CONTROL SYSTEMS LABORATORY

OPTICAL SIMULATION OF ANTENNA IMAGES

Report R-109

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UNIVERSITY OF ILLINOIS · URBANA · ILLINOIS

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by

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SUMMARY

An experimental evaluation of antenna image quality as related to the aperture illumination of a high resolution antenna was made. An optical method of simulating antenna images was employed to form photographs that were evaluated by human observers. By this means a representative class of illuminations was studied and the optimum of the class determined.

The conclusion drawn from the evaluation was that antenna image quality is not highly sensitive to aperture illumination and that a uniform illumination is close to optimum for the import class of applications investigated.

A detailed description of the experimental procedure is given and reproductions of some of the images analyzed are included. The result of the experiment is presented in the form of a graph showing relative image quality as a function of the antenna illumination parameter varied.

ACKNOWLEDGMENT

The suggestion that this study be undertaken came from Dr. J. P. Ruina of this laboratory. Appreciation is expressed to Dr. H. W. Sinaiko for his advice regarding the planning of the testing phase of the experiments and to the authors' co-workers who gave of their time to evaluate the images. The patience and cooperation of the personnel of the Photo Laboratory were most helpful.

The report contains extracts from a dissertation submitted by J. J. Myers in partial fulfillment of the requirements for the Ph.D. degree at the University of Illinois.

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I. INTRODUCTION

General

This report is the second of a group of three reports giving the results of a theoretical and experimental study of antenna resolution and image quality as related to aperture illumination. The first part of the study[1] was an investigation of mathematical quality criteria used for evaluating antenna images; the second part, reported here, was an experimental evaluation of antenna image quality making use of an optical simulation technique and human observers; and the third part[2] was an experimental evaluation of antenna image quality making use of a mechanical observer. A related study is the subject of another CSL report.[3]

The background material is largely given in the report of the first part of the study[1] and so is not repeated here. Although considerable insight into the characteristics of an imaging system and of the images[4] made with it may be obtained by mathematical methods, ultimately image quality must be determined by an observer, at least until the relation between the mathematical criteria and the subjective criteria of an observer are clearly understood. It seems unlikely that this understanding will ever be reached.

The most direct experimental method for determining the effect of aperture illumination on the quality of the image is to construct an

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1. Myers, J. J., "Antenna Image Quality Criteria", Control Systems Laboratory Report R-108, Univ. of Illinois, Urbana, Ill., Dec. 1958.
2. Myers, J. J., "Assessment of Antenna Image Quality by a Mechanical Observer", Control Systems Laboratory Report R-110, Univ. of Illinois, Urbana, Ill., Dec. 1958.
3. Rawcliffe, R. D., et al, "Optical Simulation of Radar Resolution", Control Systems Laboratory Report R-111, Univ. of Illinois, Urbana, Ill., Dec. 1958.
4. The term "image" is used throughout this report in the optical sense, that is, meaning the "picture" of some object or set of objects after reception by an antenna system and after linear detection or processing.

antenna or set of antennas and to vary the illumination, while observing the effect upon the image quality as assessed by means of an observer. This method is both expensive and time-consuming if the study is to be extensive. In practice, it probably would not be used for an exhaustive study of aperture illumination, although in specific instances it might be feasible.

An alternative method, which is more appealing, is to simulate the antenna imaging process by suitable means and to judge the images so generated, taking into account the limitations of the simulation procedure. If the method of simulation is sufficiently simple and flexible, a wide range of illuminations may be studied relatively quickly and at small cost.

For the study reported here a simulation method was used, viz., an optical method of distorting photographs to form images that were evaluated by human observers. The technique was applied to the assessment of image quality for the same class of aperture illuminations used in the other two studies.[1,2]

The optical studies and the mechanical observer studies are complementary in that the former or "subjective" evaluation involved the psychological and physiological factors of human observers, whereas the latter or "objective" evaluation was completely independent of these factors.

A human observer assessing the quality of a photographic image will invoke such criteria as "sharpness" or "definition" or "similarity" or perhaps "resolution". These criteria, as applied by a human observer, are not subject to precise quantitative control because of the many subjective factors involved. Hence, there is a certain randomness to be expected in evaluations of image quality because of differences between observers or variability of a single observer. Nonetheless, by appropriate design of experiments involving human observers, it is quite possible to obtain subjective evaluations that are valid and meaningful.[5]

Many studies[6,7,8] have been made of photographic picture quality as related to the aperture illumination (lens characteristics) used in the imaging process. These studies have investigated largely the effects of aberrations. The effects upon image quality of resolution, scale, and contrast has been the subject of study[9] from the standpoint of aerial photography; and the effect of aperture size (and to a limited extent aperture illumination) upon the recognizability of certain types of ground targets has been studied for antennas.[3]

In the optical study images were formed through imaging systems with aperture illuminations given by (1 + A cos 2 x/L), where x is the aperture coordinate, L is the antenna length, and A is an aperture illumination parameter defined over the interval (-1,1) (see Appendix B of <u>CSL Report R-108</u>). In the study, five illuminations of the class, including the two extremes (given by values of A = ± 1.0), were used in forming images for evaluation. The results are given as a function of the aperture illumination in graphs of the same form as those presented for the numerical calculations of quality.

It was not expected that the experiments performed should be exhaustive. Instead, the intent was to develop a method of approach, including the generation of masks, the formation of a suitable

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5. Edwards, A. L., <u>Experimental Design in Psychological Research</u>, Rinhard and Co., Inc., New York, 1950.
6. Baldwin, M. W., Jr., "The Subjective Sharpness of Simulated T.V. Images", <u>B.S.T.J.</u>, pp. 563-86, Oct. 1940.
7. Croce, P., <u>Etude d'une methode de filtrage des images optiques</u>, Doctoral Thesis, University of Paris, 1954.
8. Higgins, G. C., and L. A. Jones, "The Nature and Evaluation of the Sharpness of Photographic Images", <u>J. Soc. Mot. Pic. and TV Engrs.</u>, v. 58, pp. 277-90, Apr. 1952.
9. "Criteria for Detection and Recognition of Photographic Detail", <u>Tech. Note 69, Pt. 1</u>, Boston University, Boston, Mass., Sept. 1950.

randomized object, and means for evaluating the results in a manner that would show the dependence upon aperture illumination. It was also the intent of the experiment to determine an optimum illumination under a restricted set of conditions.

The optical technique employed appears to have been developed largely during the studies of Rawcliffe, et al,[3] although the use of off-focus imaging (without weighting of the entrance pupil by means of masks) is a common technique employed to investigate sharpness in images.[6,8] Contributions to the technique resulted from the study reported here. They were the means for making circularly symmetrical masks and the development of a method of forming random objects for image-making.

Experimental Method

The method for simulating antenna images optically consisted of forming on photographic film the image of some illuminated object through an off-focus lens system (camera) in front of which was placed an entrance pupil (mask) whose density (absorption) varied as some function of the radius. This variation was the same as the power radiation pattern of the antenna simulated. The images so formed were "smeared" in the same way that an antenna image is smeared because of finite aperture and a given aperture illumination. By using different masks, several antenna radiation patterns were simulated and the corresponding range of equivalent aperture illuminations were investigated. A human observer then passed judgment on the quality of the resulting images according to a particular criterion of image quality.

As used in the study referred to before, this simulation technique permitted the determination of the antenna size required for identifying certain types of ground objects. The effects of sidelobes were not investigated at length. The technique was modified for this study so that the image through an antenna of a fixed size but with several illuminations could be evaluated.

The design of an experiment of this type is perilous because of the many factors, some of which are unknown, that can influence the result. It seemed that the method of devising the experiment as performed minimized the role of the differences between individual observers arising from training, motivation, perception, etc. Experimentally it was determined which factors were of consequence in influencing the results. Hence it is believed that the differences between images due to differences in aperture illumination were brought out legitimately by the experiment performed.[10]

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10. Two interesting experiments have been reported[9,11] involving the recognition of forms against complex backgrounds. Although different information was desired than desired from the present experiment, the studies are relevant.
11. Boynton, R. M., and W. R. Bush, "Recognition of Forms Against a Complex Background", J. Opt. Soc. of Am., v. 46, pp. 758-64, Sept. 1956.

II. PROCEDURE

Image Formation[12]

A focussed, aberration-free optical system maps points in the object plane into corresponding areas of the object plane. Microscopic examination of the image of the point object shows that the image consists of a Fraunhofer diffraction pattern. If the lens system is defocussed, the image of the point object broadens and there is a transition from a Fraunhofer diffraction image to a Fresnel image.

The off-focus Fresnel pattern is an approximate image of the aperture of the lens system, with some spurious response at edge transitions of the image due to diffraction at the edges of the aperture. The shape of the image and distribution of intensity in it may be changed at will by varying the shape and density of the aperture. For example, if there is placed in front of the lens a circular aperture whose density is a function of radius, the image of a point will also be a circle and the intensity in the image will vary in the same way that the density of the mask varies, that is, the point image will faithfully reproduce the mask shape and intensity, except possibly for a magnification factor.

In the point image there is, of course, some distortion due to diffraction effects. However, if the optical system is sufficiently off-focus, then these effects are small compared to the off-focus effects, and the image is a sufficiently good reproduction of the mask used.

It is interesting to consider the frequency content, or transfer function, of the imaging process using the off-focus lens system and variable-density masks. Consider first a mask of uniform transmission so that the off-focus image is to the first approximation constant across the main disk. Neglecting the small diffraction effects (small

12. See CSL Report R-108.

in terms of the scale of the off-focus image), the transfer function of this uniform disk is approximately the Fourier transform of a rectangular distribution, i.e., of the form ($\frac{1}{x}$ sin x). Thus, the transfer function of the imaging system has been modified by defocussing and the use of a mask. Through introducing this second order phase distortion plus amplitude weighting, within limitations imposed by the geometry of the experimental setup the transfer function may be modified at will by appropriately choosing the mask. Clearly, the transmission of the mask required is approximately the Fourier transform of the transfer function desired. The frequency content of off-focus images has had extensive treatment in the literature,[13,14,15] but, for the purposes of this experiment, the explicit frequency content was of only indirect interest.

The arrangement described above and used in the experimental study is shown in Fig. 1b. A photographic object consisting of a film transparency (approximately 1½" x 2") was mounted on opal glass and illuminated from behind by a uniform light field obtained by the array of flourescent lamps shining through additional sheets of opal glass. The camera (with mask in front of the lens) was mounted with the lens at a distance from the object of approximately the focal length of the camera lens. The image of the object was recorded on photographic film placed a short distance (approximately 1") from the focal plane of the camera. The off-focus distance was not critical and depended upon the degree of smearing desired. However, sufficient spreading of the image had

13. Hopkins, H. H., "The Frequency Response of Defocussed Optical Systems", Proc. Roy. Soc. (London), v. 321A, pp. 91-103, 1955.
14. Linberg, P., "Measurement of Contrast Transmission Characteristics in Optical Image Formation", Optica Acta, v. 1, pp. 80-93, Sept. 1954.
15. Parrent, G. B., and C. J. Drane, "The Effect of Defocussing and Third Order Spherical Aberration on the Transfer Function of a Two-Dimensional Optical System", Optica Acta, v. 3, pp. 195-97, Dec. 1956.

to be used to make the scale of the distorted image large in comparison with the scale of the main lobe of the point diffraction image of the camera when in focus.

Masks

The masks used in the experiment constituted the entrance pupil of the camera used in making images. They were made of photographic film. The film was exposed appropriately so that the curve of transmission as a function of radial distance from the center of the mask was the same as the curve of the power radiation pattern of the antenna that was being simulated.

In Fig. 2 are reproduced in full size the five different masks used in the formation of images. There are also given in the associated curves the corresponding antenna radiation patterns and the measured density of the actual masks. Limitations of the duplicating process for this report do not show clearly the proper graduation of density. Formation of the masks constituted one of the more tedious parts of the experimental work.(see the Appendix).

The choice of proper overall mask size was made on the basis of experimental data that showed the optimum size to minimize undesired diffraction effects. The optimum size depended upon the lens used. For the setup employed in the study reported here, this size was about one-inch diameter. Since the mask size was limited, it was not possible to include a complete diffraction pattern (which would, in fact, extend to infinity). After due consideration, it was decided that the mask should include only the first sidelobe of the antenna radiation pattern since higher order sidelobes, by the method employed for evaluation of results, were insignificant in terms of their smearing effect on the image. The total transmission range in the mask was about 200:1, which gave the opportunity to include sidelobes greater than 0.5%.

In use, the masks were mounted in gelatin filter frames that were inserted in a suitable holder mounted on the front of the camera lens.

Objects

Images were made of objects consisting of random Roman capital letters on a background of random shapes of the same density (Fig. 3). The objects were formed on photographic film, which in use was illuminated from behind by a uniform light field. Upon direct viewing, most or all of the letters could be read, in spite of the obscuring effect of the random shapes; when distorted by the off-focus camera and mask, the letters were less legible, and the percentage of letters which could be identified varied from 12% to 92%, depending upon the amount of distortion and the perceptivity of the observer.

The choice of object form was arbitrary. It appeared desirable to use objects that were not simple geometric forms, e.g., converging lines, squares, etc., and whose spectra were reasonably broad. This choice was based upon the fact that, in general, the objects imaged through an antenna consist of random type radiators whose angular size, shape, and reflectivity or luminance cannot be predicted. A possible exception in one respect is radio astronomy where for many types of stellar objects the angular size is vanishingly small. Even in such cases, however, the positions of the sources will be random. It also seemed desirable to have readily identifiable object forms to avoid difficulties in scoring due to a lack of a clear understanding on the part of the observers as to just what form was being identified.

The random background, or noise, corresponded to random radiators and not to receiver noise. That is, it was spatial noise and so was smoothed in the imaging process in the same way that the identifiable letters were smeared. This corresponded, roughly speaking, in a radar map to random return amongst which were geometrical shapes, such as airfields. Both the background and the letters were high-contrast object forms (approximately 10,000:1). This object, it should be noted, did not result in the type of image which would be formed after hard-limiting following reception.

Technique

Formation of Images

For assessment by the observers there were formed 25 different images using the method described above. There were formed five for each of five different aperture illuminations, the five for any illumination differing from each other only in the registration between letters and the random background. It was intended that the values for the aperture illumination factor, A, should correspond to the values -1.0, -0.5, 0, 0.5, and 1.0. However, inaccuracies occurring in the process of making masks caused the illumination factors to be more closely -1.0, -0.4, 0.1, 0.5, and 1.0.

The average contrast of each image made was approximately the same as that of each of the other 24 images. Each undeveloped film containing the latent image was given the same photographic processing. The result was a set of 25 images. Each developed image was mounted between glass sheets and identified by a number which did not reveal to the observer the particular characteristic of the image.

The objects used in forming the images consisted of negatives of the objects reproduced in Fig. 3, that is, the letters were clear and appeared as light objects rather than dark objects to the film on which the image was recorded. Hence the image film as viewed by the observers contained dark letters on a mottled background. It had been determined experimentally previously that white letters on a mottled background were much more difficult to identify.

Observers

For the experiment there were chosen five "maximum cooperative" individuals selected on the basis of their ready willingness to spend the time necessary to view over a period of about a week the 25 different images, and their willingness to make reasonable effort to do their best in finding the letters. Each was believed to have had about the same incentive in helping to make the results significant. All of the subjects were graduate or former graduate students, and none had poor eyesight, although one wore glasses.

Each subject was given the same training by having him view a series of five images without it having been revealed to him that the results of his evaluation would not be used in the scoring of overall results. Thus it was felt, based on the fact that only the recognition of Roman letters was required, that the training of the observers was uniform and that each had about the same acquaintance with the general appearance of the letters after distortion through the imaging system.

Method of Viewing Images

For viewing, the images were illuminated from behind by mounting them on a frosted glass plate illuminated from below by an incandescant lamp. The glass around the image was covered by an opaque sheet. The brightness of the lamp was controllable by the observer to suit his own preference by changing the voltage on the lamp. Changing the voltage resulted in some change of color with light level, but over the range of illumination used the effect was not severe.

At the beginning of the sessions, each observer was presented with a set of printed instructions that were not changed during the course of the observations. For recording his results, that is, his identification of the individual letters in the rows, he was provided with paper forms ruled so that there was one square for each of the 60 letters presented in each image. The disposition of the squares was the same as the letters in the images. A low-power reading glass was supplied for him to use or not as he chose.

At the evaluation session (observers were used one at a time) the subject was seated in a darkened room in relative isolation and was given whatever time he desired to try to identify each of the letters in each of the five images presented to him in a particular order during that session. He chose viewing distance, magnification, and light level as he found best suited to his particular convenience. A single session varied in length, but averaged about 30 minutes per observer. Subsequent sessions about a day apart were held until all images had been evaluated. A sixth session presented to each observer a repeat of the images of the first session to yield a measure of the amount of learning that had occurred during the course of the sessions.

Earlier sessions run on a group basis by projecting images one at a time on a conventional beaded screen for simultaneous viewing by a diverse group were unsuccessful and inconclusive due to both the conditions of viewing and, it is believed, a lack of adequate incentive on the part of some members of the group. Individual viewing of the images by carefully selected subjects as adopted for the test was much more successful.

Experimental Design

The basic experimental plan involved a 5 x 5 x 5 "Latin square" design[5] which is shown in Fig. 4. All of the variables were randomized such that each of the 25 images was presented to each of the five subjects in a different order. In each session there were presented one at a time five images made with five different aperture illuminations, each with a different letter-background registration.

Scoring

The individual scores for each image were obtained by noting the percentage of correct identifications. Erroneous identification was counted the same as no identification. Subjects were advised in the instructions that there would be no penalty for incorrect identification, but each was urged not to guess. To avoid reduction of dynamic range of the data due to subjects remembering key letters, viz., the first six letters of the first line and the first letters of all but the last line, the key letters were ignored in the scoring. The result was that out of a possible 60 letters there were 50 used in the actual scoring.

III. RESULTS

The results of the 125 analyses of images are given in the histograms of Fig. 6 and the curves of Figs. 5 and 7. Referring to Fig. 5, the score of each observer is given for each observation as a function of the aperture illumination, each curve corresponding to a particular letter-background registration. The results of these observations are given in summary form by the histograms of Fig. 6 which show the frequency distribution for each of five different aperture illuminations. From these data the mean and the standard deviation of the observations were determined. The results are plotted in the overall quality curve of Fig. 7.

Observer learning was investigated by having each subject reassess at the conclusion of the experiment the first five images he had examined. He was not aware that the images had been seen before. Out of a possible 250 correct identifications, the average for the five observers during the first trial was 148 as compared to 198 the second trial. This difference indicates the extent of learning during the experiment. However, the design of the experiment was such as to avoid bias from this cause. Statistical analysis of the differences between performance of the five subjects showed these to be due to chance rather than to some "real" difference between observers.

No significant statistical difference between the images, corresponding to values of the aperture illumination factor between 0.5 and -0.4, were found. However, a distinct difference in image quality for the two extremes as compared to the center values is evident. The flatness of the curve of the mean in Fig. 7 suggests that image quality is insensitive to the aperture illumination factor and that, accordingly, there would be little justification for attempting to obtain special illuminations much different from uniform.

It might reasonably be argued that the results of the experiment would have been different had there been used different subjects. For example, the results might have been significantly different had there been used an object with a continuous range of intensities rather than the black-white intensities used. This objection is a valid one because certainly smearing of low-intensity objects due to sidelobe energy from much higher intensity objects would be more evident with a continuous range of intensities in the object. However, it is believed that the differences would be one of degree only and that, in spite of the high contrast of the objects used, the results obtained do not differ greatly in form from the results that would have been obtained with this different object set.

There is need for carrying on further investigations of this type with different forms of objects in order to investigate the differences discussed in the paragraph above. For the present study, time was not available for investigating exhaustively the various possible object types which might have been used. In fact, the objective of the study did not require that such investigation be made.

It is interesting to note that the results obtained from the experiment reported here are similar to those obtained from the experiment using a mechanical observer,[2] that is, the optimum illumination, as determined by the mechanical observer, was close to uniform.

IV. CONCLUSIONS

From Fig. 7, it is evident that the measure of image quality used in this optical experiment was not sensitive to small differences in images and that no statistically significant difference was found between the aperture illuminations in the range of the aperture illumination factor, A, between -0.4 and 0.5. It is evident, however, that an appreciable deterioration of the image (in terms of the similarity of the distorted letters to known shapes of the letters) occurred for aperture illuminations at the extremes of the class of illuminations investigated.

It is, nonetheless, apparent that aperture illuminations close to uniform are nearly optimum by the measure of image quality applied in this experiment.

APPENDIX

Mask Making

The generation of masks was done by a two-step procedure: 1) a film was produced with variation of density in one dimension only that was inverse to that of the final mask; 2) a small piece of this film was used as described below for generating the final mask.

Referring to the sketch of Fig. 1a, light from a 500-watt mercury vapor lamp (G.E. H100-A4) was passed through two lenses (f:4.5, 27 cm), a green filter (Wratten #74), and two polarized filters (Kodak Series 7 Pola-Screen) to form a uniform light field of about four inches diameter whose intensity could be controlled over a range of about 2000:1 by rotating one of the two polarized filters. The green filter was used to provide light approaching monochromatic in order that good cancellation in the polarized filters could be achieved. The line voltage to the mercury-vapor lamp was stabilized to give good short-term stability of the light output.

In the first step, the uniform light field was arranged to fall on a 0.004" x 2" slit (Fig. 1a). This slit was caused to travel at a uniform rate in a linear direction perpendicular to the length of the slit, and the light passing through it was allowed to fall on a 4" x 5" sheet of panchromatic film (Ilford HPS) that was almost in contact with the slit. During the course of the travel of the slit over a distance of approximately three-quarters of an inch, the intensity of the light was changed in a prescribed manner so that the density of the developed film varied correspondingly.

The intensity of the light was adjusted as follows. A vertical transparent cursor with a fiducial line was caused to travel in a linear direction synchronously with the travel of the slit by means of a synchronous motor, a gear box, and a lead screw. Attached to one of the two polarized screens was a second cursor which was caused to travel with a rotational motion by means of a small hand crank and a lead screw that were turned by the operator. The two cursors were arranged on a large plotting board on which was drawn a curve that described the desired film density as a function of distance. In operation, the vertical cursor was started from one edge of the plotting board and caused to travel at a uniform rate (9/16-inch/minute) in synchronism with the travel of the slit in front of the film (at 1/16-inch/minute). The hand wheel on the second cursor was then turned at such a rate as to keep the fiducials on the two cursors crossed over the curve of film density which had been plotted based on calibration curves of the system (which gave angle of polaroid filter vs. density of the finished film). By this means, it was possible to form variable-density film whose density varied in a prescribed manner.

Development of the film was then done in a Calumet one-gallon nitrogen-burst unit according to a standardized procedure (in Ilford ID-48 developer, 12 minutes at 68°, agitated by nitrogen bursts of two seconds duration every 20 seconds with nitrogen at five pounds pressure).

For the second step, a small piece of the variable density film was then mounted over the V-slit (of about 8° angle) in the device of Fig. 1a. The device was then rotated about the apex of the V-slit at a rate of approximately two r.p.s. with light from the uniform light field, as used in the first step, falling on it. This exposed a second 4" x 5" sheet of film (also Ilford HPS). In order to avoid the formation of undesired radial lines in the exposed film resulting from either inaccurate gearing in the rotating mechanism or resulting from synchronism between the variations of light intensity (due to the 60 c.p.s. light source) and the rotation of the V-slit, there was provided means for rotating the film holder during exposure through an angle of about 2° by hand in a random manner.

The light intensity, adjustable at will by appropriately rotating the polaroid filter, was chosen so that the total exposure time for the final mask was about one minute. Thus, because the V-slit rotated approximately 30 times during this period, the discontinuity in density due to starting and stopping the exposure was immeasurable in the masks. After exposure in this manner, the same development was given the film as described above for the first step. The result was the finished mask with rotational symmetry. The completed full-size masks are reproduced in Fig. 2 with the measured and calculated density shown on the graphs.

During the manufacturing of masks, errors due to variations in film γ (slope of density vs. log exposure curve), variations in development procedure, departures from the desired plotted curves followed by the cursors, and variations in light level were cumulative. Hence, the density of the final masks differed from the desired density. In practice, many masks were made and the best ones were selected for use.

Better masks could be generated by this procedure by having more precise control over the film processing, by providing mechanical following of the plotted curves with the cursors, as contrasted to the hand following, by better control of the light level, and by perhaps more careful procedure at each step of the process. However, with the apparatus and the facilities available at the time of manufacturing the masks, it appeared impracticable to obtain better masks without unwarranted additional effort.

Film density was measured with a Welch Scientific Company Densichron. Final maximum densities were about 2.8 density units, and the range from background level to maximum density was about 2.3 density units; this gave masks in which sidelobes as low as about 0.5% could be included.

Object Film

As shown full-size in Fig. 3, the film which constituted the object in the experimental work contained six rows of 10 capital Roman letters, with all letters being in random order (as selected from a table of random numbers). The letters were arranged on a random background so that when imaged there would be smearing of the energy from the random background into the letters that were to be identified.

Both the sizes and forms of the background shapes were randomized so that there would be represented a fairly broad spectrum. The maximum size of background objects was chosen to be about the same as the letter size, and different registrations between the background and letters were used in order to avoid penalizing unduly any letter of any image because of it always being obscured by the same background object.

The background was formed by exposing Eastman Royal X Pan film to a white card to about 20% of normal exposure. This was tray-developed in Eastman Dektol (full-strength) at 75° F for five minutes and given a normal fix and wash. This resulted in a film with a uniform grey background and a high graininess as compared to film as normally processed. This grain was subsequently enlarged in a Besseler M57 enlarger with a 3½" lens onto Ansco Repolith Ortho A film and processed in Ansco Repodol developer for four minutes at 70° F. Successive enlargements resulted in a series of films of increasing grain size. A set of five such films were chosen and used together to expose a final sheet of Repolith Ortho A film. An attempt was made to obtain about 50% coverage of the film by the background. That this was achieved was verified by making a reversal of the film and comparing its average density with the original. The background film and the film containing the letters (Fig. 3) were used together in exposing a final film. There resulted five object films.

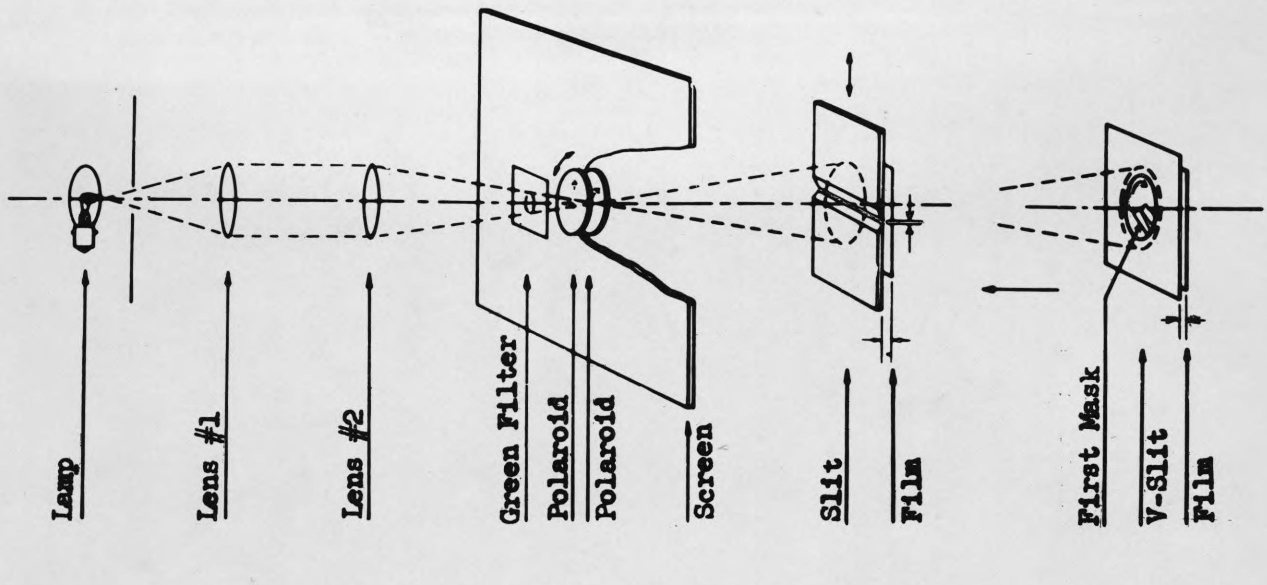
Image Making

In making the images, the film used for the object was illuminated from behind by four six-watt flourescent lamps separated from the film by three sheets of opal glass (Fig. 1b) to yield a uniform light field. This film was placed at a distance from the camera of approximately the focal length of the camera lens (a Zeiss Tessar f:4.5, 210 mm) to form an image of about unity magnification.

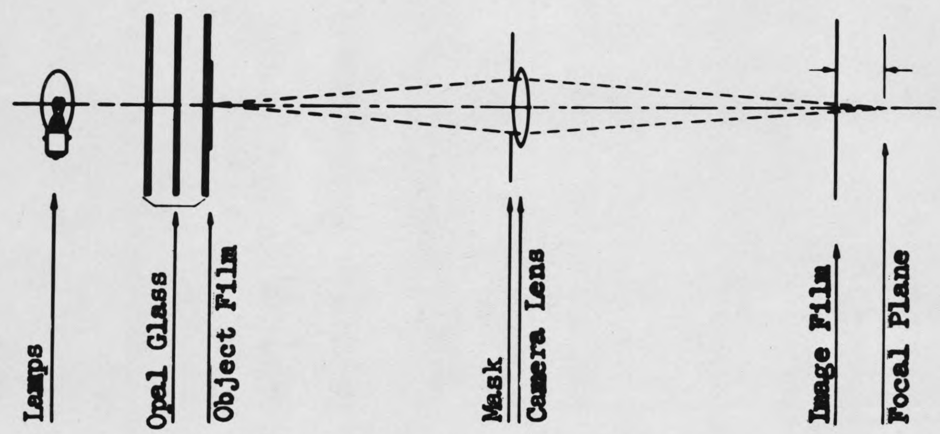
The same average density for each image was obtained by integrating and measuring the light in the image, as viewed on the ground glass screen of the camera, over an area of about one-half square inch and using the relative light values so measured as an index of the amount of exposure time required. Typically this was of the order of 1/10 to 1/2 second for the masks used.

Development of the resulting image formed on the film was done in the same manner as described above for mask making. Various development times were tested initially until it was determined that the development time was a second order effect, at least over a reasonable range of development time, insofar as discernability of the letters in the final images was concerned.

Upon completion, the images were mounted between slide glasses and appropriately identified with a number that gave the aperture illumination and the letter-background registration. A total of 25 images were manufactured and used in the evaluation procedure, i.e., five different aperture illuminations were used, each for five different letter-background registrations.



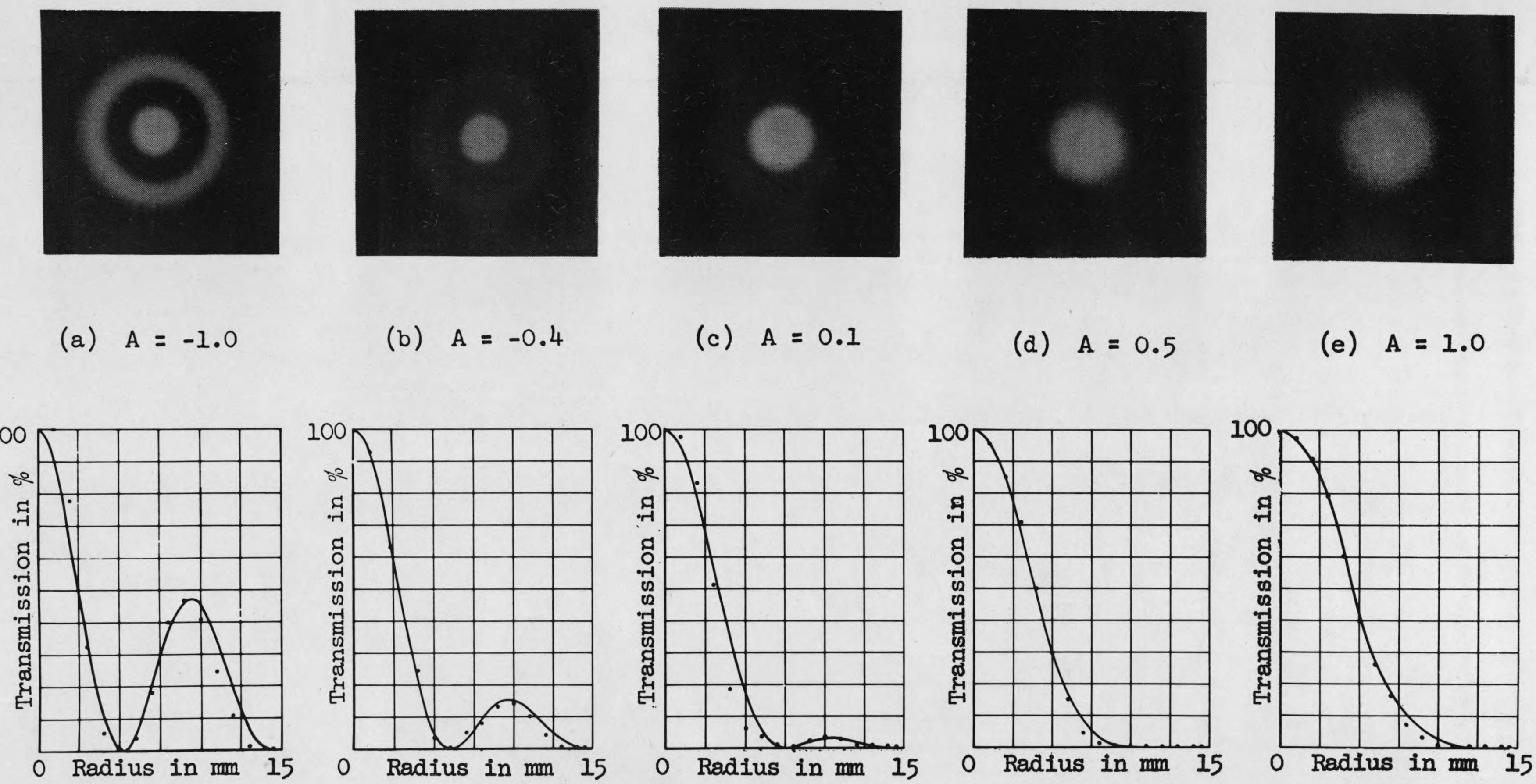
(a) Schematic of experimental setup for making masks. Either the slit or the V-slit is used, the former for the first mask, the latter for the final mask.



(b) Schematic diagram of experimental setup for making images.

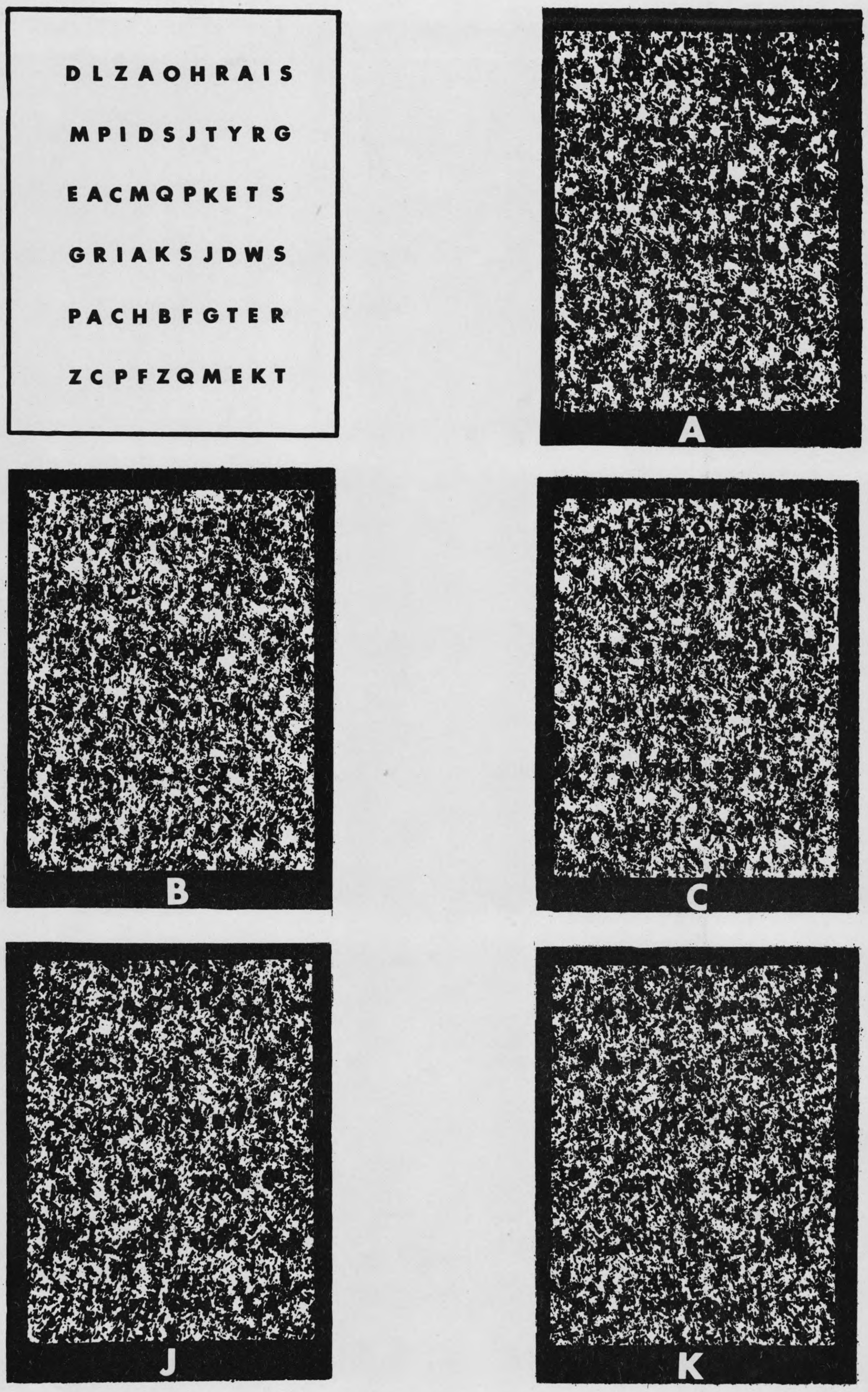
Simplified sketches of experimental setups used in optical experiment

Figure 1



Reproductions of masks used in optical experiment. The illumination factor, A, is indicated for each mask. The solid lines on the curves indicate the calculated transmission and the dots indicate the measured transmission.

Figure 2



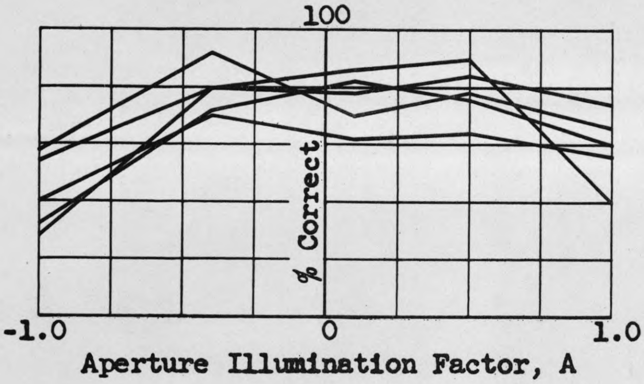
Reproduction of objects used in optical experiment. The unobscured letters are shown, but they were not used in forming images. The scale is full size.

Figure 3

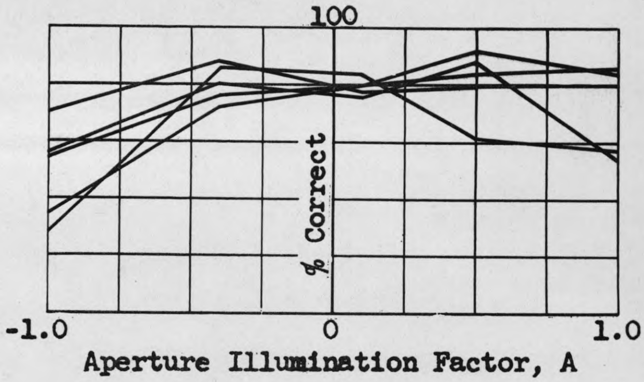
Trial	Observer 1		Observer 2		Observer 3		Observer 4		Observer 5	
	Registration	Parameter, A	Registration	Parameter, A	Registration	Parameter, A	Registration	Parameter, A	Registration	Parameter, A
1	A	-1.0	J	0.5	B	-0.4	K	1.0	C	0.1
2	J	-0.4	B	1.0	K	0.1	C	-1.0	A	0.5
3	B	0.1	K	-1.0	C	0.5	A	-0.4	J	1.0
4	K	0.5	C	-0.4	A	1.0	J	0.1	B	-1.0
5	C	1.0	A	0.1	J	-1.0	B	0.5	K	-0.4
6	B	0.5	K	-0.4	C	1.0	A	0.1	J	-1.0
7	K	1.0	C	0.1	A	-1.0	J	0.5	B	-0.4
8	C	-1.0	A	0.5	J	-0.4	B	1.0	K	0.1
9	A	-0.4	J	1.0	B	0.1	K	-1.0	C	0.5
10	J	0.1	B	-1.0	K	0.5	C	-0.1	A	1.0
11	C	-0.4	A	1.0	J	0.1	B	-1.0	K	0.5
12	A	0.1	J	-1.0	B	0.5	K	-0.4	C	1.0
13	J	0.5	B	-0.4	K	1.0	C	0.1	A	-1.0
14	B	1.0	K	0.1	C	-1.0	A	0.5	J	-0.4
15	K	-1.0	C	0.5	A	-0.4	J	1.0	B	0.1
16	J	1.0	B	0.1	K	-1.0	C	0.5	A	-0.4
17	B	-1.0	K	0.5	C	-0.4	A	1.0	J	0.1
18	K	-0.4	C	1.0	A	0.1	J	-1.0	B	0.5
19	C	0.1	A	-1.0	J	0.5	B	-0.4	K	1.0
20	A	0.5	J	-0.4	B	1.0	K	0.1	C	-1.0
21	K	0.1	C	-1.0	A	0.5	J	-0.4	B	-1.0
22	C	0.5	A	-0.4	J	1.0	B	0.1	K	1.0
23	A	1.0	J	0.1	B	-1.0	K	0.5	C	-0.4
24	J	-1.0	B	0.5	K	-0.4	C	1.0	A	0.1
25	B	-0.4	K	1.0	C	0.1	A	-1.0	J	0.5

Experimental design for judging quality of images formed optically with distortion simulating the effect of changing antenna aperture illumination. Twenty-five different images were judged, involving five different registrations between noise and letters and five different aperture illuminations.

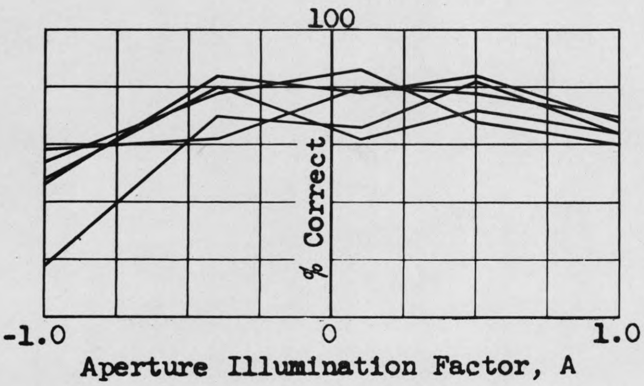
Figure 4



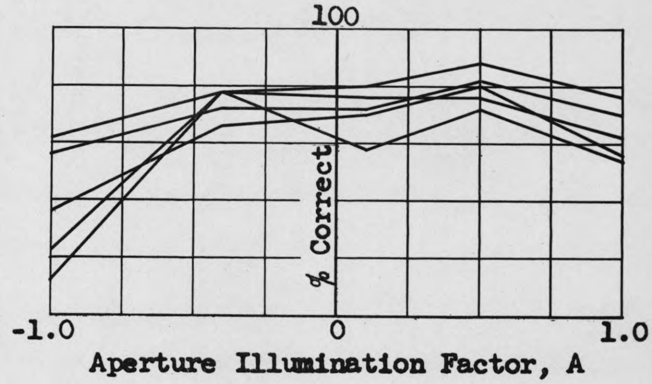
(a) Observer 1



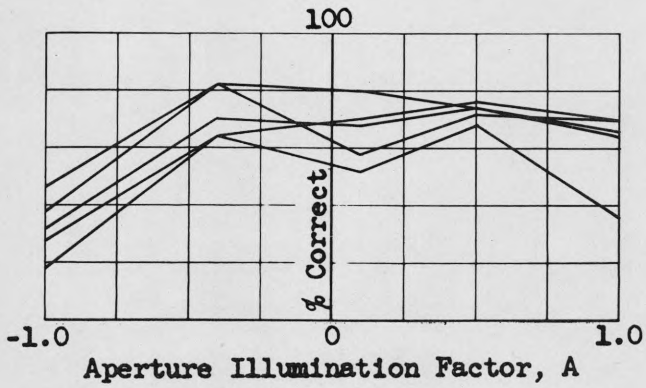
(b) Observer 2



(c) Observer 3



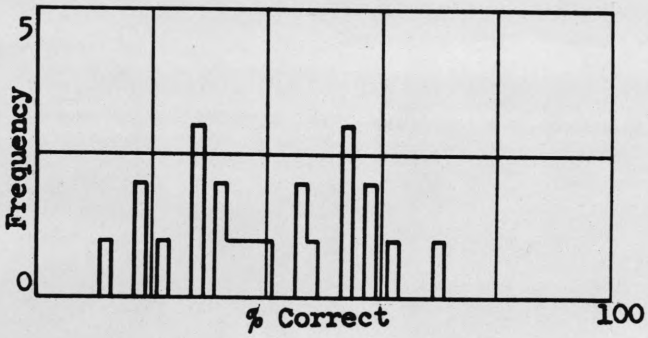
(d) Observer 4



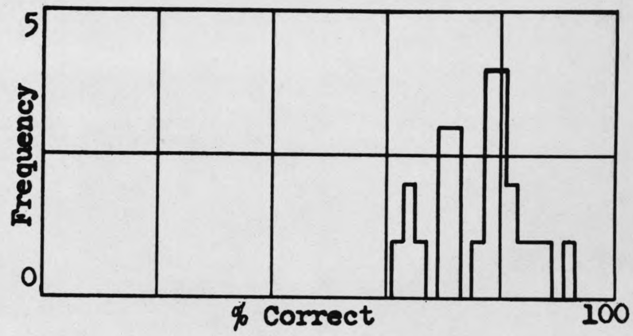
(e) Observer 5

Experimental results of image assessment by five observers. Each graph gives the results for five letter-background registrations as a function of aperture illumination.

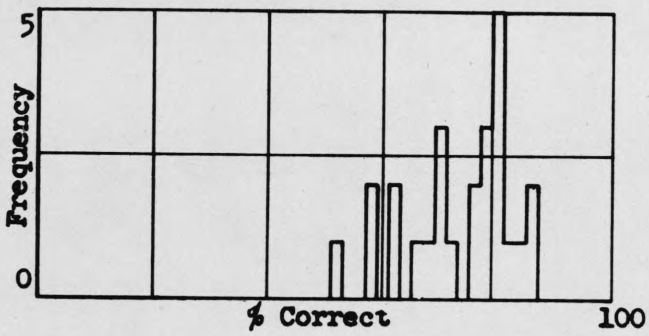
Figure 5



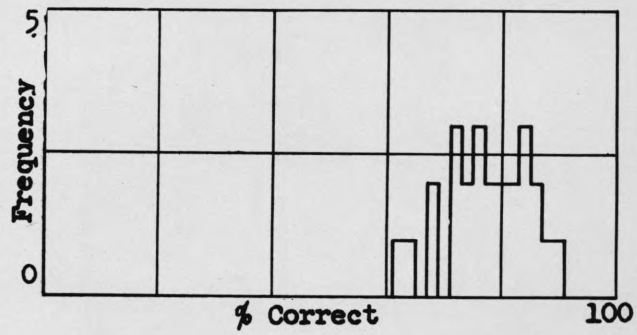
(a) A = -1.0



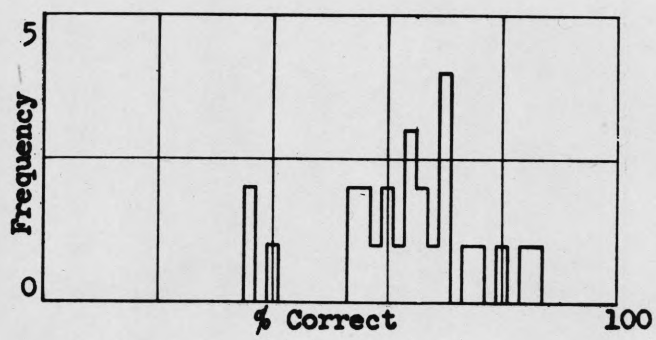
(b) A = -0.4



(c) A = 0.1



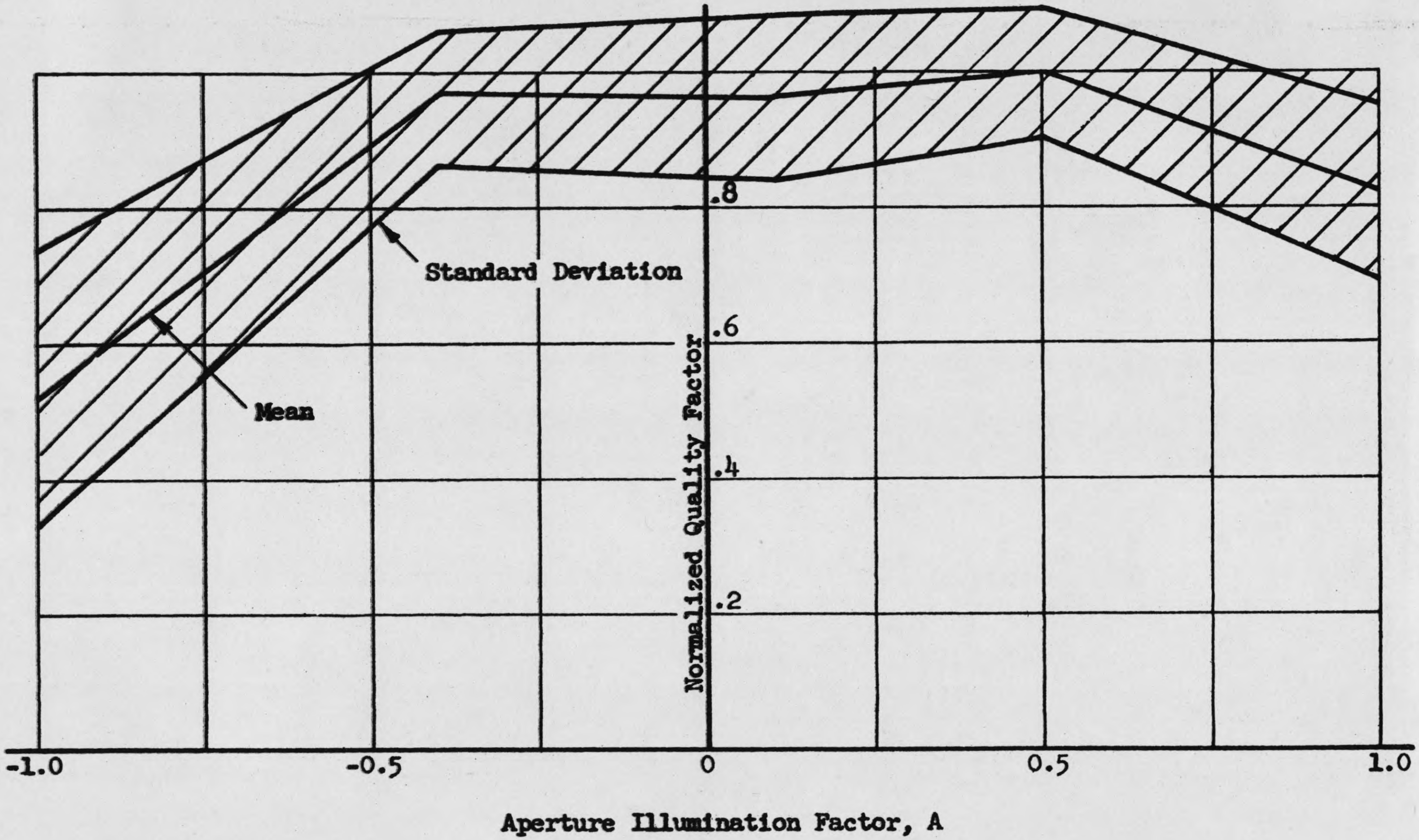
(d) A = 0.5



(e) A = 1.0

Experimental results of image assessment by five observers. Each graph gives results of 25 observations from five observers, each assessing five images . "A" is the antenna aperture illumination parameter.

Figure 6



Relative image quality for aperture illumination (1 + A cos 2πx/L) as determined by observers in optical experiment. The data has been normalized so that 1.0 represents the best illumination of the class.

Figure 7

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