enough from the monitor so that, when the camera was focussed, the monitor raster (horizontal distance) was 5.08 cm wide on the camera film. A light meter was used to maintain nearly constant brightness on the monitor screen so that constant camera exposures could be made. Measurements of contrast and resolution were made by eye and depended on subjective rating by the observer to determine what was barely visible or what was barely resolvable. Two observations were made for each measurement, either by two observers (the authors) simultaneously or first by one observer and then the other. The observer sat with the monitor near eye level and usually within 3 feet.

RESOLUTION MEASUREMENTS

General Remarks

Resolution in television is a measure of the ability to delineate picture detail. Limiting resolution is usually expressed in terms of the maximum number of lines per picture height, which can be discriminated on a test chart (see ref. 2). In this paper the number of lines refers to the total number of alternate black and white lines of equal width, called TV lines. Resolution can be different for the horizontal and vertical directions on a television screen (ref. 1). With the equipment of this investigation, the horizontal resolution was about 2.4 times the vertical and was the only resolution measured.

Resolution can be determined with several types of charts, for example, the standard RETMA 1956 chart, the USAF resolution chart, and the frequency burst chart (fig. 3). The latter was used for this investigation for two reasons. First, because we wanted to determine whether limiting resolution could be measured quantitatively by displaying the video signal on an oscilloscope, and second, since horizontal resolution was the only concern, this simple chart gives a simple video signal that is easily correlated with the pattern. The chart produces frequency bursts for each group of lines and has corresponding numbers of TV lines when the chart is imaged so that the reference length occupies 83.9 percent of the horizontal raster. If the chart is imaged so that the reference length occupies a different percentage of the horizontal raster, the number of TV lines from each segment is inversely proportional to the fraction of the original horizontal raster length now occupied by the reference length. For example, if 41.95 percent of the raster is occupied by the reference length the number of TV lines is doubled from the values marked on the chart.

It was desired to measure the resolution for varying degrees of contrast and over a range of background light levels. Percent contrast is defined as $|B_s/B_b - 1| \times 100$ (ref. 3), where B_b and B_s are the brightness of the background and source, respectively. It should be noted that when contrast is measured, the larger area is considered the background. When the background is lighter, contrast is limited to 100 percent; however, when the background is darker, the contrast has no upper limit. Resolution charts generally have dark lines on a light background similar to the type in figure 3. Glass slides were made of the resolution chart covering the range from 7- to 98-percent contrast. As projection light is reduced, contrast remains constant; thus, a general brightness level for the background can be set by adjusting the voltage on the projection lamp. The projected image will have the same basic contrast at this light level.

Procedure

The optical focus of the 150 mm lens was set at the mark nearest that corresponding to the constant distance from the television camera to the screen, and the electrically driven vernier focus was adjusted for the best and sharpest picture on the monitor. Control unit settings of brightness, target, contrast, and fine beam were adjusted optimally as the background lighting was changed. The size of the resolution chart projected on the screen was adjusted by moving the projector to obtain the desired reference length on the monitor raster. As explained before, this changes the effective number of TV lines of each segment from the number marked on the chart; for example, 600 TV lines were obtained from the nominal 545 line segment. As a result of the technique used, the entire resolution chart may or may not appear on the monitor. For each data run of a particular resolution, the desired contrast slide was projected to the necessary size and the background brightness was decreased by the observer to the point where the lines as seen on the monitor were judged as just resolvable. The observer sat with the monitor near eye level within 3 feet. Two observations were made for each measurement by each of two observers.

Results and Discussion

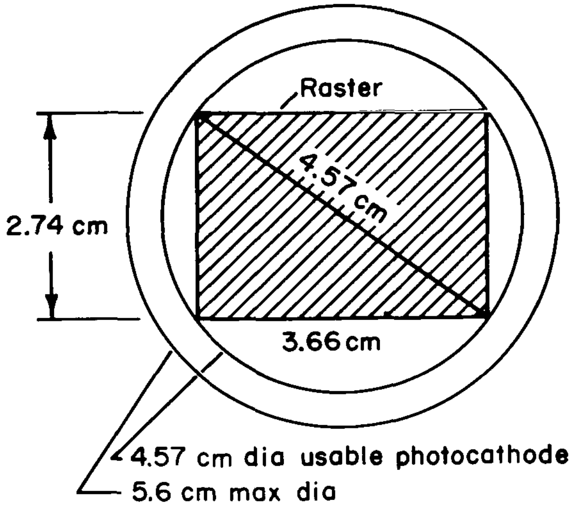
The direct results of resolution data are shown in figure 4. The data show that 850 TV lines is the maximum resolution that can be achieved with this system for bright, high contrast scenes. The lowest resolution measured was 100 TV lines. The 100-percent contrast point of this curve was obtained for a background brightness of 0.0343 cd/m^2 which, with the lens opening of f/16, corresponds to the background brightness of a dark night sky. That is, this brightness at f/16 gives a slightly lower illumination on the photocathode than would the illumination from the dark night sky with the lens wide open (f/1.8). This level of photocathode illumination is approximately 8.1×10^{-5} lm/m^2 (see appendix A for calculations). It will be noted that each curve approaches a condition where more light does not produce appreciably more resolution. This occurs approximately as the knee of the image orthicon tube characteristic is reached.

The formula in appendix A, which takes care of the lens aperture and transmission, reduces the curves of figure 4 to those shown in figure 5. The curves of figure 5 describe the basic resolution characteristics of the television system regardless of the lens used.

The calculations of appendix A were used to convert the resolution data expressed in terms of TV lines in figure 4 to angular resolution (solid line curves of fig. 6). Further calculations to show the maximum resolution achievable with the lens wide open at f/1.8 resulted in the dashed curves of figure 6. Also included as the dotted curve are data for the resolution of the human eye, taken from reference 3. The figure shows that with the lens at f/1.8 the television system will resolve considerably more than the unaided eye at brightness levels below 0.343 cd/m^2. At 0.0343 cd/m^2 the television is over 2-1/2 times better for 100-percent contrast targets, and with larger optics the angular resolution would be even better.

These various curves make it possible to determine the object contrast required for a particular resolution under various background lighting levels.

Resolution is usually given as the number of TV lines resolvable for raster height, as presented in figures 4 and 5. To compare this number with resolution achievable with film, it is convenient to express television



resolution in TV lines per mm on the photocathode where the usable size of the photocathode, as shown in the accompanying sketch, is the limiting factor. With the maximum resolution of 850 lines and the photocathode raster height of 2.74 cm, the photocathode resolution is calculated to be 31 TV lines per mm. This should be compared to the ability of motion picture film to resolve 110 TV lines per mm (ref. 1). The minimum separation that can be resolved on the photocathode is 0.0032 cm, or 0.072 percent of the usable diagonal. This permits the system resolution to be determined for any given set of optics.

There are three possible sources of error in these measurements. They are degradation of the television picture, errors associated with the object, and errors caused by the observer. A systematic study was made of these sources of error and a subjective analysis showed that the errors attributed to the first two sources were negligible.

The greatest source of error was the subjective means of determining limiting resolution. Factors such as eye fatigue, exposure of the eye to different lighting conditions (which determine its adaptation), and experience in making observations all affect the results. Rather than trying for the extreme in resolution, an attempt was made to standardize on the point at which lines were quite definitely separated, so rather than the standard 50-percent (ref. 4) chance of seeing separate images at limiting resolution, probably 80 to 90 percent was achieved. This, of course, means the measured "limiting resolution" is lower than that given in the standard (ref. 2). The actual settings were an average of what two observers felt was resolvable.

The measured resolution capability of the television system, under the conditions previously mentioned, is approximately 87 percent of the maximum capability of the image orthicon tube, as determined by extrapolation of manufacturer's data for similar type tubes. Thus the values of resolution presented represent those it is believed would be achieved with the actual use of this equipment.

MINIMUM PERCEPTIBLE CONTRAST

General Remarks

Contrast is a measure of the brightness of an object relative to its background. The lowest contrast that may be detected is called the minimum perceptible contrast and depends primarily on the size of the object and the background brightness. It will be recalled that percent contrast was defined as $|B_s/B_b - 1| \times 100$. This investigation was limited to conditions in which the spot was brighter than the background because normally objects in space are illuminated internally or by reflected sunlight. Thus, the contrast is not limited to 100 percent but can and did get much larger for the range of target sizes and background brightness used.

An attempt was made to measure quantitatively the minimum perceptible contrast of targets. The television video signal on an oscilloscope was examined visually; however, the combination of monitor and eye was more sensitive to low contrasts than the oscilloscope measurements. Thus, when the target signal was increased so that it could just be discerned on the oscilloscope, it was already visible to the observer watching the monitor screen.

The minimum perceptible contrast was measured for a series of spot sizes corresponding to subtended angles at the lens from 0.20 to 7.41 minutes of arc over a range of background light levels. The 85 mm television camera lens was set at f/16. The resulting spot sizes on the photocathode of the image orthicon were calculated (as in appendix B) and ranged from 2.62×10^{-3} to 2.04×10^{-2} cm. The background light levels were varied from 0.343 to 343 cd/m^2 at the scene, resulting in light levels of 8.75×10^{-4} to 8.75×10^{-1} lm/m^2 on the photocathode of the camera tube (see appendix A).

Small circular light spots were produced by target units. Figure 7 shows a disassembled target unit. Two independently controlled bulbs supplied the light that passed through two opal glass diffusers 3.2 mm thick and then through a hole in the face plate. A neutral density filter was placed between the pieces of opal glass when necessary to reduce the output light level a large amount. The neutral density filter allowed near rated voltage to be maintained on the bulbs to reduce changes of color temperature. The front of the target unit face plate was flat white to match the screen. Face plates with different sized holes were used to vary the size of the target spot. The part of the opal glass that contacted the face plate was sandblasted with a fine abrasive to reduce any specular reflections of external light.

For the calculation of low contrast conditions, a direct measurement of spot and background brightness was not feasible because of the limiting accuracy of the photometer (5 percent of the reading). Instead, a modification of the method used by Blackwell to determine low contrast (ref. 4) was used; that is, only the small difference in brightness between the spot and background was measured directly. First, the background brightness was set. Then one of the two independently controlled bulbs in the target unit brought the target spot to the same brightness as the background. The other bulb was then used to adjust the contrast of the target spot to the minimum perceptible contrast. Finally, both the first target bulb and the background illumination were turned off and the remaining brightness of the target spot was measured as the actual difference between the brightness of the background and the target spot. The contrast was then computed from the measured brightness levels.

The brightness of all spots was measured except the smallest (0.20 minute of arc) which had to be calculated from illumination measurements made with the photometer at a known distance from the target spot. The brightness level of this spot was adjusted by eye to match the background level. The error in making this adjustment should be slight because of the good contrast sensitivity of the eye (ref. 4) and the high contrast levels associated with the 0.20 minute of arc spot size.

Procedure

Two subjects were used to measure the minimum perceptible contrast of the small circular light spots. Each subject in turn watched the television monitor to determine when the target spot was barely visible while the other set the background brightness to the desired level and adjusted the spot brightness slowly in one direction. Rather than stare at the known position of the target image, the subjects deliberately looked away from the target image area and then scanned the area. This technique gave more consistent results than just staring at the known position of the image and trying to judge when the image was or was not present.

Minimum perceptible contrast measurements consisted in observing when a spot disappeared from the monitor as contrast was gradually reduced and also when it reappeared as contrast was gradually increased. The readings were generally close and the average was used in plotting the data.

Photometric measurements were made of the targets and the background. Since the fundamental characteristics of the television system were desired, these measurements were later converted to the photocathode of the television camera tube. The correction applied to the scene contrast measurements to convert them to photocathode image contrasts depends upon the transfer characteristics of the optical system. The contrast measurements of the scene are identical to those of the photocathode image, provided the optics involved merely reduce the scene proportionally and the light loss through the lens is uniform. On the other hand, distortion of a very small image, such as that caused by the resolution limitation of the optics, can drastically reduce the contrast of the image as compared to the scene.

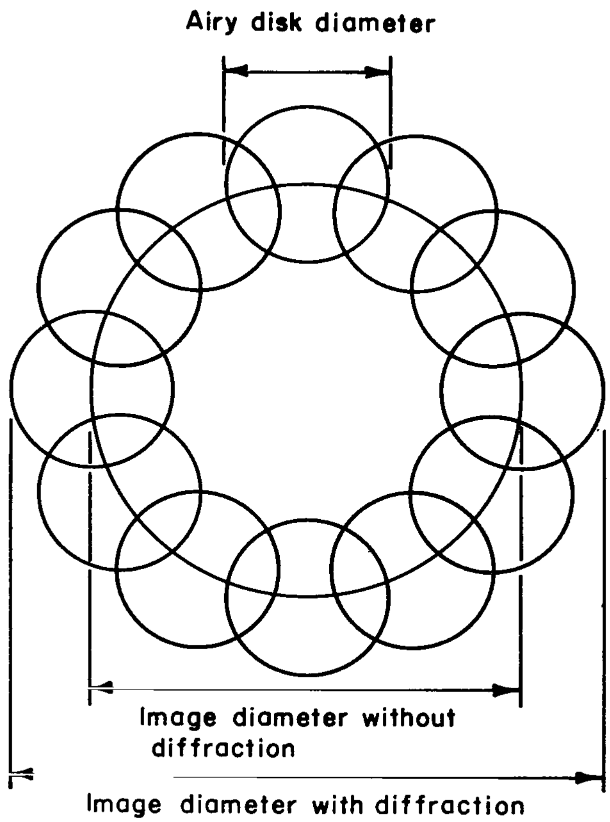
Results and Discussion

Minimum perceptible contrast data are plotted in figure 8 for targets subtending angles of 0.20, 0.93, 1.85, 3.71, and 7.41 minutes of arc, where the measured background brightness was converted to illumination on the photocathode by use of the formula in appendix A. It can be seen that the curves become steeper as the background illumination on the photocathode is decreased and also as the target size becomes smaller. The smallest target subtended an angle, approximately one-half the theoretical resolution of the lens at f/16 (0.43 minute of arc). This accounts for the very large scene contrasts for this spot, as will be explained later. The data in figure 8 were taken for the television system optimized for each spot size in turn. There is a factor of approximately 3 between the respective curves for the four larger target spots, whose diameters are in a ratio of 2. The upward trend of the two lowest curves at the higher illumination levels is attributed to the reduction in sensitivity of the television camera at high light levels.

The contrast threshold for the human eye to a 3.60 minute of arc spot has been plotted as a dashed curve on figure 8 for approximate comparison with the television response. The data for the eye, as found in reference 4, were modified, as explained later, for fair comparison with the full 5.6 cm lens aperture (f/1.5). While direct comparisons are impossible because of the different techniques, the data of reference 4 are the best available. It will be noted that the television system with full aperture is more sensitive than the eye until the light level approaches the upper operating limits of the television system.

Since the resolving power of the lens is limited, the contrast of the target spot at the scene is not the same as the contrast of the spot image on the photocathode. Figure 9 shows the minimum perceptible contrast of the image on the photocathode. The lowest contrast was 5 percent, corresponding to the 7.41 minute of arc target or to 0.020 cm on the photocathode. The curves of figure 9 have the same shape as those of figure 8 but the minimum perceptible contrast measured at the scene has been changed (by the method of calculation shown in appendix B) to give the theoretical contrast on the photocathode. As can be seen, these curves are all somewhat lower than the corresponding curves of figure 8 and have been brought closer together because the uppermost curve of figure 8 (0.20 minute of arc spot) has the greatest correction applied to it while the largest spot has the least correction. These calculated contrasts are 3 percent and 68 percent, respectively, of the measured values. The curves of figure 9 are separated by an average factor of approximately 2.

Minimum perceptible contrast measurements of the television system were obtained with a lens aperture of f/16 to avoid the difficulty of obtaining and measuring the very low light levels that would have accompanied measurements at the maximum lens aperture of f/1.5. For example, to obtain a photocathode illumination of 10.76 lm/m^2 (1 foot candle) at f/1.6 requires a scene brightness 100 times lower (the ratio of the f-numbers squared) than the scene brightness at f/16. However, using the lens at this high f-stop increases the size of the diffraction pattern and, in turn, affects the operating scene contrasts.



The adjacent sketch indicates the manner in which the geometrical image size is affected by the lens. It can be seen that the diameter of the image with lens diffraction equals the diameter of the image without diffraction plus the diameter of the Airy disk. For the particular lens used, good agreement was found between calculated and measured image size.

The contrast of the image on the photocathode is determined by the measured target spot contrast and the image size calculated as above. The larger area of the image with diffraction results in the image contrast being reduced from that of the object.

The image contrast for the same scene contrast would, therefore, be greater at f/1.5 than at f/16 because there would be less Airy disk distortion in the image at f/1.5. Thus, the scene contrast could be reduced as the lens is opened up and still maintain the same contrast on the photocathode of the television tube. The amount of reduction of the scene contrast when the lens is changed to f/1.5 would depend on the target size. For example, the scene contrast for the 0.20 minute of arc spot would be reduced to approximately 0.07 of the value on figure 8 while contrasts for the 3.71 minute of arc spot would be reduced to approximately 0.7 of its value. The fact that the 0.20 minute of arc spot would be resolved with the f/1.5 aperture accounts for the large change in the scene contrast, as mentioned previously. A detailed discussion of contrast and other visibility factors can be found in reference 5.

Some remarks are in order concerning the curve of the eye on figure 8. Data of figure 8 for the television system were obtained with an aperture of f/16 for convenience, but the television maximum capability with the available lens aperture of f/1.5 should be used for the fairest comparison with the eye. The reference data of the eye were given as a function of scene brightness. The brightness levels of these data, expressed in cd/m^2, were multiplied by 0.290 to convert them to corresponding photocathode illumination for the lens at f/1.5. The multiplication factor is composed of the conversion factor of the lens as given in appendix A (2.55×10^{-3} lm/m^2 at the photocathode per cd/m^2 at the scene, with the lens at f/16) and the additional term, $(16/1.5)^2 = 113.8$, necessary to account for the lens aperture change from f/16 to f/1.5.

During the initial tests one interesting fact came to light that had not been expected. When three different spot sizes (0.93, 1.85, 3.71 minutes of arc) were viewed with the television system and the spots adjusted to the same brightness (smallest spot easily seen), the spot images on the monitor were in approximately the same size relationship to each other as the spots on the screen; however, when the two larger spots were adjusted to give the same number of lumens as the smallest (i.e., the product of brightness and area for each spot is the same), then the spots all appeared the same size on the monitor. Furthermore, as the f-number of the lens was gradually increased, the monitor representation of all the spots decreased to the minimum size of approximately three scan lines and they then disappeared simultaneously. A partial explanation of this phenomenon was attempted. The spot areas were in a ratio of 1:4:16. Hence, for the same number of lumens per spot their brightness was in the ratio of 1:1/4:1/16. Contrast is defined as $|B_s/B_b - 1|$. For readily discernible spots B_s/B_b is considerably greater than 1 and contrast can be approximated at B_s/B_b. As the lens f-number is increased, this ratio is approximately maintained at the photocathode; so when the spots simultaneously disappear, their minimum perceptible contrast should be in the ratio of 1:1/4:1/16. This is approximately checked by the data of figure 8 where the minimum perceptible contrast for these three spots is roughly in the ratio of 1:1/3:1/9. No further investigation of the seeming similarity of spot size was conducted.

ACCURACY

General Remarks

If landmarks or points, such as stars, are displayed on a television monitor the question immediately arises as to how accurately their angular distance apart can be determined. To determine the inherent accuracy of the system a measurement calibration procedure was developed to permit compensation for overall system nonlinearity from the scene to the monitor presentation.

The accuracy of a television measurement system is affected by the various optical transfer characteristics, the stability and linearity of electronic circuits, the readout method, size and brightness of the source, and the television adjustments.

There are several readout methods that could be used. A direct measurement of distance on the monitor screen gives particularly poor accuracy because of large parallex effects. Electronic readout schemes may have serious error sources associated with using such complex equipment. For this investigation the monitor screen was photographed and then the film was read with precision optical equipment. The film readout method was chosen as being easy, direct, and accurate.

Procedure

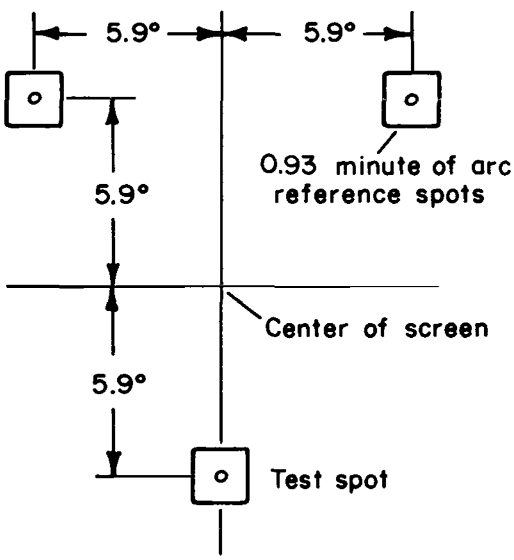
All measurements were made with the 85 mm television lens set at f/16. In order to determine accuracy the target units previously used for contrast measurements were precisely located on a reference grid and the monitor screen was photographed. All monitor photographs were made with the camera described in the experimental equipment section. Distances between spots on the film were measured to 0.05 percent of the field of view. Measurements were first made to determine the effects of spot size, spot brightness, background brightness, and television adjustments on accuracy. Further measurements established correction data for image position on the monitor screen.

Results and Discussion

In order to obtain the highest overall measurement accuracy it was necessary to establish both horizontal and vertical angular scale factors. The angular scale factor may be defined as the angular separation between points on the object screen for each centimeter on the film. Throughout this discussion the figures given apply only to the particular lens used (85 mm). Any other lens will have a different scale factor. To determine the scale factor required, first, a measurement of the film position of several targets whose actual angular separation was known and, second, a correction calibration for position distortion over the entire monitor screen. When these conditions were satisfied an overall angular error of 0.27 percent in the measurement of about 12-1/2° was obtained. When only one pair of known points appeared in the field so that, for example, only a horizontal angular calibration measurement could be made and no position correction calibration for the monitor screen was used, the error was about 7 percent of the measured separation. Finally, when no known targets were viewed but a position correction calibration was available the error depended strongly on the particular combination of television system adjustments but was generally less than 1.0 percent of the measured value of about 12-1/2°. The various factors that affect measurement accuracy were investigated and the results are presented and discussed in the following sections.

1. Target size and brightness.

It was found that changing the size of a spot over the range from 0.20 to 7.41 minutes of arc did not cause any systematic error in determining the location of the spot; that is, the standard deviation of the angular distance between the two 0.93 minute of arc reference spots, located on the object screen (see sketch), was on the average, as much or more than the standard deviation of the distance from each reference spot to the test spot whose size was varied. The largest standard deviation of this set of measurements was 2.85 minutes of arc or 0.36 percent of the angular separation. During these measurements the brightness of all target spots was adjusted so that they could easily be seen on the television monitor. If the angular scale factor were determined from the two known reference spots and if the separation between a reference spot and the test spot were calculated from the measured film distance and the scale factor, an error of 7 percent of the true separation could result from the position distortion on the monitor, as will be discussed later.



A 1.85 minute of arc test spot was used with the two 0.93 minute of arc reference spots to find the effect of changing spot brightness on accuracy of location. The contrast of the test spot was varied from minimum perceptible contrast to 2000 times this value. Again, increasing brightness caused no systematic error, even though the image on the monitor bloomed considerably. The largest standard deviation obtained was 1.75 minutes of arc or 0.22 percent of the distance measured.

Measurements were made on several photographs taken for each set of the above data. The main readout errors occur in positioning the cross wires of the film reader to the centroid of each spot. The sharpness of the image of the target spot on the film affects how well the cross wires can be set. For five readings of a fixed angular distance there was a standard deviation of 0.58 minutes of arc or 0.085 percent of the average reading.

2. Television system adjustments.

The variation in angle readout with television adjustment (target and fine beam only) is established by the data presented in figure 10. This figure shows the effect of changing either of the adjustments as the other is kept fixed for 171 cd/m² background brightness. The target setting had the greater effect and could change the angle readout by as much as 0.9 percent of the reading, the fine beam setting by about 0.5 percent of the reading. The range of these adjustments covered what could conceivably be called a usable picture on the monitor.

The curves of figure 11 show the effect of two types of adjustment of the television system as the background brightness was varied. The dashed line, labeled "rough television adjustment," was obtained while the effect of size was being determined. The graph is for a 1.85 minute of arc diameter spot but data for other size spots follow this curve very closely. The other curve, shown as a solid line labeled "fine television adjustment," was obtained while finding the effect of contrast. If "fine" television adjustments are made for the scene, the angle readout increases as shown in figure 11 as the background brightness increases. This means that if no direct scale factor can be established from known points in the field of view, the accuracy will be limited to the order of 1 percent of the reading, although corrections could be made if the background brightness were known.

The reason for labeling the curves of figure 11 as rough and fine adjustment is as follows. While the data were being taken on the effect of size (dashed curve), the brightness was set so that the spot was easily visible against the background. Then the television target and fine beam dials were adjusted to sharpen the monitor image. This did not require precise setting of the controls. While data were being taken on the effect of contrast (solid curve), the target spot brightness was set near the minimum perceptible contrast for each level of background brightness. Then the television adjustments needed to get the best picture on the monitor did require critical or "fine" setting of the target and fine beam dials.

There are two adjustments for focus on the television camera. One focuses the lens, as on any camera, and the other positions the image orthicon tube along its axis with respect to the lens. This is done by an electric motor through a rack and gear arrangement. Normally the lens focus is set to the estimated object distance and then the electrical focus switch that controls the motor is jogged until the best focus is obtained, as judged from the picture on the monitor. The effect on angle readout as electrical focus is deliberately changed, as measured from its "best" focus position, is shown in figure 12. The curve shows a 1.14-percent change of angle readout for each mm change of distance between the image orthicon tube and the lens. Two experimenters, each making six settings of the best electrical focus by watching the monitor, had an average deviation of 0.482 mm from the reference position. This corresponds to an average change in the angle readout of 0.55 percent of the reading.

3. Operating stability.

A factor that affects angular scale factor is the line voltage supplying the system. This effect was measured by taking pictures of two fixed reference spots as the voltage to the television system was varied. With the measured image distance on the film at 120 volts as a standard, the image distance increased as the voltage was either increased or decreased from this level. The increase amounted to 2.5 percent of the measured value for 130 volts and about 0.7 percent of the measured value for 110 volts.

A test was made to find the overall stability of the system. Power was turned on and the system warmed up for 2 hours. A picture was taken of the two fixed reference spots. Five hours later another picture was taken. This was repeated for 3 days. Readout of these films showed a maximum angular variation of 0.56 percent from the average measured angle.

4. Position correction calibration.

Figure 13 shows representative horizontal and vertical position correction calibration curves which are a measure of system distortion. Both horizontal (X) and vertical (Y) angular distances from the center of the field of view are given in minutes of arc subtended at the lens. Positive X and Y directions are to the right and up from the center of the screen, respectively. The horizontal corrections measured varied from about +36 minutes of arc to -2.5 minutes of arc while vertical corrections varied from about +4.6 minutes of arc to -17.5 minutes of arc. These corrections must be added algebraically to the angular values actually measured on the film to obtain the corrected position.

As an example of the use of these curves, consider the horizontal correction for a point having measured horizontal and vertical coordinates of 237 and 177.7 minutes of arc, respectively. From the top curve of figure 13, labeled for 177.7 minute of arc vertical position, for the horizontal distance of 237 minutes of arc, a correction of +10 minutes of arc is read on the graph. The corrected value of the horizontal coordinate is then 247 minutes of arc.

A family of curves similar to those of figure 13 was obtained to cover the central area of the screen, as indicated on figure 14. The reference grid established on the object screen is based on a 177.7 minute of arc spacing, both vertically and horizontally. Figure 14 shows the reference grid (with straight strings crossing the reference dots on the object screen to make it more visible) and the extent of overall system nonlinear distortion as indicated on the monitor screen. The horizontal and vertical angular scale factors were determined from the best straight lines through plots of distance measured on the film versus the angle subtended from the center of the screen to the reference points on the horizontal and vertical center lines, respectively. By additional tests it was found that interpolation between the reference points anywhere in the field gave as good results as attempting a calibration correction using intermediate reference points on the screen.

5. Verification of accuracy.

Two tests were made to establish the validity of the correction procedure. The first test used two parallel diagonal lines, one subtending about 250 and the other about 1280 minutes of arc. These lines were marked by targets placed over grid reference points for each end point of the lines. The second test used four targets arranged randomly but in the general form of a triangle with one point near the center of the triangle and the screen. The angles subtended by these lines ranged from 350 to 900 minutes of arc.

Data read from a photograph of the television monitor for the horizontal and vertical coordinates of each end point of the two lines of the first test were corrected by use of curves similar to those of figure 13. Standard scale factors, determined as in the preceding section, were used to compute the angular coordinates of each point from the center of the screen. The angular measure of each line was then calculated. When a comparison was made between the calculated length and the length measured directly, the maximum error amounted to 1.1 percent of the actual length. However, if the distance of either line was assumed to be known and was used to determine the scale factors for the computation, then the error was less than 0.1 percent of the actual length for the other line.

A similar procedure was followed in determining the various angular distances of the triangular configuration. The maximum error in distance using the standard scale factors was 0.63 percent of the true length. Using the best scale factors from assumed knowledge of one of the distances gave a maximum error of 0.27 percent of the true length for any other distance.

All the factors discussed may interact and so produce changes larger or smaller than any one alone. If greatest accuracy is desired, it is apparent that calibration must be obtained for the particular television adjustments, for the electrical and optical focus actually used, and for the scale factors existing when the data are taken. In addition, corrections must be made to take care of distortions over the field of interest. As explained in this section measurement errors can be reduced to only 4 percent of what they otherwise might be by use of corrections and proper scale factors.

CONCLUDING REMARKS

Under suitable conditions a television system can be used as an aid to the human eye to make navigational measurements of a 12-1/2° angular distance to an accuracy of 99.73 percent. Before a television system can be used to measure objects it must display them on the monitor as resolvable objects. The capability of the television system to display objects under various lighting conditions and for certain type targets was established. Although the results presented apply only to the equipment and measurement methods used, they generally show the factors to be considered and their trends. The technique is general and may be applied to any television equipment. The conditions of evaluation were made as realistic as possible.

With the standard TV lens used, the television system can provide the human observer better resolution and contrast discrimination than the unaided eye. The television monitor provides a more sensitive target detection indicator than direct examination of the video signal.

The technique used for measuring low contrast and the method for calculating the actual contrast on the photocathode (for high quality optics) are applicable to work of this type.

The basic approach of using a correction procedure is well suited to making measurements with a television system. For maximum measurement accuracy it is also necessary to obtain a calibration from the field of view to establish the angular scale factors for both coordinate axes. Once the objects are displayed their size and brightness have negligible effect on measurement accuracy. The accuracy was achieved with an 85 mm lens that had 23.6° field of view. Similar accuracy should be possible with good quality lenses, regardless of field of view.

The data for a television system can be used for any specific application of television to a measurement system. Optical transfer characteristics can be combined with the measured television characteristics to establish an overall system capability for given or assumed lighting and contrast of particular targets.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Dec. 23, 1965

APPENDIX A

SYMBOLS AND RESOLUTION CALCULATIONS

SYMBOLS

A	area, cm^2
B	brightness (luminance), cd/m^2
C	contrast
D	diameter, cm
E	illumination, lm/m^2
F	light flux, lm
FL	focal length, cm
f#	f-number of lens, FL/D
I	light intensity, candela (cd)
L	lens to object distance, cm
M	magnification to get the number of TV lines marked on the resolution pattern
m	magnification of lens
N	number of TV lines resolved
R	reflectance of surface
S	space of 1 TV line, cm
T	lens transmission
α	angle between normal to surface and line of sight, subscript determines unit
θ	angle between objects that can be resolved, subscript determines unit
λ	wavelength of light, cm

Subscripts

a	Airy disk
b	background or scene
bi	background of the image
c	central
i	image
l	lens
m	minute of arc
o	object
pc	photocathode
r	radian
s	source (spot)
sc	screen
si	source image (spot image)
sic	central portion of source image

RESOLUTION

Relationship Between Background Brightness and Photocathode Illumination

The following formula is used to calculate photocathode illumination for the two television lenses 521 cm away from the scene and set at f/16

$$E_{pc} = \frac{B_b T \pi}{4(f\#)^2(1 + m)^2}$$

For the 150 mm lens the transmission T was measured to be 0.81; m equals image size divided by object size, or lens focal length divided by object distance (521 cm), giving approximately 0.029. Substituting

$$E_{pc} = \frac{\pi \times 1.81 B_b}{4(16)^2(1.029)^2} = 2.35\times10^{-3}\ B_b$$

For the 85 mm lens with a measured transmission of 0.88 the corresponding photocathode illumination is $2.55\times10^{-3}\ B_b$.

Comparison of Illumination for Two Conditions

Dark night sky.- Brightness of dark night sky equals 4.42×10^{-4} cd/m^2 (1.29×10^{-4} ft-L). Photocathode illumination from dark night sky with 150 mm lens set at f/1.8, E_{pc_A}:

$$E_{pc_A} = \frac{4.42\times10^{-4}\ \pi\ 0.81}{4(1.8)^2(1.029)^2} = 8.20\times10^{-5}\ \frac{\mathrm{lm}}{\mathrm{m}^2}$$

Low brightness test condition.- Background brightness, B_b, equals 0.034 cd/m^2 (0.01 ft-L). Photocathode illumination from low brightness test condition with 150 mm lens set at f/16, E_{pc_B}:

$$E_{pc_B} = 2.35\times10^{-3}\times0.034 = 8.06\times10^{-5}\ \frac{\mathrm{lm}}{\mathrm{m}^2}$$

Angular Resolution From the Projected Resolution Chart

To determine the resolution in minutes of arc at the lens from the projected chart marked in TV lines, the following calculations are made.

$$\theta_r = \frac{S}{L}$$

1 minute of arc = 2.91×10^{-4} radian and L = 521 cm.

$$\theta_m = \frac{S}{521\times2.91\times10^{-4}}$$

but S = 19.05/N on the original chart 19.05 cm high. $S_{sc} = (19.05/N) \times M$ and M is 4.92 for our experimental setup

$$\theta_m = \frac{19.05\times4.92}{N\times521\times2.91\times10^{-4}} = \frac{618}{N}$$

For example, 100 TV lines resolved has an angular resolution of 6.18 minutes of arc under the specified conditions.

APPENDIX B

MINIMUM PERCEPTIBLE CONTRAST FORMULAS AND CALCULATIONS

IMAGE SIZE ON PHOTOCATHODE

For all symbols see appendix A.

For a lens

$$\theta_r = \frac{1.22\lambda}{D_l}$$

an average light wavelength, λ, of 5460×10^{-8} cm was used. For an 85 mm lens at f/16

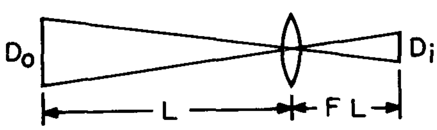
$$D_l = \frac{FL}{f\#} = \frac{8.5}{16} = 0.53 \text{ cm}$$

and

$$\theta_r = \frac{1.22 \times 5460 \times 10^{-8}}{0.53} = 1.26 \times 10^{-4} \text{ rad}$$

A small angle approximation for the size of the Airy disk, D_a, is:

$$D_a = 2FL\,\theta_r = 2 \times 8.5 \times 1.26 \times 10^{-4} = 2.13 \times 10^{-3} \text{ cm}$$



From the adjacent sketch the magnification, m, for $L = 589.3$ cm is seen to be:

$$m = \frac{D_i}{D_o} = \frac{FL}{L} = \frac{8.5}{589.3} = 1.44 \times 10^{-2}$$

For a perfect lens the image size is equal to the object size times the magnification. Actually, the diameter of the Airy disk for the lens at f/16 must be added to get the calculated image size; thus,

$$D_i = mD_o + D_a$$

For $D_o = 0.0343$ cm , $D_i = 1.44 \times 10^{-2} \times 0.0343 + 2.13 \times 10^{-3} = 2.62 \times 10^{-3}$ cm. The subtended angle , 2α, of the 0.0343 cm target spot is:

$$2\alpha_r = \frac{0.0343}{589.3} \qquad 2\alpha_m = \frac{0.0343}{589.3 \times 2.91 \times 10^{-4}} = 0.20 \text{ minute of arc}$$

The calculated image sizes and subtended angles of the target spots are:

Object diameter, cm	Subtended angle of target spots, minute of arc	Calculated image diameter, cm
0.0343	0.20	2.62×10^{-3}
.159	.93	4.42×10^{-3}
.318	1.85	6.71×10^{-3}
.636	3.71	1.13×10^{-2}
1.27	7.41	2.04×10^{-2}

RELATIONSHIP BETWEEN OBJECT CONTRAST AND RESULTANT IMAGE CONTRAST

A formula will be developed for the contrast of the image on the television photocathode, working from the measured object contrast and the various known distances and constants for the experiment.

First, find the illumination in the target image. Assume the target spot can be treated as a point source at the distance used. Then,

$$I_s = \frac{B_s A_s \cos \alpha_r}{10^4} \tag{B1}$$

Illumination of the lens, E_l, by the spot is found by

$$E_l = \frac{I_s \, 10^4}{L^2} \tag{B2}$$

Total flux into the lens is

$$F_l = \frac{E_l A_l}{10^4} \tag{B3}$$

The lens transmission, T, decreases the entering flux to that found in the spot image, F_{si}, and the central spot of the Airy disk contains only 84.8 percent of the light in the total image. Thus,

$$F_{sic} = 0.848 \, TF_l \tag{B4}$$

$$E_{sic} = \frac{0.848 \times TF_l \times 10^4}{A_i} \tag{B5}$$

When equations (B1), (B2), and (B3) are substituted into equation (B5) and $\alpha_r = 0$ is used

$$E_{sic} = \frac{0.848 \, TA_s A_l B_s}{L^2 A_i} \tag{B6}$$

The illumination of the background on the image plane, E_{bi}, as previously given in appendix A but neglecting m, is

$$E_{bi} = \frac{TB_b \pi}{4(f\#)^2} \tag{B7}$$

The formula for contrast is

$$C = \frac{B_s - B_b}{B_b} \tag{B8}$$

However, the brightness readings on the photocathode (image plane of lens) are not known. It is known that $B = E \times R$, and if the reflectance, R, of the photocathode is uniform, the formula for contrast on the image plane becomes

$$C_i = \frac{E_{sic} - E_{bi}}{E_{bi}} \tag{B9}$$

Substituting equations (B6) and (B7) into equation (B9) and simplifying, we find

$$C_i = \frac{0.848 \times 4(f\#)^2 A_l A_s B_s}{\pi L^2 A_i B_b} - 1 \tag{B10}$$

From equation (B8)

$$B_s = (C_o + 1)B_b \tag{B11}$$

and inserting this in equation (B10)

$$C_i = \frac{0.848 \times 4(f\#)^2 A_l A_s (C_o + 1)}{\pi L^2 A_i} - 1 \tag{B12}$$

Putting in the known values of $A_l = 0.221$, $f\# = 16$, and $L = 589.3$

$$C_i = 1.76 \times 10^{-4} (C_o + 1) \frac{A_s}{A_i} - 1 \tag{B13}$$

When the spot diameters and the corresponding calculated image diameter are used to compute the respective areas, the resulting equations used to reduce the data for each spot size are

$$C_{i(0.0343)} = 0.0302(C_o + 1) - 1 \qquad C_{i(0.318)} = 0.394(C_o + 1) - 1$$

$$C_{i(0.159)} = 0.227(C_o + 1) - 1 \qquad C_{i(0.636)} = 0.556(C_o + 1) - 1$$

$$C_{i(1.27)} = 0.679(C_o + 1) - 1$$

REFERENCES

1. Fink, Donald G.: Television Engineering. Second ed., McGraw-Hill Book Co., Inc., 1952.

2. Standards Committee: IRE Standards on Video Techniques: Measurement of Resolution of Camera Systems, 1961. Proc. IRE, vol. 49, no. 2, March 1961, pp. 599-602.

3. Anon.: IES Lighting Handbook. Third ed., Illuminating Engineering Society, 1962 (c1959).

4. Blackwell, H. Richard: Contrast Thresholds of the Human Eye. J. Opt. Soc. Am., vol. 36, no. 11, Nov. 1946, pp. 624-642.

5. Duntley, Seibert Q.; Gordon, Jacqueline I.; Taylor, John H.; White, Carroll T.; Boileau, Almerian R.; Tyler, John E.; Austin, Roswell W.; and Harris, James L.: Visibility. Applied Optics, vol. 3, no. 5, May 1964, p. 549.

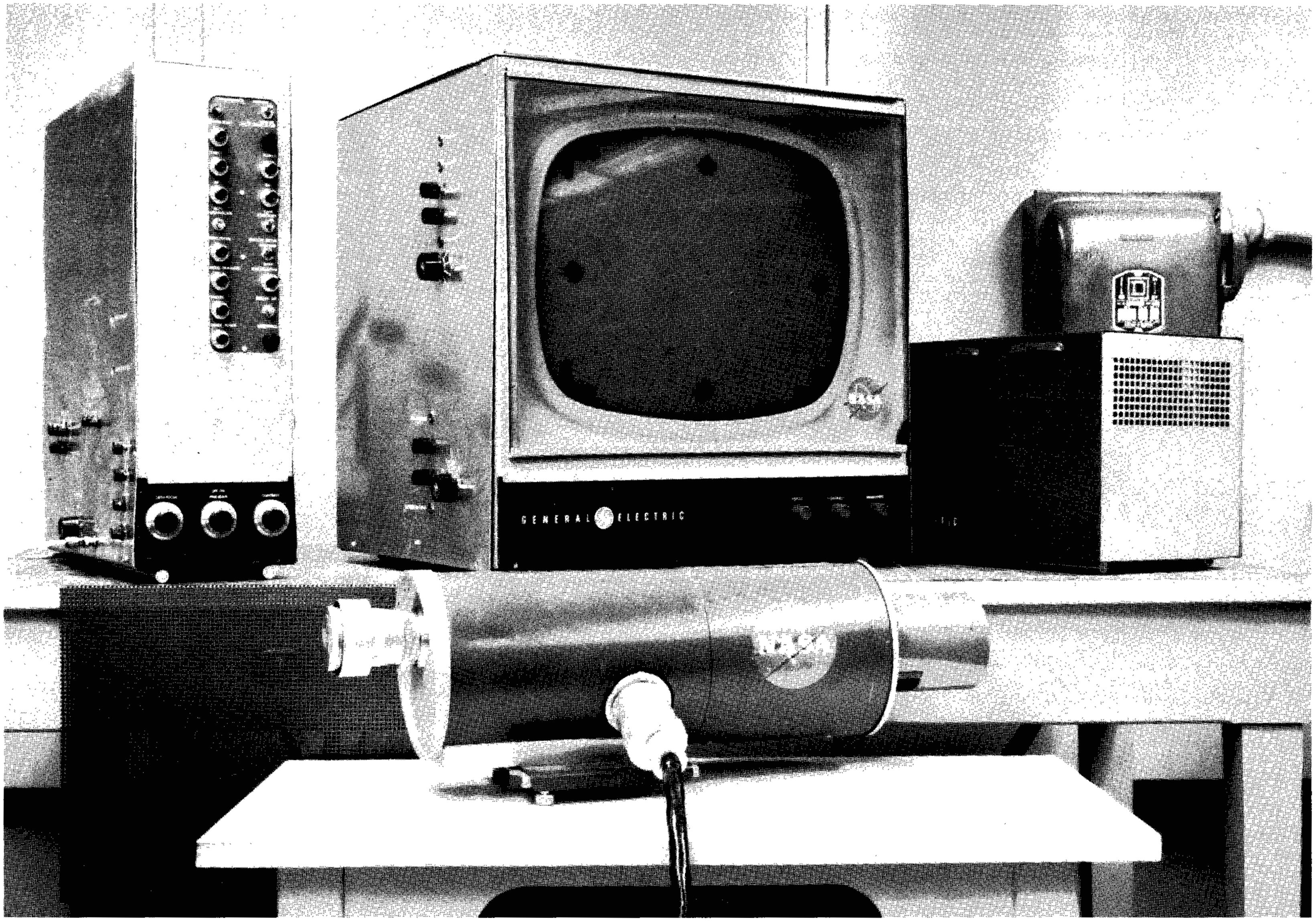
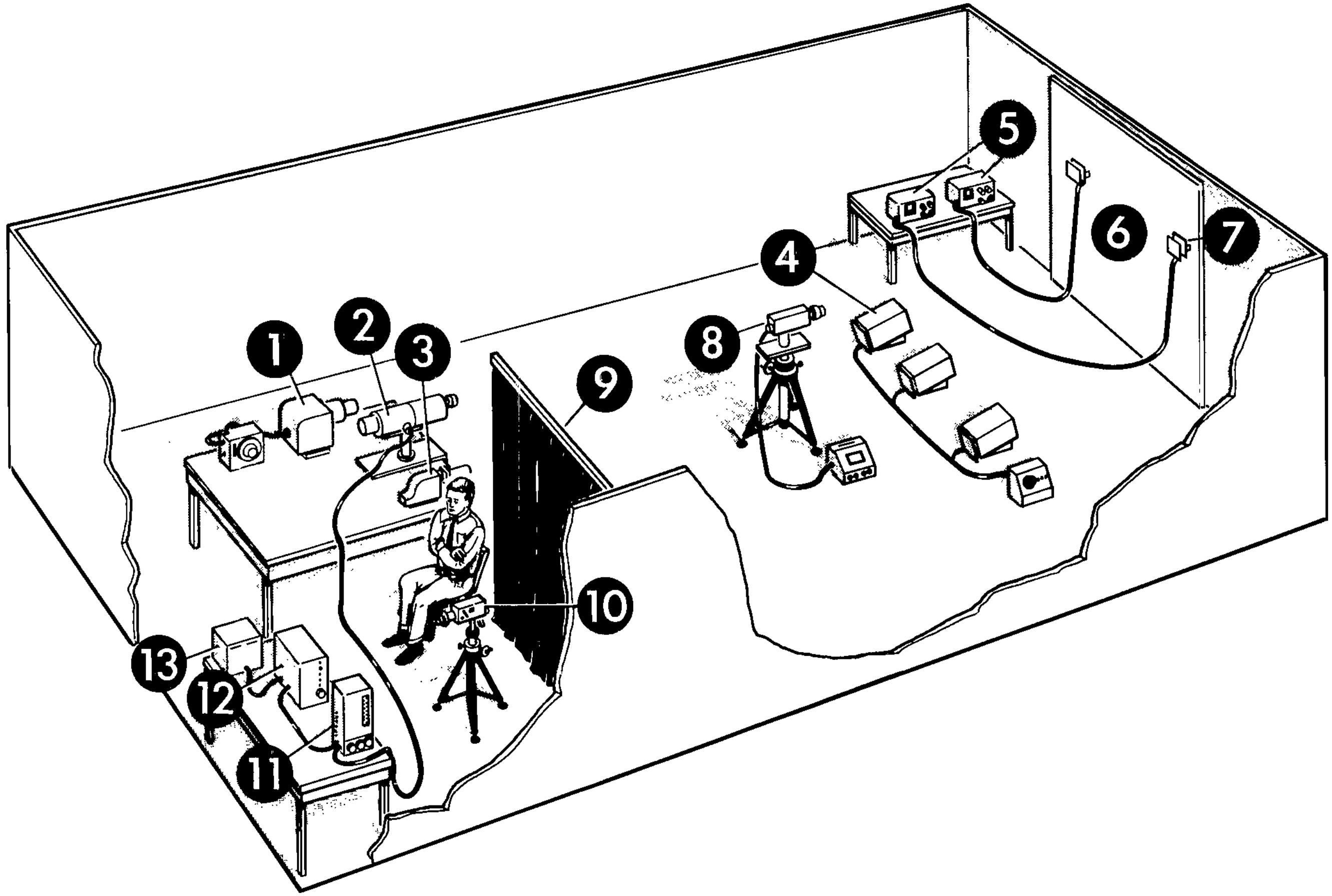


Figure 1.- Components of television system.

A-33963



1. Slide projector with intensity control
2. Television camera
3. Background lighting projector
4. Light sources and control
5. Power supply
6. Screen
7. Target unit
8. Photometer
9. Light shield
10. Photographic camera
11. Television control unit
12. Television monitor
13. Television power supply

Figure 2.- Laboratory arrangement.

A-35562

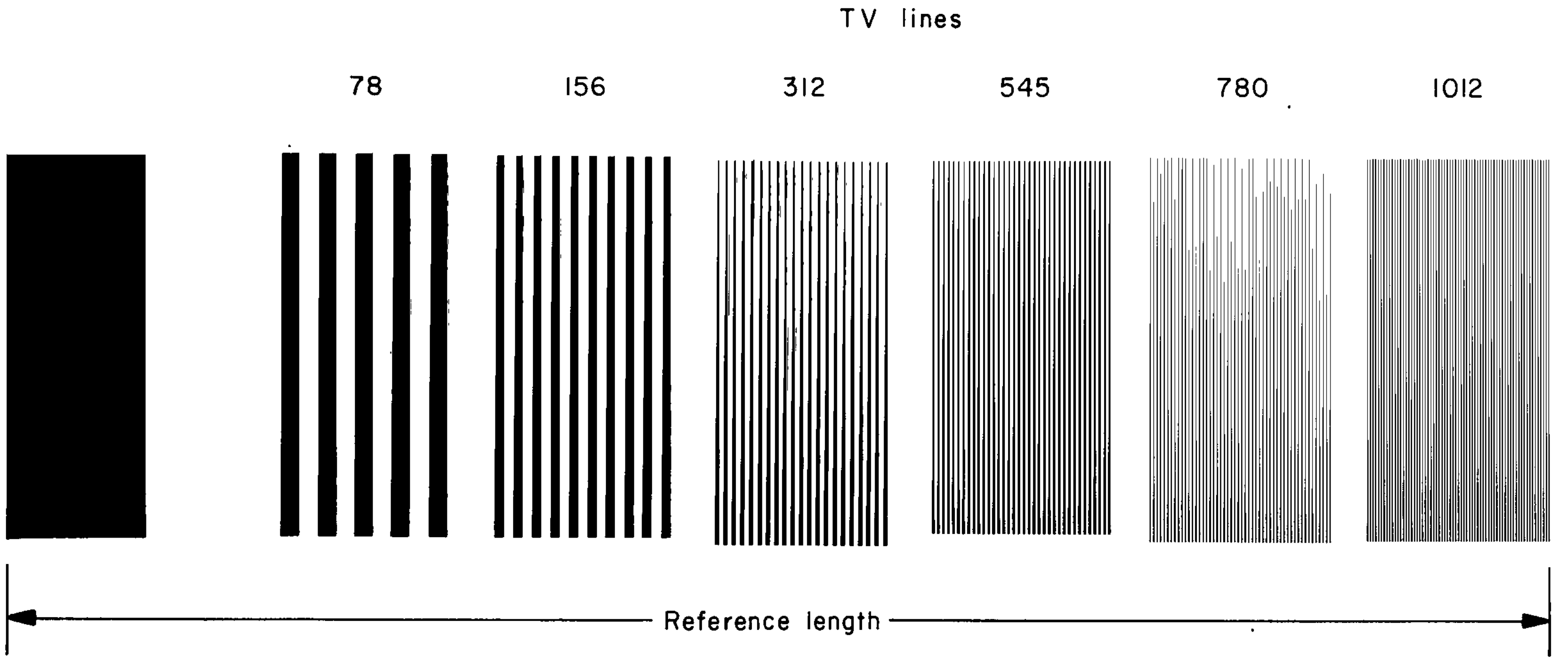


Figure 3.- Resolution chart used.

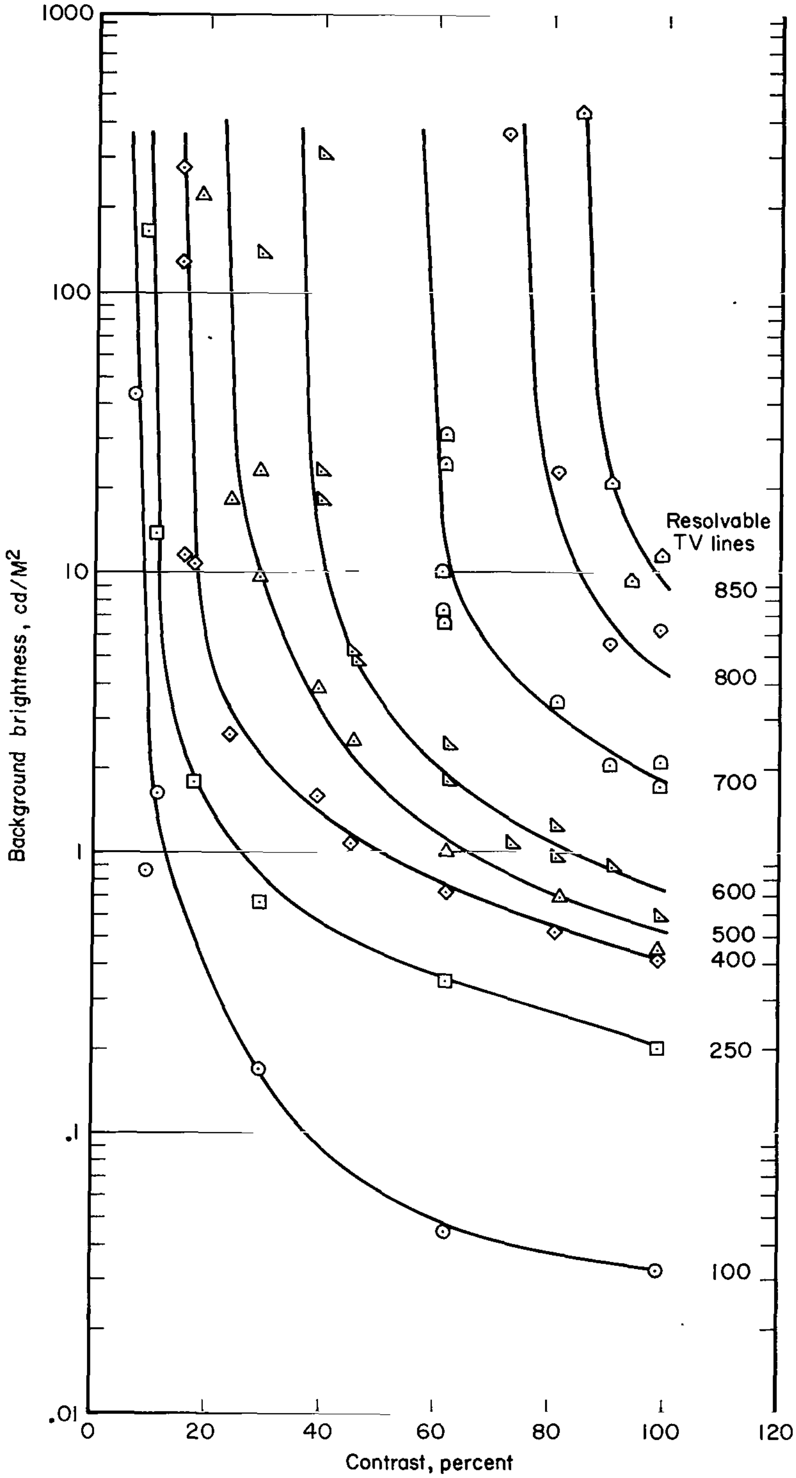


Figure 4.- TV lines resolvable on the monitor for various contrasts under different background brightnesses. Optics: 150 mm lens set at f/16.

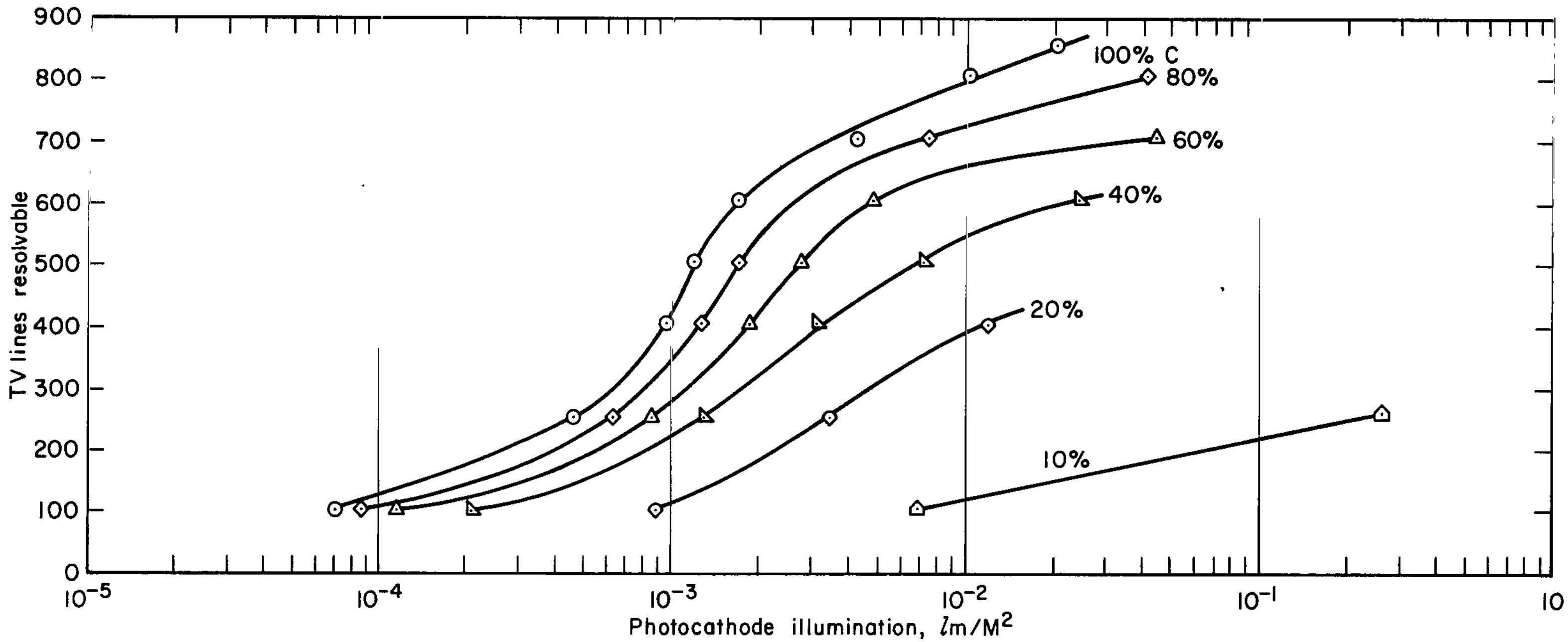


Figure 5.- TV lines resolvable on the monitor for various contrasts under different illuminations.

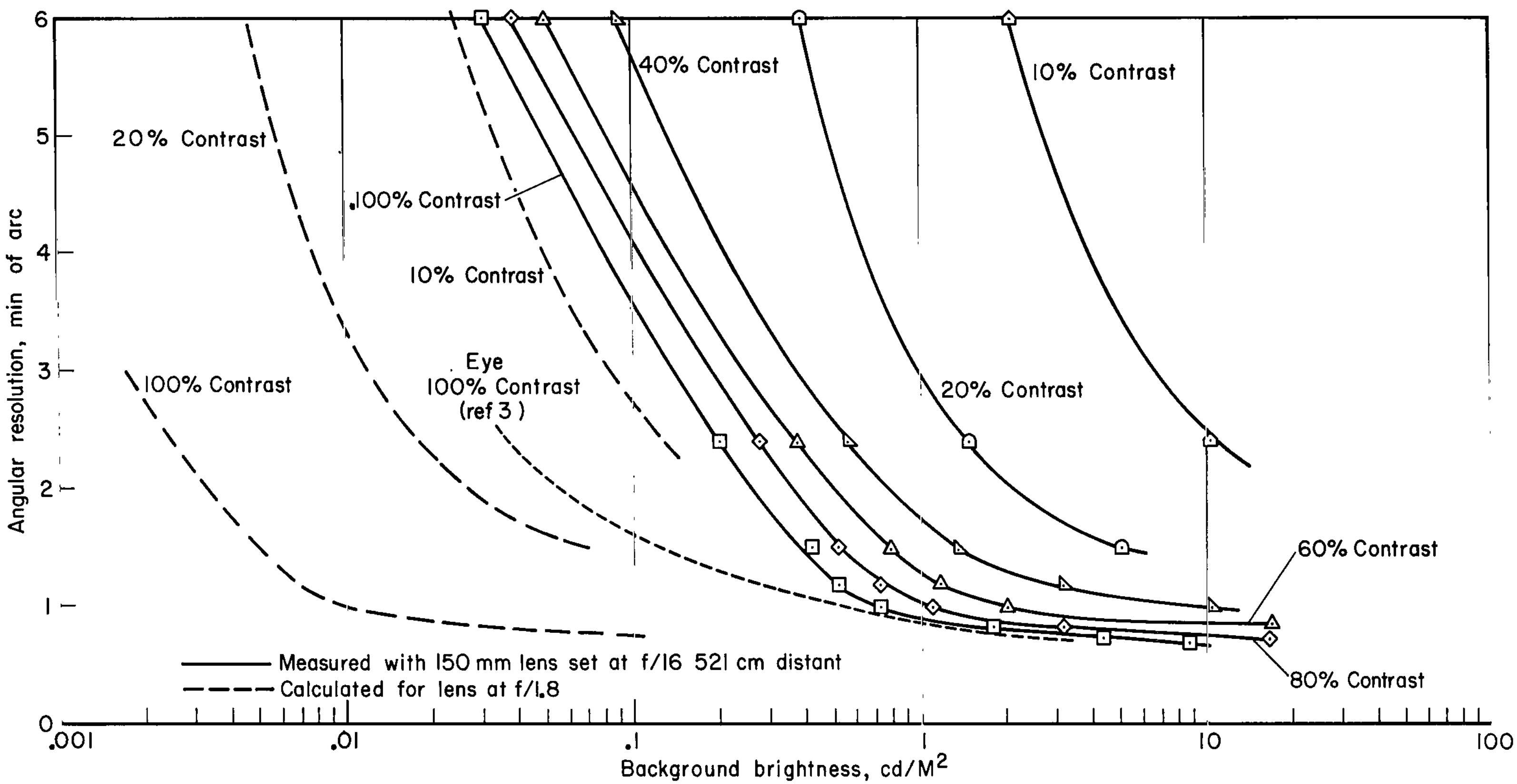
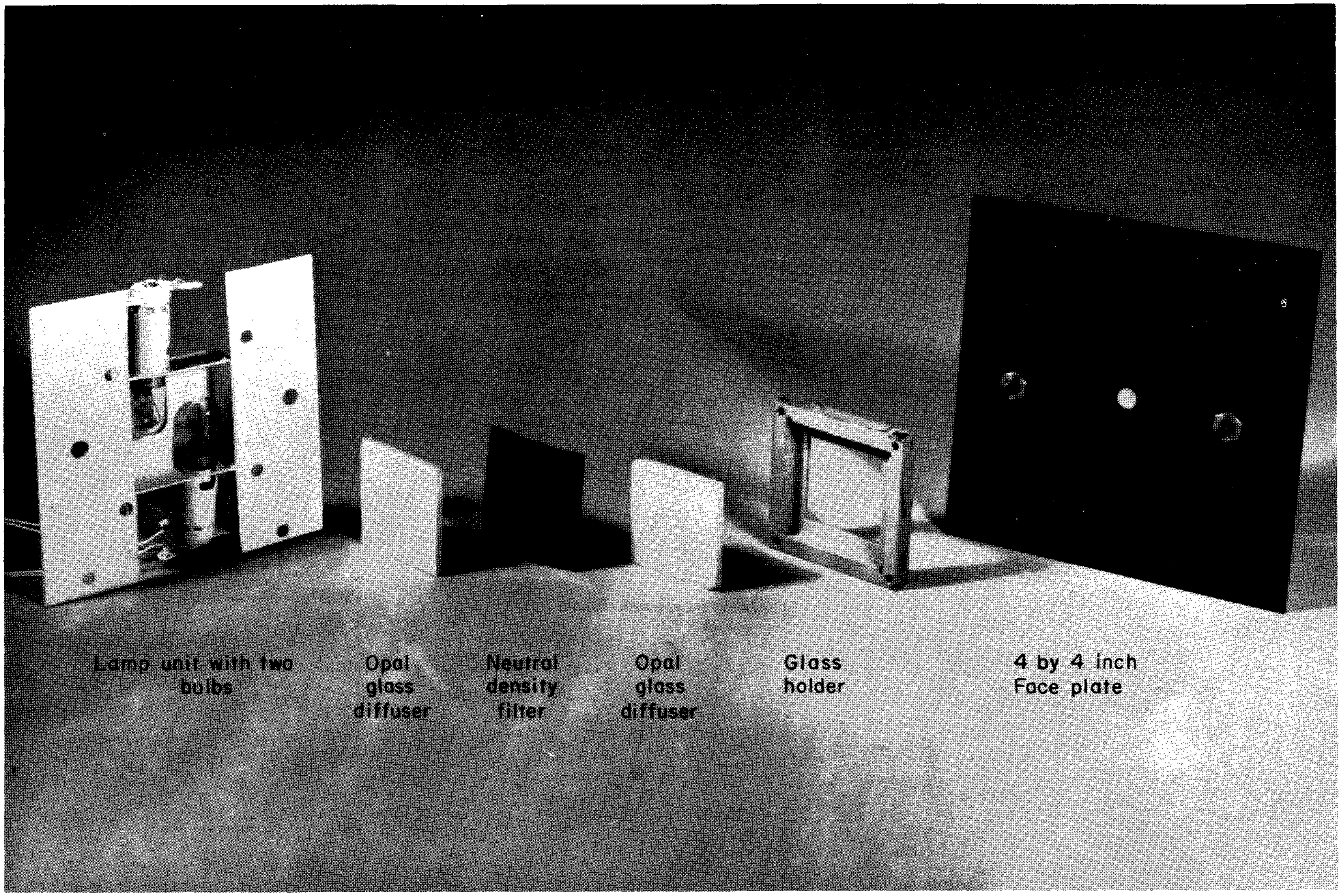


Figure 6.- Angular resolution for television system.



A-33964.1

Figure 7.- Components of target unit.

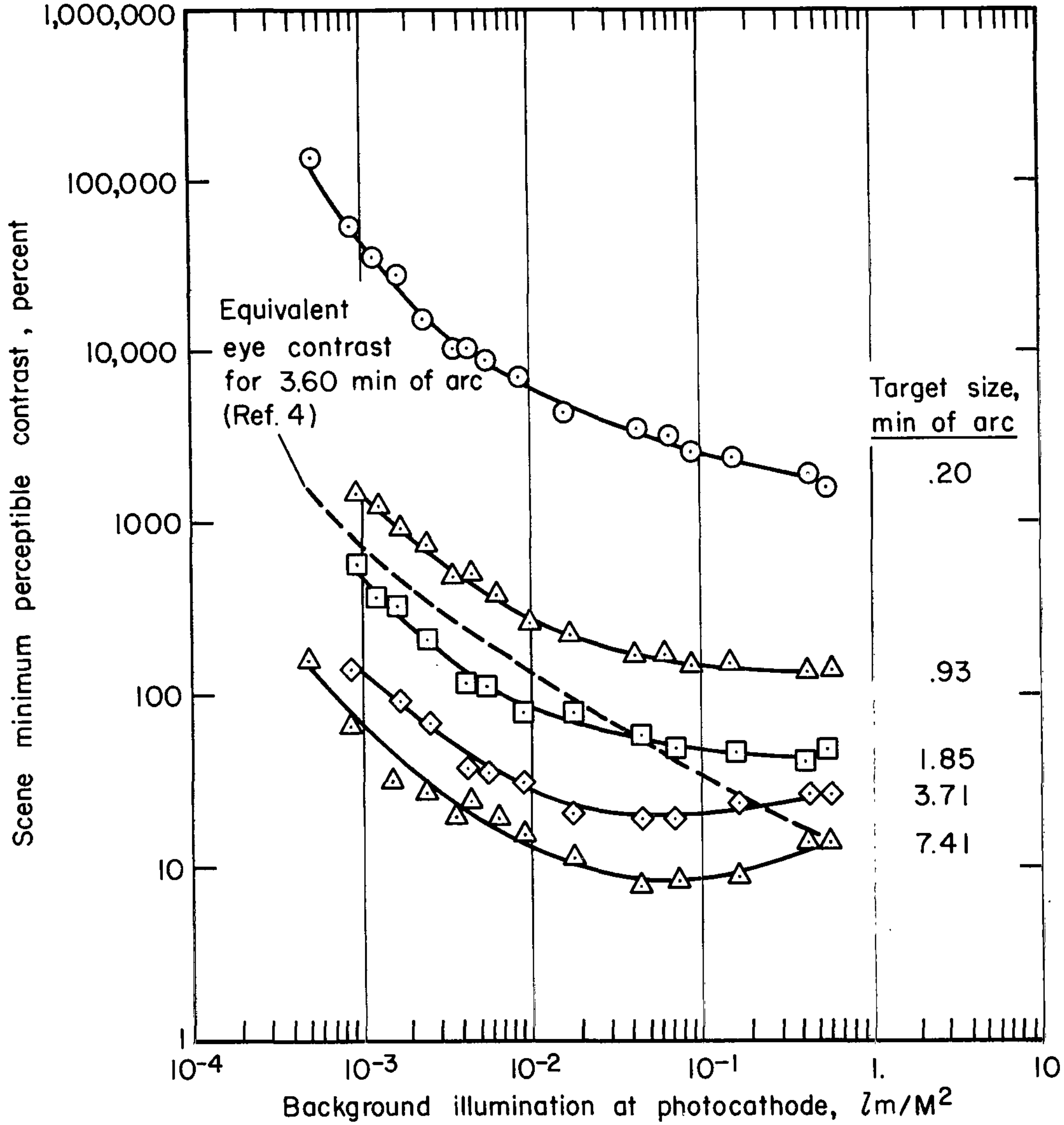


Figure 8.- Minimum perceptible contrast at scene (for small spot targets as a function of background illumination). Optics: 85 mm lens set at f/16.

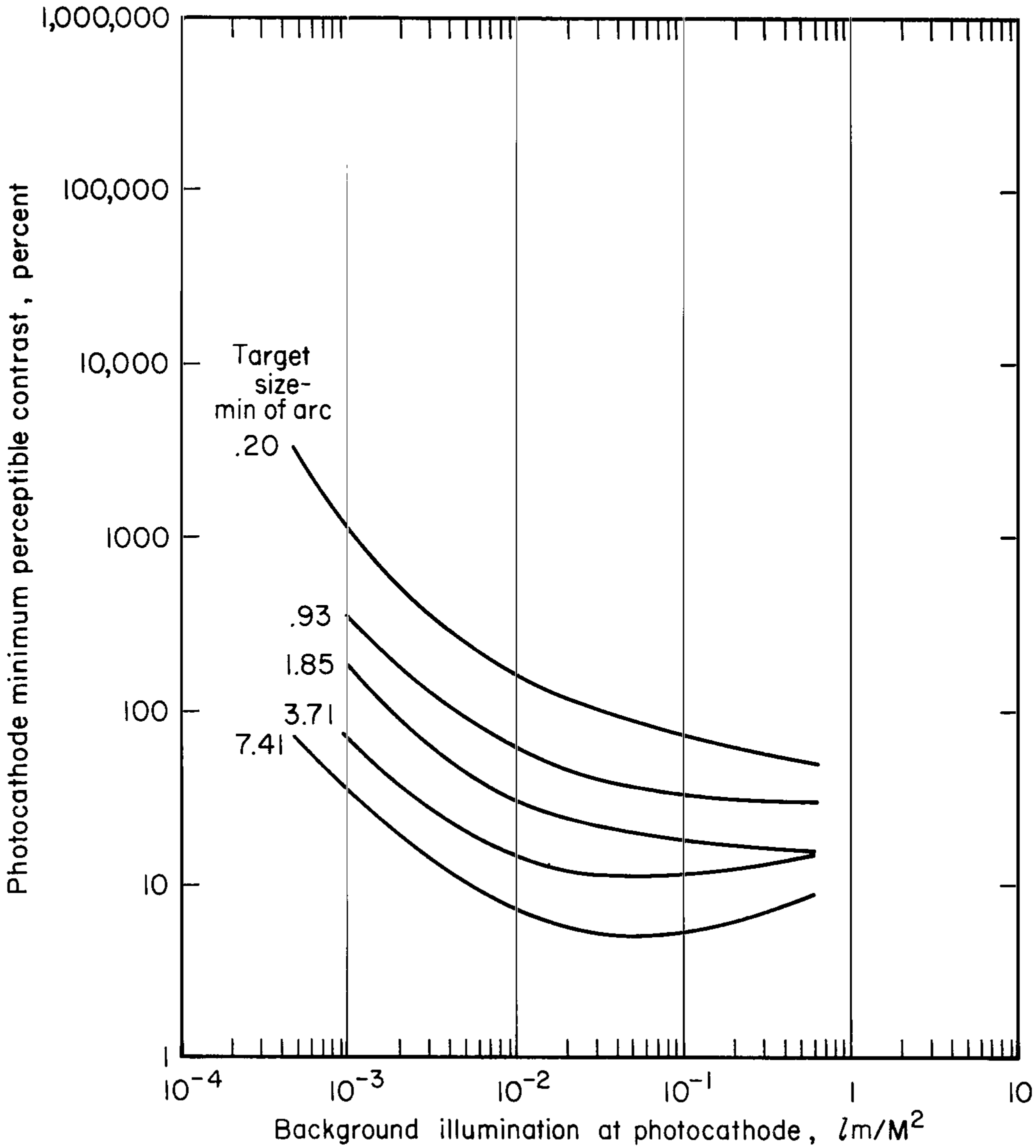


Figure 9.- Calculated minimum perceptible contrast on photocathode (for small spot targets as a function of background illumination). Optics: 85 mm lens set at f/16.

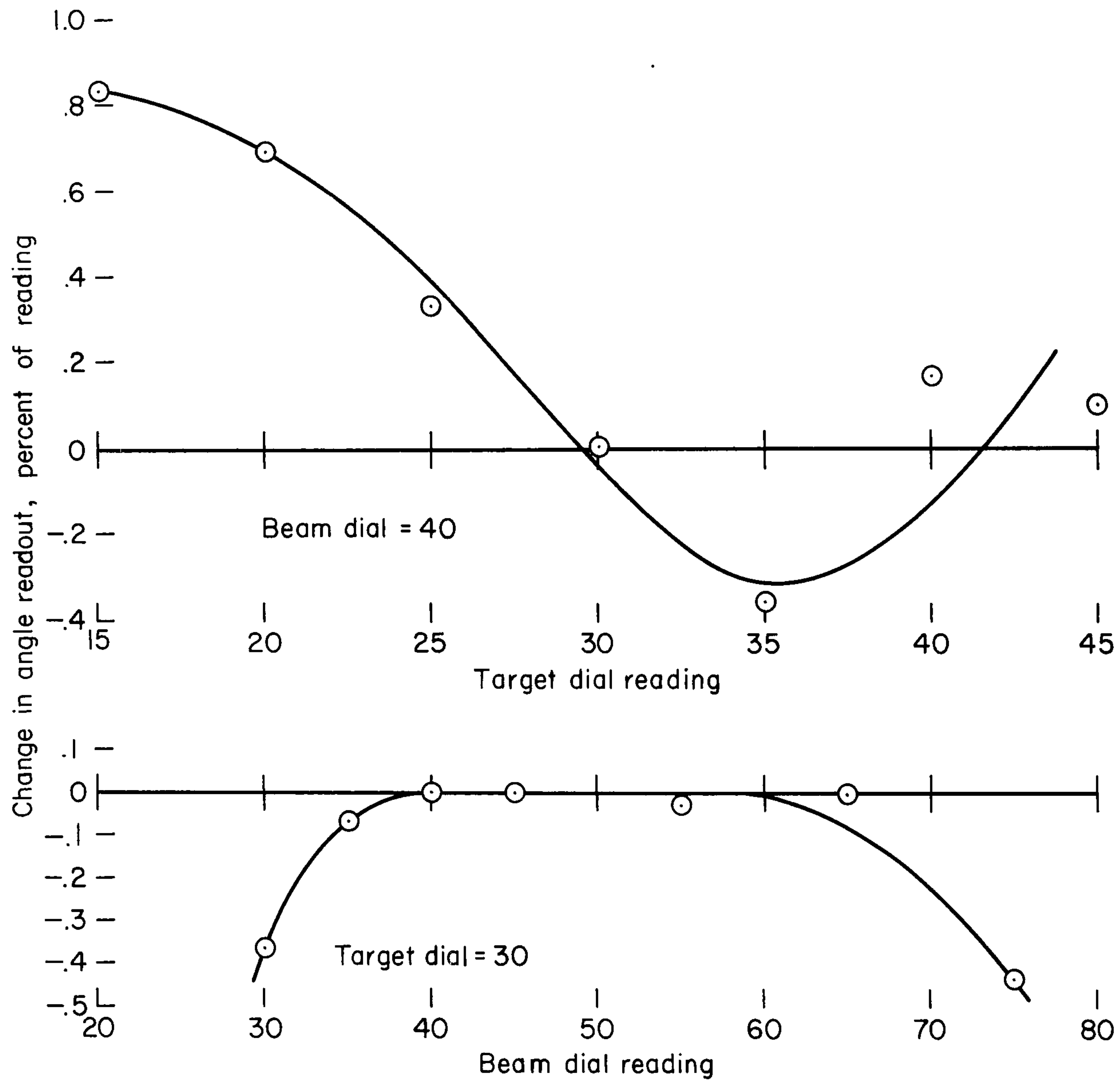


Figure 10.- Change in angle readout with either target or fine beam dial settings.

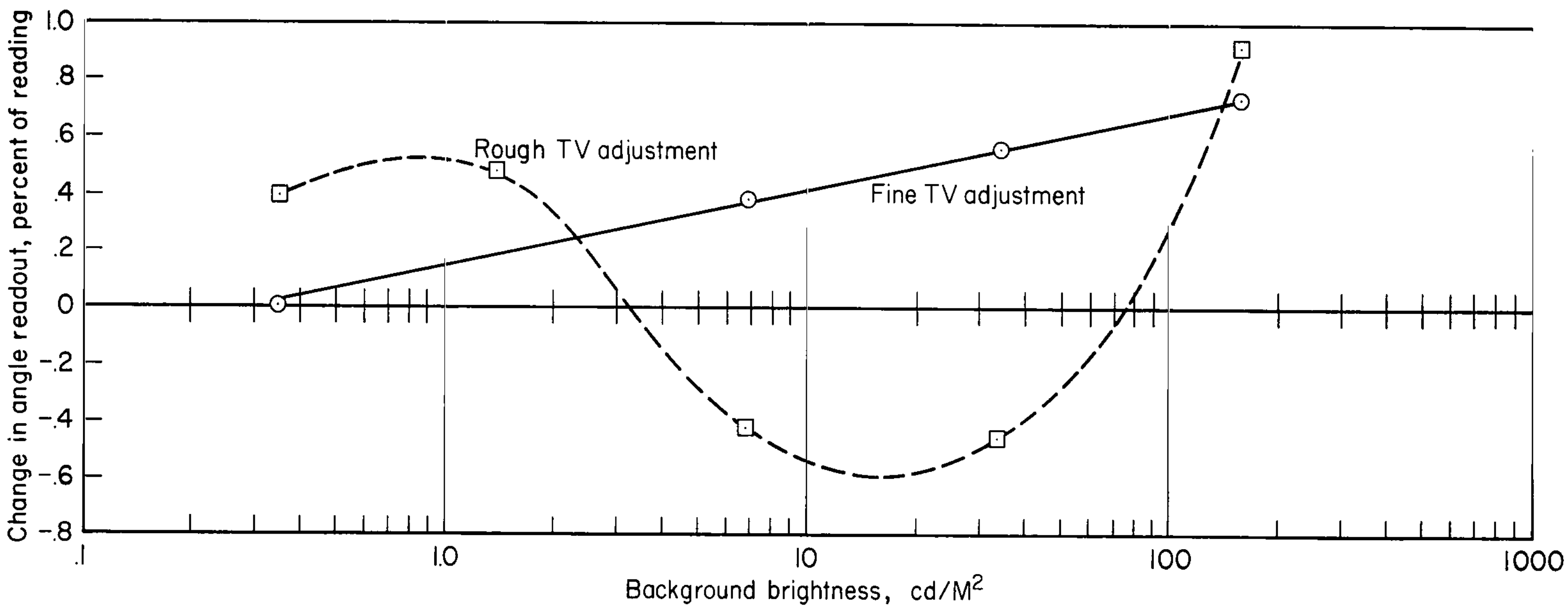


Figure 11.- Change in angle readout as a function of background brightness for two methods of TV adjustment.

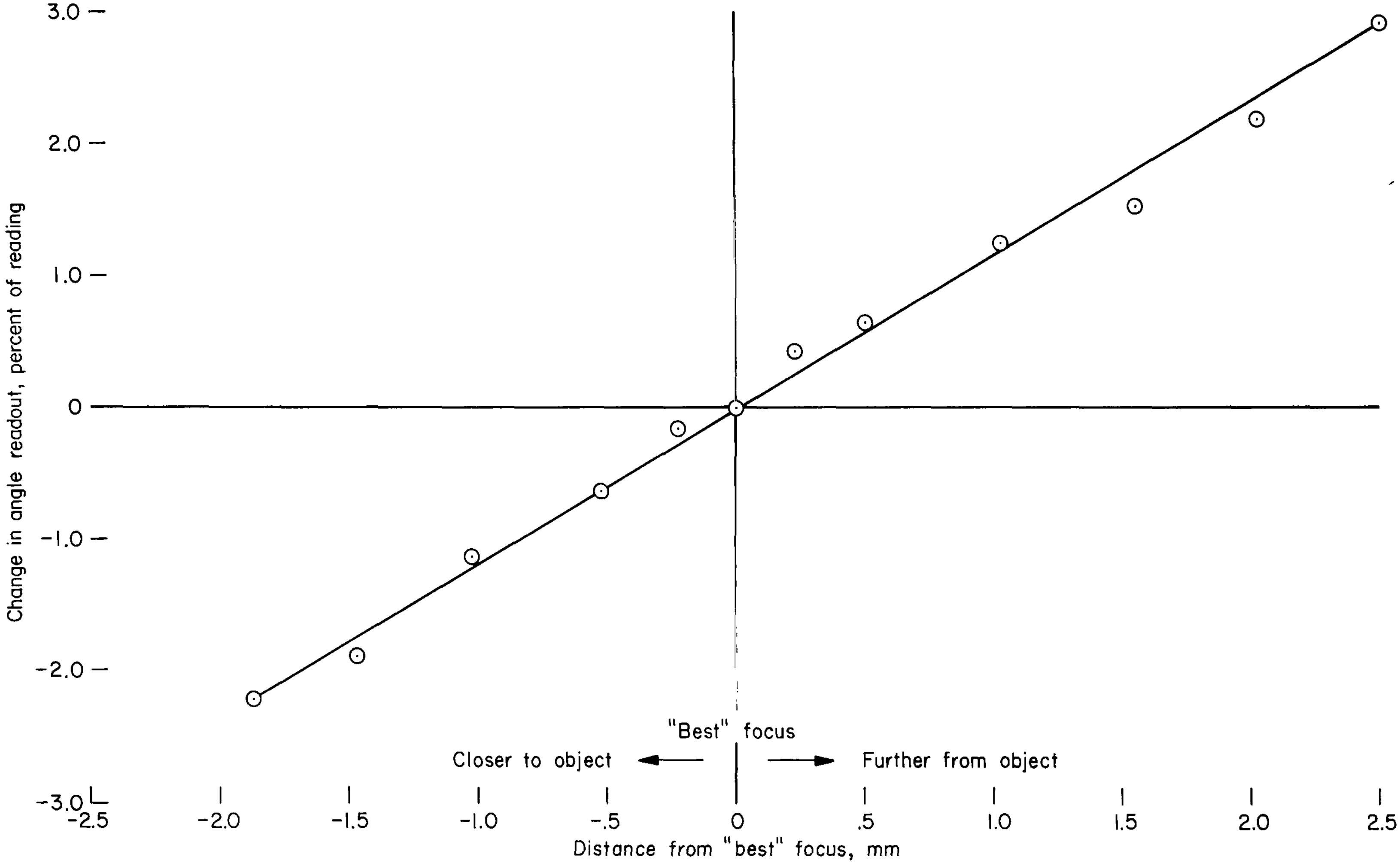


Figure 12.- Change in angle readout as a function of focus.

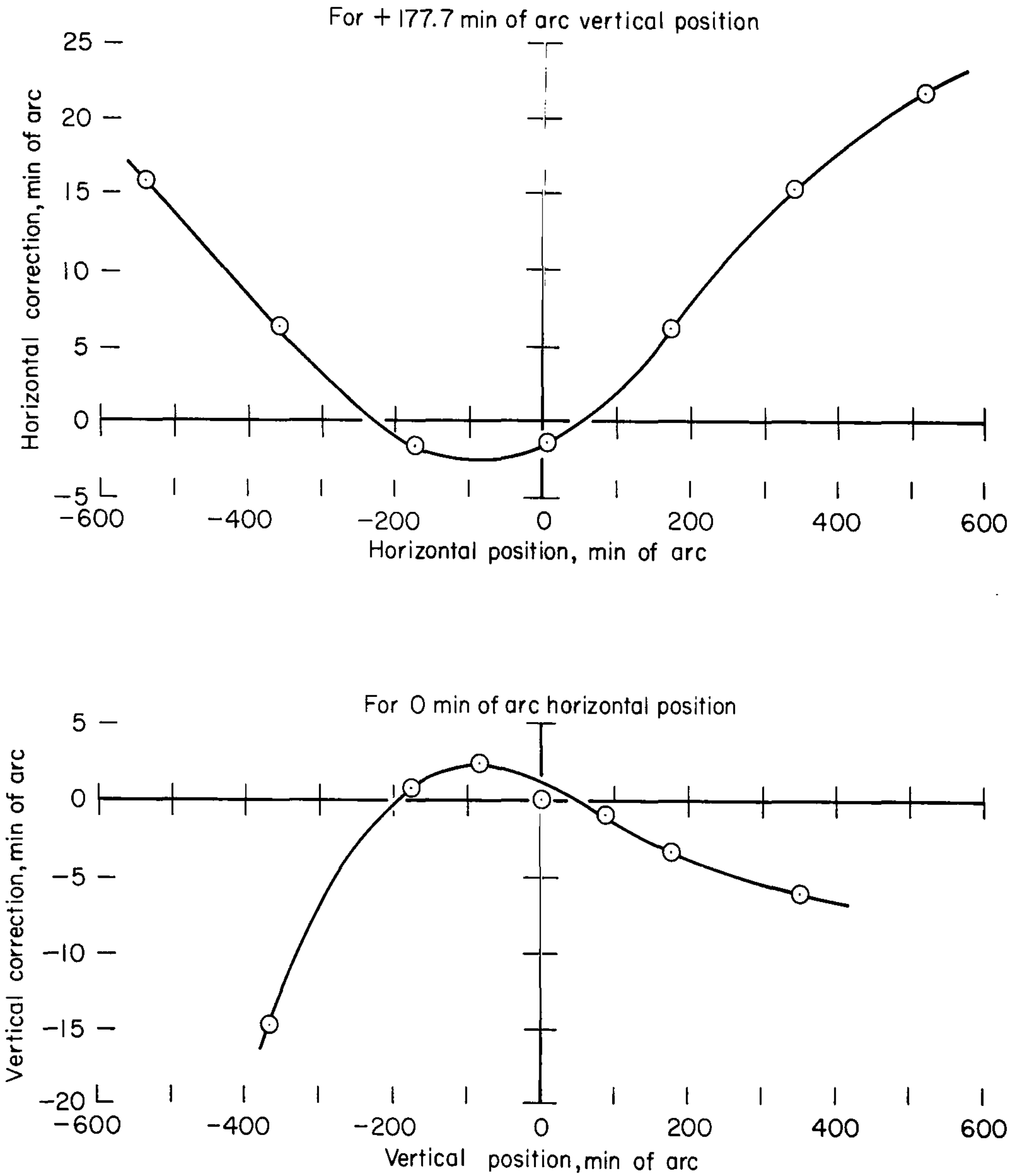


Figure 13.- Position correction curves for representative horizontal and vertical positions.

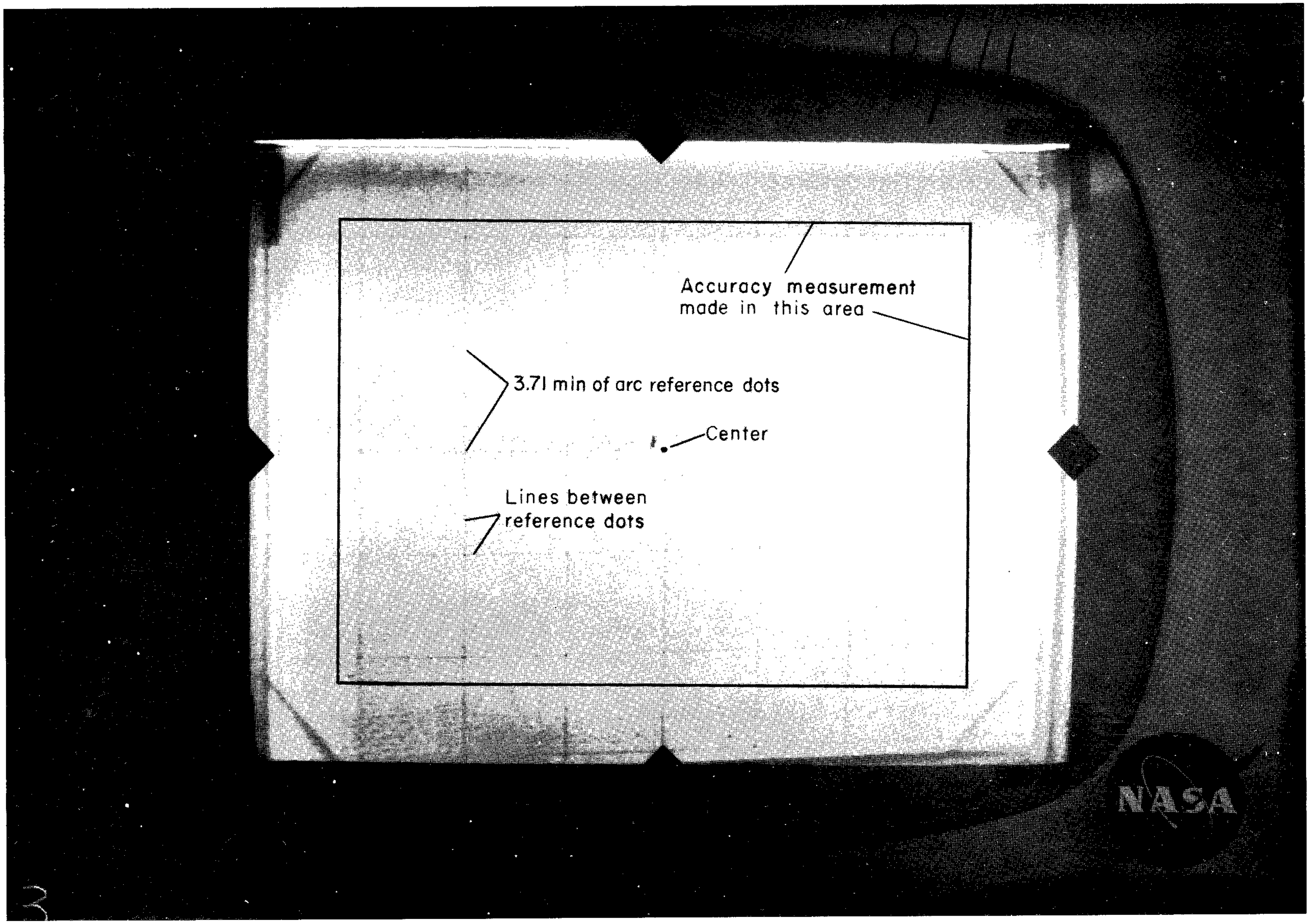


Figure 14.- Distortion of the television system.

NASA-Langley, 1966 A-1093