THREE-DIMENSIONAL COLOR TELEVISION SYSTEM FOR REMOTE-HANDLING OPERATION

J. A. Mauro

General Electric Company
Pittsfield, Massachusetts

INTRODUCTION

The first prototype of a 3D color television system for remote-handling operations is analized and evaluated. The closed circuit single channel system has been designed and built for ANP Dept. Idaho Test Station, Idaho, for hot radiation laboratory operations. The measurement accuracy of depth displacements in the object space and image space, the reliability, and operator performance with this viewing system is discussed from the standpoint of geometrical, physiological, and psychological optics.

Three-dimensional television is practicable for remote-handling operations. Color enhances the sensation of depth but considerably reduces light transmission. The reliability in the measurement of depth displacements is decreased by "diffusion" effects of the colored images at the television screen. This should be given particular attention for a future prototype. In this system the limitations in monocular resolution (image definition) are basically imposed by the inherent characteristics such as the number of scanning lines, non-linearity of the scanning beam and non-constancy of focus throughout the picture area. Nevertheless, stereoscopic (depth) resolution is high since such resolution is geometrically independent of monocular image quality. Preliminary tests with observers possessing 10 seconds of arc stereoacuity have substantiated the calculated values by discerning 1/16-inch to 1/32 (1/64 observed occasionally) inch depth displacement for targets at 9 ft. distance from the camera objectives.

PSYCHO-PHYSIOLOGICAL COMPONENTS IN DEPTH PERCEPTION

In monocular vision, without moving the head and without instrumentation, all we can tell is the direction of an object in the field of view; but binocular vision affords the possibility at least of forming some estimate of distance as well, provided the object is not too far away as compared with the interpupillary distance and provided also that the requisite data are sufficiently accurate and can be conveniently employed. Binocular perception of depth depends essentially on an unconscious process of triangulation, the vertices of the triangle being the centers of rotation of the two eyes at a fixed interval apart and the point of intersection of the pair of lines of fixation.

Geometrical Aspect of Monocular Depth Perception

An accurate stereoscopic screen presentation requires faithful reproduction of the relative spatial position of objects in the original scene. This presentation must fulfill several conditions of monocular perspective if form, size, and depth are to be correctly represented stereoscopically.

If the presentation is accurate, then a single picture viewed with one eye at the appropriate distance is sufficient to establish measurements of object distances provided we know the actual sizes of all the objects and the distance of one of these objects. And, if the picture is viewed so that one of the images subtends the same angle as the corresponding object, a scaled flat representation of the actual scene is produced on one picture. Ordinarily, our estimate of the actual linear dimensions of an object is based on this angular size, registered by the linear size of the retinal image and coupled with the estimated distance of the object from the eye. An eye would appreciate the visual angle subtended by an object of 1 cm. in diameter at 100 cm. distance, but no judgment could be made of the actual linear extent of 1 cm. if there were no knowledge of the 100 cm. distance. In the absence of anything upon which to base an estimate of distance, the object might as well be 10 cm. at 1000 cm. distance. Conversely, we are assisted in our estimates of the distances of objects by a knowledge of their sizes. If we add shadows and colors properly to the picture, we would have, as the artist normally represents in his paintings, the illusion of relief, i.e., a sensation of monocular depth. It is obvious that, if these images are not depicted to subtend the same corresponding angles at eye as the objects of the original scene, this representation would appear distorted from lack of geometrical similarity, even though the casual observer does not consciously recognize the incongruity.

If a single camera (monocular condition) is placed in one position with respect to the scene, then the picture produced would have to be viewed from only one position from the observer in order that he might get a true depiction of the original scene. For example, if a photograph is made of two objects, A and B, where A is the closer object and a definite distance from the camera, then, relative to this object, B will be some distance from A. Now if this picture is viewed by an observer at a distance such that the image of A does not subtend the same angle as object A, the observer will not be able to determine the distance AB in the photograph.

The eye of the observer looking at the outside world is unconsciously aware of the relative angular subtense of all objects in space and, therefore, places all objects in what appears to be reasonably correct positions. If objects are known to be of the same size to the observer, but subtend different angles at the eye, the objects will be projected to their correct locations to correspond with their angular subtenses. Hence, if one of two objects of equal size in the scene subtends an angle (at the eye) equal to one-half the other, then the object subtending the smaller angle will appear to be twice as far. If the location of a known reference object is accurately determined and its angular subtense measured with a theodolite, then all other objects of the same size occupying different spatial positions, relative to a common observation point, can be located by their angular subtenses. If the relative sizes of all other objects are known, they too can be similarly located. This is a simple geometrical relation.

However, the unaided eye cannot measure angles with this degree of accuracy. Nevertheless, with experience, the spatial relations of objects can be reasonably well proportioned in the mind. For example, the inexperienced baby looking at the moon through the window imagines it to be in the plane of the window, or perhaps even closer, and tends to reach out for it.

Under proper conditions, a highly corrected camera sees all points in correct perspective. If objects in the field of view are of the same size but located at different distances, then, in Figure 1A, the angular subtense (θ) would be the object height (h), divided by the distance from the camera (d)

thus, $$d = \frac{h}{\tan \theta}$$

The objects are of equal height (h) = $O_1A = O_2B = O_3C$, and are depicted on the film plane as O'A', O'B', O'C'. If the observer's eye is at L, then the angular subtense for each object

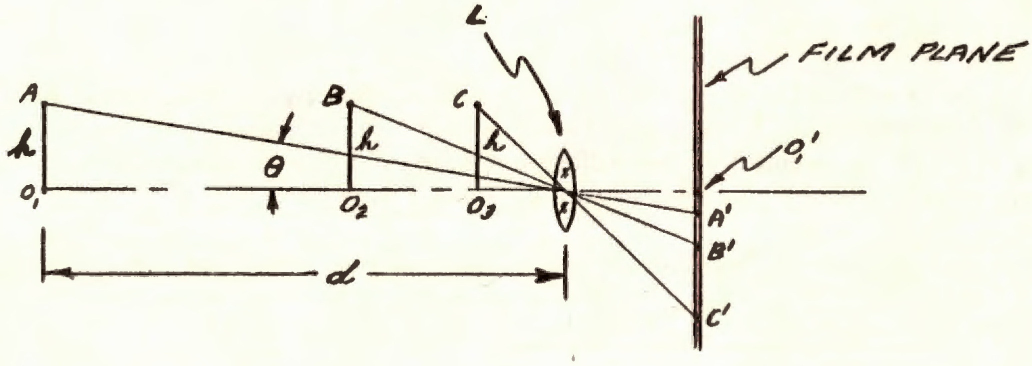


Fig. 1A

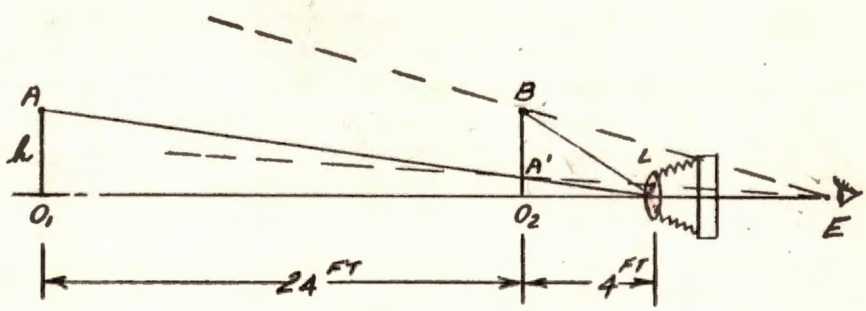


Fig. 1B

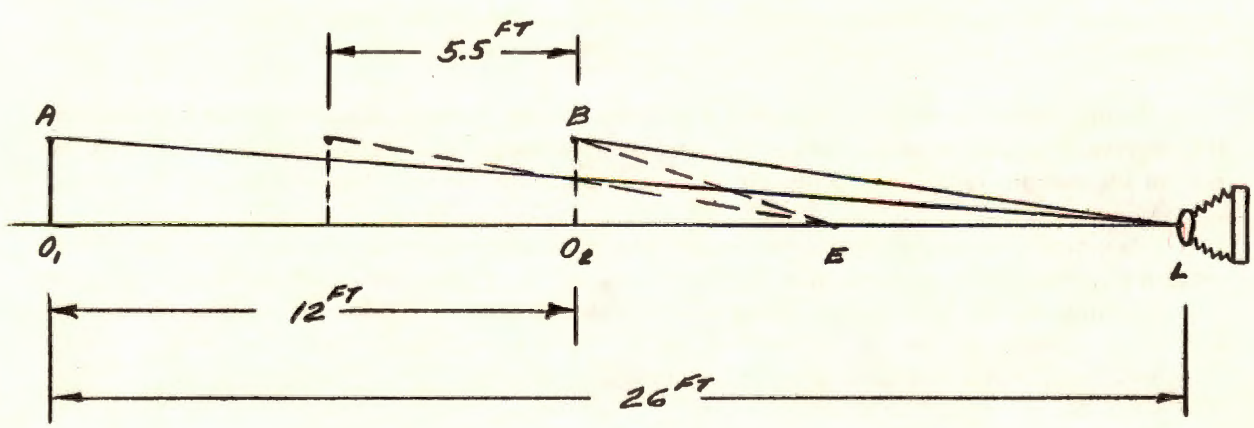


Fig. 1C

and corresponding image will be equal whether the eye is looking directly at the objects or at the images on the film plane; and all points would be projected into space and visualized in correct perspective. This is, essentially, monocular visualization of correct perspective without the aid of any other monocular clue and, of course, without stereopsis.

However, if a photograph taken at one distance is observed from some other distance such that the angular subtense for any one object in the picture is not the same at the eye as it was at the camera, then false perspective will be visualized. See Figures 1B and 1C.

For example, in Figure 1B

O_1A and O_2B are equal in height (h)
O_1 is 24 ft. from O_2
O_2B is 4 ft. from camera (L)

Hence, on the photographic film which is placed in the plane of O_2B, the image height O_2A' (of object O_1A) is 1/6 of O_2B. To an observer's eye E placed 8 feet from the picture, O_2B appears normal in height, and since O_2A' is 1/16 of O_2B, then O_1A will appear 6 times as far or 48 feet. Thus, the distance (depth displacement) between two objects at O_1 and O_2, which is actually 24 feet in the original scene, appears to be greater (48 feet) when the photograph is viewed from distances (8 feet in this case) such that the angular subtense of the images in the photograph at the eye is less than the angular subtense of the original objects at the camera lens.

In Figure 1 C,

O_1A + O_2B are equal in height (h)
O_1 is 12 feet from O_2
O_1 is 26 feet from Camera (L)

Since distance O_1O_2 = 12/26 = 46% of camera distance O_1L, then to an observer (E) six feet from the image plane, O_2 will appear .46 x 12 = 5.5 feet from O_1. Thus, the distance (depth displacement) between the two objects at O_1 and O_2 which is actually 12 feet will be interpreted as 5.5 feet because the angular subtenses of the images on the photograph at the eye are greater than the angular subtenses of the corresponding objects in the original scene at the camera.

In other words, for faithful reproduction of sizes or distance of objects from a photograph, the observer's eye must be located at the center or perspective as defined by the relative position of the camera lens. Any other viewing position, therefore, must introduce distortion of depth.

As stated previously, the artist depicts scenes in correct perspective and with the aid of other monocular clues produces the illusion of depth. If an observer moves backward and away from the picture, the background objects will appear to spread and recede into the picture. This is the illusion of "movement" or "motion" in the picture brought about by changes in relative angular subtense and other monocular clues such as color, shade, shadow, etc.

As mentioned before, the eye is not a calibrated measuring instrument and cannot discern exact spatial positions of objects. However, the brain will tend to place objects in a reasonably well-proportioned relationship according to past experience. Furthermore, since the object sizes and distances are usually not accurately known, geometrical determinations cannot be made from a single photograph. As is well known, aerial photography requires stereoscopy for making accurate measurements of the terrain.

Thus far, consideration has been given to vertical angular differences (or angle of elevation) and the bipolar parallactic angle which defines the displacement toward or away from the observer (ordinarily referred to as "depth"). Application of the above thinking in horizontal angular displacement (bipolar latitude) will indicate that lateral and/or vertical displacement of the observer's eye relative to camera position will also introduce distortion. Thus, it should be evident that the camera position defines the center of perspective and that the observer's eye must assume this position for geometrical correspondence to perceive true perspective.

Binocular Depth Perception (Stereopsis)

A scene reproduced on a television screen cannot be reliably measured binocularly or stereoscopically when the picture is not in correct monocular perspective.

By means of stereoscopic vision it is possible to utilize two photographs of a scene, each taken from a different aspect to accurately measure the disparities between two corresponding points in the picture. Knowing the distance to one of the objects, as well as the base line or interaxial distance, it is then possible to make accurate quantitive determinations of relative positions of objects in space.

Two basic points must be remembered regarding binocular depth perception:

1. Stereopsis gives very accurate relative depth discrimination. This means that stereopsis will make it possible for the observer to tell which of two object points separated in space is nearer (or farther).

2. Binocular vision cannot, of itself, give a reliable estimate of actual or absolute distance from an observer to an isolated object point. The base line and the distance to one object point is required.

Hence, it should be obvious that, while stereoscopic methods permit very accurate geometrical determination for objects in depths, monocular clues such as form, shadows, colors, perspective, blocking, etc., will enhance the sensation of depth, but will not necessarily contribute to actual measurement accuracy.

Three-dimensional television viewing is not unlike motion picture viewing and, therefore, must require adherence to several factors in depth perception which are most fundamental. First, the images on the screen must be sharp and of equal size (retinal image disparity within 0.1% for sensitive observers). Secondly, the angular subtense of the images at the observer's eyes must be the same as the angular subtense of the two objects at the camera lens. This implies that there is one position for viewing the screen and obtaining faithful representation —

namely, the orthostereoscopic position. Thirdly, the images must be presented to corresponding eyes, each with complete occlusion from the other eye, for best, comfortable stereoperception. Finally, if monocular presentation at the screen is not accurate, the stereoscopic presentation will tend to magnify the inaccuracies and, if the inaccuracies are large, the stereo-presentation will be distorted.

Normally, in most picture viewing the observer is not fully aware of the actual spatial positions of objects within accurate measurable amounts. For instance, it does not matter ordinarily to the casual observer whether a mountain in the rear of the panoramic scene is 20,000 feet or 25,000 feet away, just as long as the presentation is reasonably balanced and in keeping with normal experience.

Now, if the interaxial distance or the base line is increased in binocular vision, then the distance between objects in space will become more easily discernible; however, an increase in base line would tend to exaggerate the distortions in those pictures which are not faithful monocular representations of the original scene. Hence, in a stereoscopic presentation, it will be much safer if the interaxial distance between the two cameras is equal to the interocular distance of the observer, since the orthostereoscopic position is, very often, not conveniently assumed. This is recommended to permit comfortable, natural viewing and to avoid distortions of the original scene which would otherwise give the effect of either unnatural giantism or dwarfism in a scene. Again, the monocular clues for depth perception such as overlay, perspective, shadows, parallax,and height must faithfully be represented geometrically, to prevent false perspective. Here, when monocular clues are consistent with all binocular disparities, they greatly reinforce the stereoscopic sense of depth. However, if the binocular clues are not consistent with the monocular clues (a situation which is inevitable when telephoto or wide angle lenses are used), the monocular clues exaggerate and distort the binocular disparities.

Sometimes attempts are made to conceal false perspective by separating stereoscopic camera lenses by some distance which is different from the normal separation of human eyes. The result is a conflict between stereoscopic sensation and perspective. Such a conflict can be resolved only by perceiving distorted shapes, sizes,and distances. As a matter of fact, no choice of camera separation can eliminate false perspective or correct the distortion caused by false perspective.

On the other hand, if monocular perspective is correct, then considerable variation of camera separations is tolerable. The same cannot be said for considerable deviations from correct monocular perspective, even when the camera separation is equal to the normal distance between the two eyes.

Stereoscopic Acuity

For an average base line or interpupillary distance of 62.25 mm., the so-called radius of stereoscopic vision is found to be about 450 mm., on the assumption that the limiting physiological angle of depth perception is equal to half a minute of arc, which is the ordinary "conventional value" of this angle for man. This means that the naked eye alone, with this stereo-acuity, cannot discriminate differences of distance or depth of objects that are more than 450 meters away or a little over a quarter of a mile.

The use of the "conventional value" of 30 seconds of arc as the minimum perceptible parallactic angle for the so-called "average" observer introduces implications that very often have caused difficulty in the appreciation of the stereoscopic acuity in man.

Two objects in space must be separated by a certain distance before one of the objects can be appreciated as being nearer than the other. The minimum distance that the two objects in space must be separated (or their relative binocular parallax) expressed in angular measure defines the binocular or stereoscopic acuity. The binocular or stereoscopic acuity (n) is equal to the smallest resolvable difference in depth (Δ x) at the distance x by an observer whose interpupillary distance is e.

Therefore $$n = e. \frac{\Delta x}{x^2}$$

Experimental results have been found to vary considerably among individuals. Some persons with good visual acuity and training in binocular viewing have stereoscopic acuity as precise as 5 seconds of arc, or even 2 seconds of arc under favorable conditions. Others cannot determine parallax differences of 60 seconds or even a few minutes of arc, while in some the stereoscopic sense is lacking entirely. In 1926 Langlands showed that with very short duration of illumination (less than 1 millisecond) the stereo-acuity falls to about 10 seconds in individuals with high stereopsis. With the same individuals, increasing the illumination exposure to 0.3 second, the acuity rises to 5 seconds of arc, and with constant illumination the stereo-acuity rises to 2 seconds of arc. Thus, a person with stereo-acuity of, say, 20 seconds of arc and with average interocular distance can perceive depth displacements of spatial objects beyond 450 meters— more accurately, 620 meters.

The geometrical form of the space image is derived from the parallactic system of points from the left and right images on the screen and can be exactly related to the structure of the original scene. Psychologically, however, the observer's mind, though it is accustomed to the appearance of objects in the real world, may alter the interpretation of the stereoscopic sense data and construct a different image in space. This will occur when the stereoscopic instrumentation, because of improper orientation and/or adjustment, gives rise to severe distortion and is noticeable particularly when the eyes focus on a screen, that they receive binocular sense data of which the stereo component (stereopsis) is not guaranteed, by nature, to operate.

Accommodation and Convergence

The primary requirement for complete binocular vision is to obtain reasonably distinct as well as single vision of any chosen point within the binocular field of vision. This requires that the functions of accommodation and convergence shall operate in close association with one another. Ordinarily they act together without conscious effort of mutual adjustment. Thus, the two visual axes meet at whatever point for which their eyes are accommodated. In the emmetrope the amounts of accommodation (in diopters) and of convergence (in meter-angles) to do this are equal, and in the corrected ametrope they are essentially so. A small relative adjustment of the two functions is necessary when the subject fixes an object to the left or right of the median plane, as when reading across the page of a large book.

On the other hand, the uncorrected hyperope (far-sighted) of 3 diopters looking at an object at 1/3 meter must use 6 diopters to only 3 meter angles of convergence; and a myope (near-sighted) of 3 diopters requires no accommodation for the same convergence.

The amount of accommodation that a person can exert will decrease with age and the amount of uncorrected ametropia. Hence the uncorrected hyperope, who must exert more accommodation per meter-angle of convergence than the emmetrope, applies the accommodation with increasing difficulty depending upon his age and degree of hyperopia.

However, under abnormal conditions the relative convergence can be changed, i.e., the accommodation can be set for some object distance while the convergence is increased. Increasing the convergence without changing accommodation soon causes the target to appear smaller, decreasing in size until it appears blurred, at which time the accommodation and convergence continue until, finally, diplopia (double vision) occurs.

If the emmetrope fixes his convergence upon a distant screen of 6 feet he will exert 1/2 diopter of accommodation and 1/2 meter angle of convergence. If, from the same distance, the emmetrope looks at stereo-images on a screen with separation of 2.50 inches equal to his interpupillary distance, the nearness factor will be 2 (image appears half-way between screen and observer) and the convergence will be 1 meter angle. Hence, the dissociation between convergence and accommodation will be 1/2 diopter. A two-diopter uncorrected hyperope would have to dissociate 1/2 diopter also, but his total applied accommodation would be 2-1/2 diopters. Fatigue would ensue more rapidly with the hyperope.

Accommodation for the viewing screen should be as little as possible in order to make greater dissociation of the convergence possible with minimum fatigue. While the convergence can be maintained for nearness factors much greater than two when viewing screens at 15 feet distance and greater, it is advisable to reduce the nearness factor to about 1.5 for viewing distances of about 5 feet. A trained emmetropic observer viewing stereo-images on a screen at 5 feet with the nearest fused stereo-image 30 percent (nearness factor = 1.5) closer to him than the screen, would feel quite comfortable. Proper viewing distance and distance factors are discussed more fully later on in this report.

Visual Response and Persistence

When light radiation first impinges upon the retina, a latent period exists before the visual sensation is elicited by the brain. This period involves the time necessary for chemical interaction at the retina and the time before the visual cortex recognizes the disturbance or impulse. At ordinary intensities, the latent period will be between 0.20 second to 0.08 second, depending upon the state of the eye and the individuality of the observer. This period diminishes as the intensity of the stimulus is increased until finally a minimum value is reached lying between 0.13 second and 0.065 second—beyond which no matter how brilliant or sudden the flash of light may be, the sensation time or latent time cannot be lowered further.

Since the rods are more sensitive to light than the cones, it follows that peripheral (perimacular) vision is more light sensitive than central (macular) vision with the least sensitivity at the rod-free fovea. The latent period is longer in the fovea than in the periphery of the retina. And, all other things being equal, the latent period of the dark-adapted (scotopic) eye is shorter for the short wavelengths than for those of the long wavelengths.

The region of maximum sensitivity of the light-adapted (photopic) eye is in the yellow-green (at 550 mμ) whereas the region of maximum sensitivity of the completely dark-adapted (scotopic) eye is 510 mμ. Perception of light stimuli is dependent upon the intensity, duration, and rate of stimulation. The time threshold is decreased as the intensity is increased. The critical frequency for fusion of flicker varies with wavelength, and is lower for the rod area than the cone area.

The critical flicker frequency (c.f.f.) varies from 2 to 3 cycles per second at very low intensities to about 60 cycles per second at high intensities. The c.f.f. is the detection of changes of brightness in a light that is going on and off at a rapid rate. As the rate of flicker is increased, the retinal record is fused long before flicker appears. The maximum rate of flicker for fusion in the retinal record, for example, varies between 20 and 40 cycles per second, although the c.f.f. goes up to 60 cycles or even higher. If the flickering light does not go on and off, but rather alternates from one level of intensity to another, a sensation of flicker will occur. When the two levels of brightness are equal, the flicker will disappear. If the two alternating lights of unequal brightness are separated by a dark period, the flicker will be even more pronounced. The flicker disappears when two alternating lights or surfaces are equally bright, even when there is considerable difference in the color of the illuminants. Thus, colored pictures presented alternately to the eye may be above the fusion frequency threshold though the flicker will still persist because of brightness disparity.

Persistence of vision of an impression depends chiefly upon:

1. Brightness of illumination

2. State of adaptation of the eye (a dark-adapted eye is about 1000 times more sensitive than a light-adapted eye in ordinary light room and 100,000 times more than a light-adapted eye in bright daylight)

3. Locality of the stimulated area of the eye

After the latent period, the stimulus is recognized and the visual impression persists for at least 0.17 second, the time required for the three after images (Hering's, Purkinje's and Hess' after images), after which persistence may last up to 12 seconds and more (see Fig. 2). The duration of the phases depends upon both color and intensity of the stimulus. The effect

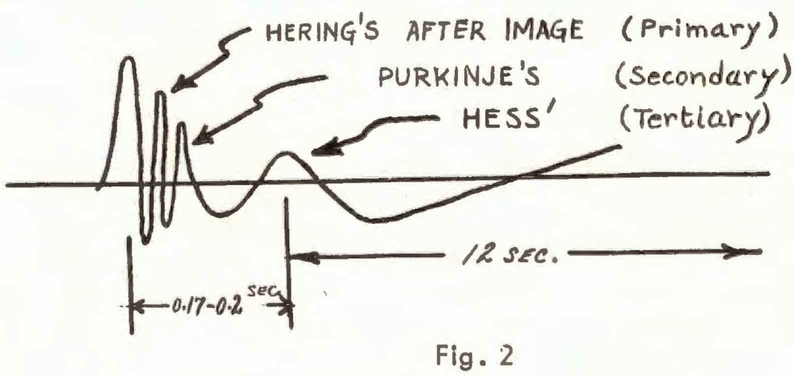


Fig. 2

of persistence varies with wavelength, the persistence being greater for yellow-green than for red or blue at the ends of the spectrum. The peripheral action is most sensitive to the blue end of the spectrum.

For ordinary heterochromatic light, under ordinary environmental conditions and with a 0.001-second flash, the persistence of vision can be taken as 0.10 to 0.15 second approximately.

THE STEREO COLOR TELEVISION SYSTEM

The stereo television equipment consists of the General Electric ITV Color Camera Chain, described in detail separately, especially adapted to a single-channel development and processing of stereo information. This is accomplished by the use of a Stereo Attachment for the Color Camera which permits alternate presentation of left-eye and right-eye optical information to the Image Orthicon tube—the active recording element of the ITV Color Camera. This information is transmitted to the Monitor circuits for processing and then presented on the Monitor Picture Tube in color for set-up purposes and on the Stereo-Viewer Tube in color for viewing. For the Stereo-Viewer, the monitor circuits develop a composite signal, consisting of sync pulses and video information, which is transmitted to the Stereo-Viewer equipment where it is processed and presented in alternate left-eye, right-eye sequence corresponding to the Camera viewing sequence. An appropriate color filter and Polaroid filter arrangement permits viewing of the developed cathode-ray picture tube image in color and in three dimensions by the use of Polaroid viewing glasses.

The general schematic of the components of the system and their electrical interconnections are shown in Fig. 3.

Camera Trunnion:

The Camera Trunnion, refer to Fig. 22, is designed to support the Camera equipment and to provide basic Camera scanning movements of 360° horizontal rotation and elevation to within 10° of the zenith. The Camera is coupled to the Trunnion by a Dither Plate Assembly which contains a motor-driven swivel designed to keep the Camera in continuous motion so that burn-in on the Image Orthicon is avoided or minimized.

The Camera Trunnion movements are motor-driven and are provided with a foot-operated remote control box and connections for remote operation. The construction provides adjustment of the vertical support for various Camera heights.

Stereo-Attachment:

The Stereo-Attachment for the Camera consists of two parallel optical systems, corresponding to the left and right eyes, having an interpupillary distance which is approximately twice that of the human. Refer to Fig. 4. These systems consist of an objective lens, L_1, a field lens, L_2, in the plane of the primary image, and a relay lens, L_3, which transfers the primary image to the photo cathode, the light-sensitive surface of the Image Orthicon. The two systems are converged through a system of mirrors, R_1, R_2, and R_4, and a beam splitter, R_3,

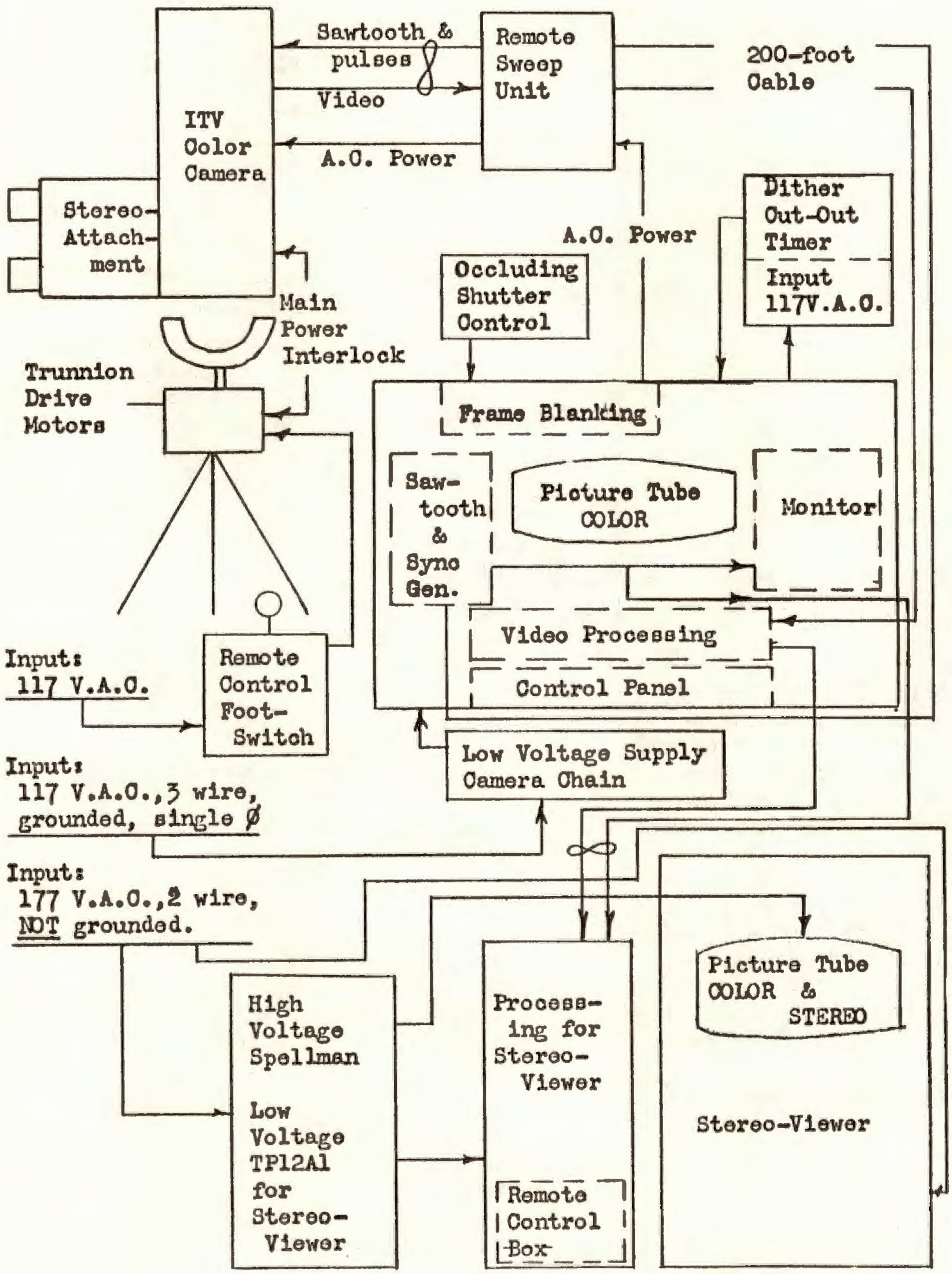
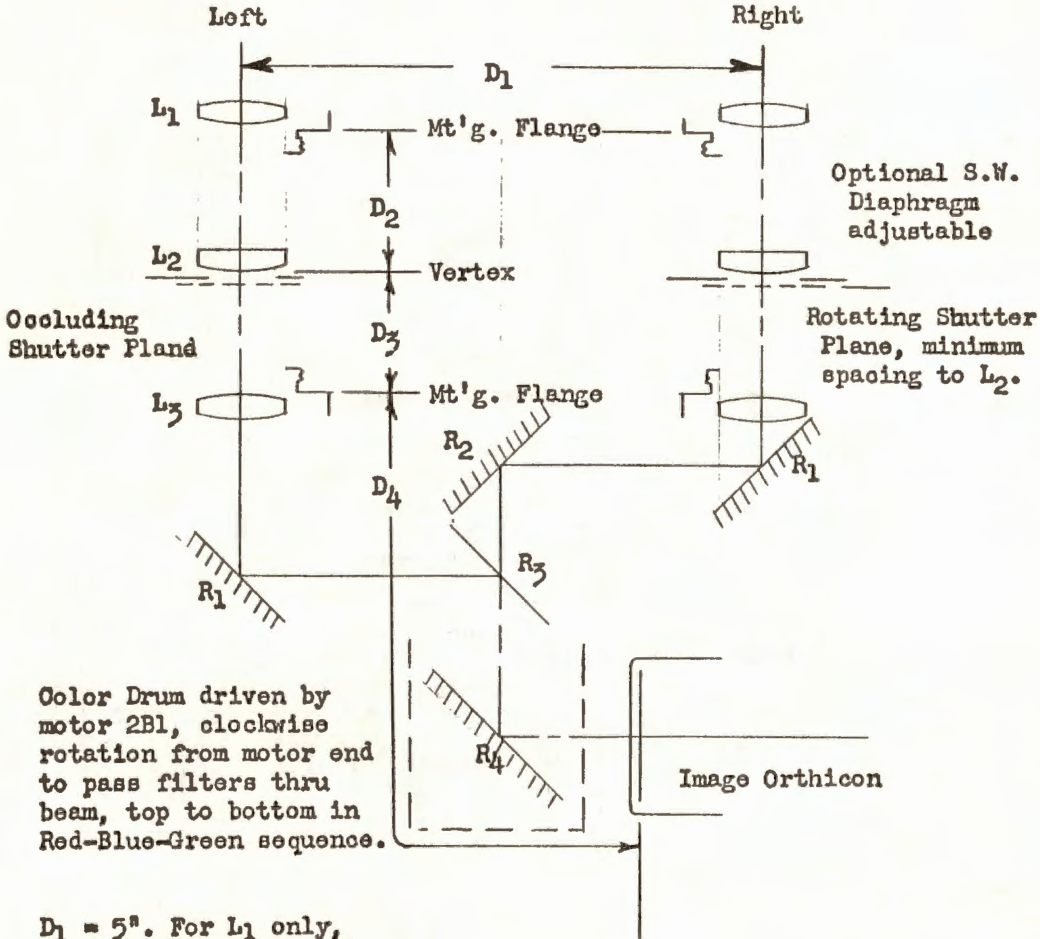


Fig. 3 System Schematic



D_1 = 5". For L_1 only, adjustable to $4\frac{1}{2}$".
D_2 = 2.6" adjustable.
D_3 = 6-3/16" adjustable
D_4 + 11-13/16" to I.O. focus adjustment.
I_1 within L_2
I_2 on photocathode of I.O.

Mirror Alignment:
R_2, R_3 & R_4 mutually perpendicular to plane of drawing within 10 seconds, and at 45 degrees to the optic axis within 10 seconds.

R_1, nominally perpendicular to the plane of the drawing and at 45 degrees to the optic axis. To be adjusted in initial set-up to superimpose images of centered lens system on I. O.

Fig. 4 Stereo-Attachment, Optical Schematic to superimpose the images on the photo cathode of the Image Orthicon. A stereo window diaphragm is located adjacent to the field lens, as is the rotating shutter.

The stereo window diaphragm is located in a position, with respect to the primary image, such that a stereo window plane is created in the apparent field of view. It is located so that, in the Stereo-Viewer, all objects appear to be viewed through the window against the background of the picture tube.

The rotating shutter is located in close proximity to the primary image plane so that it effectively shutters each system immediately following the corresponding vertical scanning position of the scanning electron Beam on the photo cathode in the Image Orthicon. The shutter rate is therefore determined by the sweep rate. It shutters the beam from the bottom to top since the primary image is inverted. The secondary image on the photo cathode is erect and therefore scanned top to bottom while the color drum rotates top to bottom to intercept the beam in close proximity to the photo cathode. The control circuits on the shutter and color drum motors and the connections for the I.O. Focus Coil have been arranged to accomplish this.

Occluding Shutters are positioned between the Rotating Shutters and the Relay Lenses. They may be operated singly or in tandem. Singly they are used to occlude one or the other of the optical systems for set-up purposes. In tandem they are used to occlude the Image Orthicon from all light to permit burn-out or recovery from an over-exposure to excessively bright fields. A Remote Control is provided with pilot lights and is attachable to the Monitor.

The mirrors, R_1, R_2, and R_4, first surface aluminum protected with silicon monoxide, are used to direct the passage of light but have no other optical effect. Mirrors R_1 are used as variables in the system alignment as discussed under Operation.

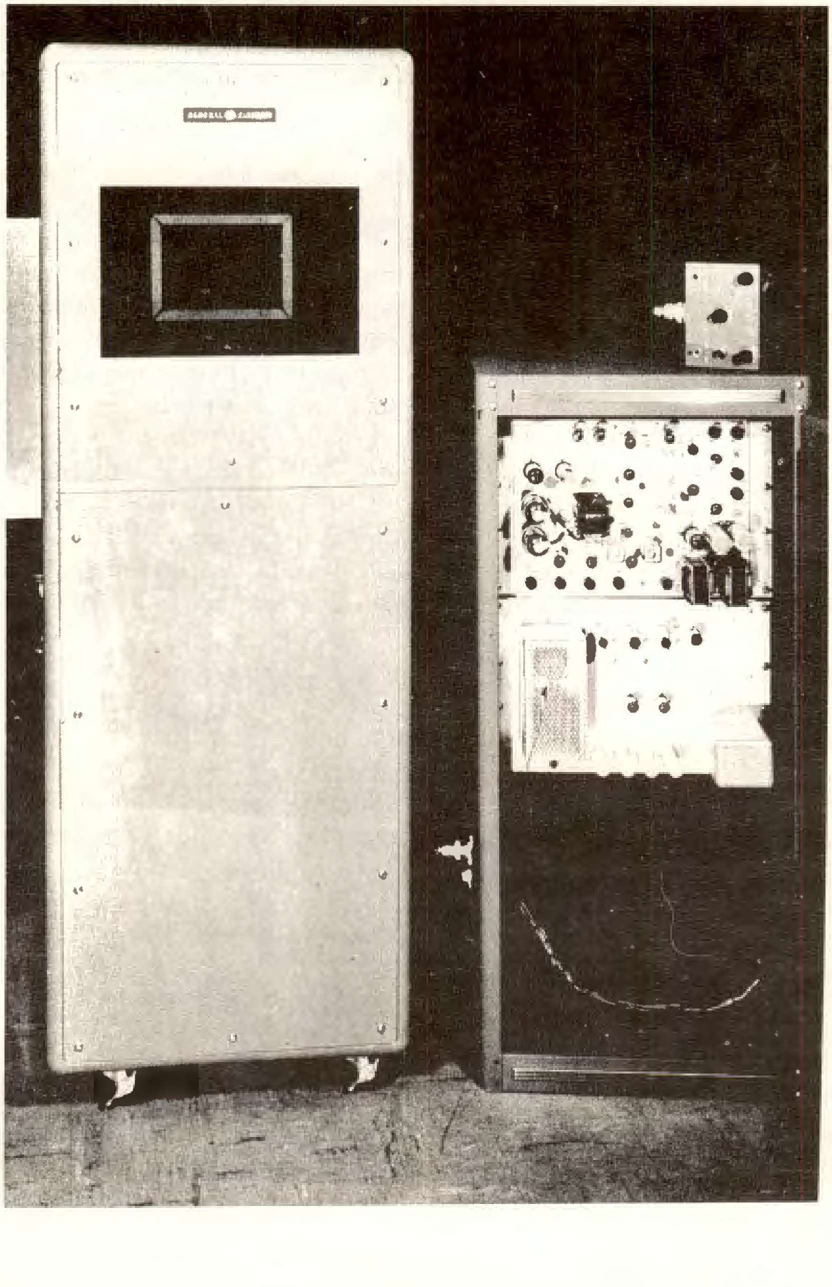
The beam splitter, R_3, is a partial reflecting, partial transmitting element used to superimpose the two light beams in equal amounts so that both images fall on the aperture of the Image Orthicon.

The Stereo-Attachment is constructed to mount in tandem with the Camera on the Camera Trunnion.

Stereo-Viewer:

The Stereo-Viewer, Fig 5, consists of a cabinet which houses a 10-inch direct view picture tube, a filter drum and a drum drive mechanism. The filter drum contains Polaroid and color filters to effect a color and stereo presentation for direct viewing with special Polaroid viewers. The composite sync and video signal is fed directly from a Monitor to the Stereo-Viewer circuits on a shielded coax-cable.

The electronic circuits of the Stereo-Viewer operate on General Electric's color ITV standards of 441 lines, 180 fields per second and an 18-megacycle bandwidth. In addition to the components located in the power supply unit as mentioned above, the Stereo-Viewer has a Video Amplifier and Sync Stripper chassis, a Horizontal and Vertical Deflection chassis, and a Deflection Interlock circuit, all of which are mounted in a cabinet, separate from the Stereo-



Viewer and connected directly by cables to the Picture Tube Assembly.

The Video Amplifier has a maximum gain of about 100, with a bandwidth which is flat to 15 megacycles and not more than 3 decibels down at 18 megacycles. The contrast control, Remote Control Box, varies the D.C. voltage on the suppressor grid of the first tube. The brightness control changes the level to which the black level is restored on the grid of the picture tube.

The Sync Stripper circuit simply strips sync pulses off the composite video signal and supplies an output to the deflection unit.

The Horizontal Deflection circuit, the first of three which comprise the deflection unit, is an oscillator drive sweep—a free-running oscillator providing pulses to discharge the saw-tooth generator. This oscillator's frequency is synchronized to the incoming sync pulses by an automatic frequency control (A.F.C.).

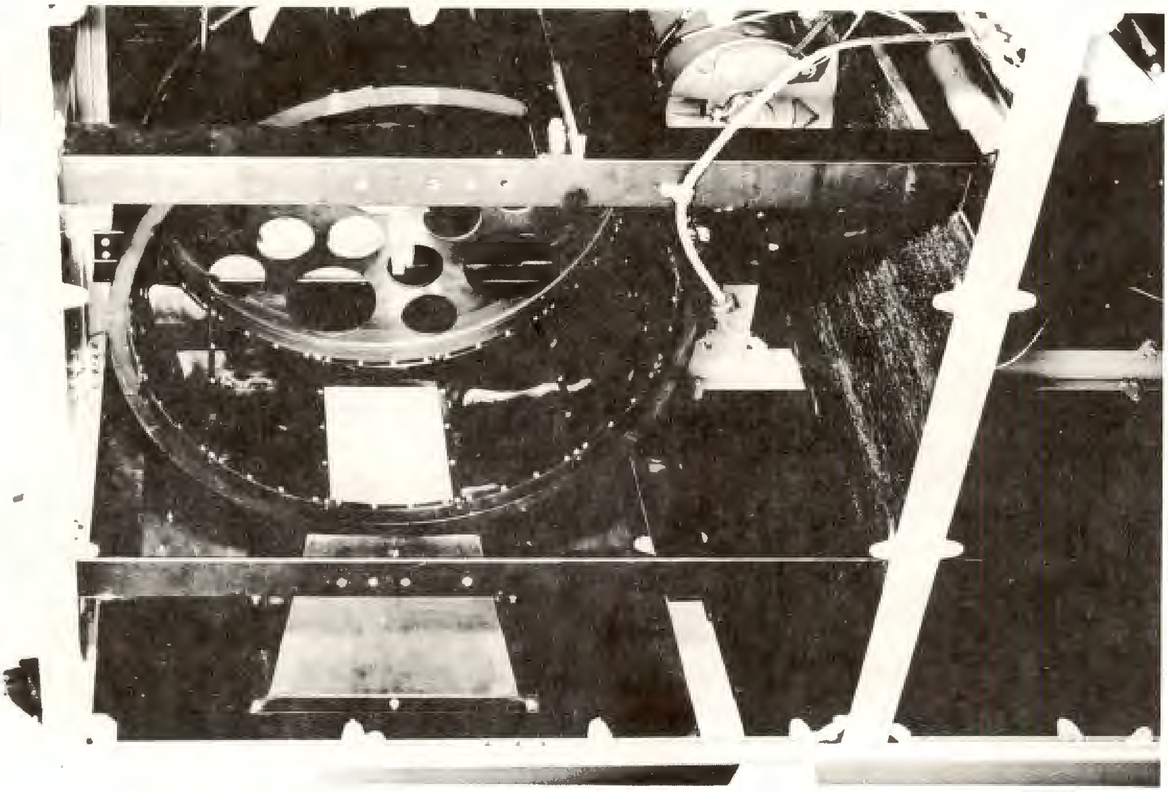
The second, the Vertical Deflection circuit, is essentially the same principle. A resonant tank circuit is tuned to twice the horizontal frequency and the output of this circuit is used to gate in the incoming vertical pulse. This gated vertical pulse controls a free-running multivibrator, the pulses from which discharge the saw-tooth generator. The reason for gating vertical pulses in at twice the horizontal rate is to assure good interlace.

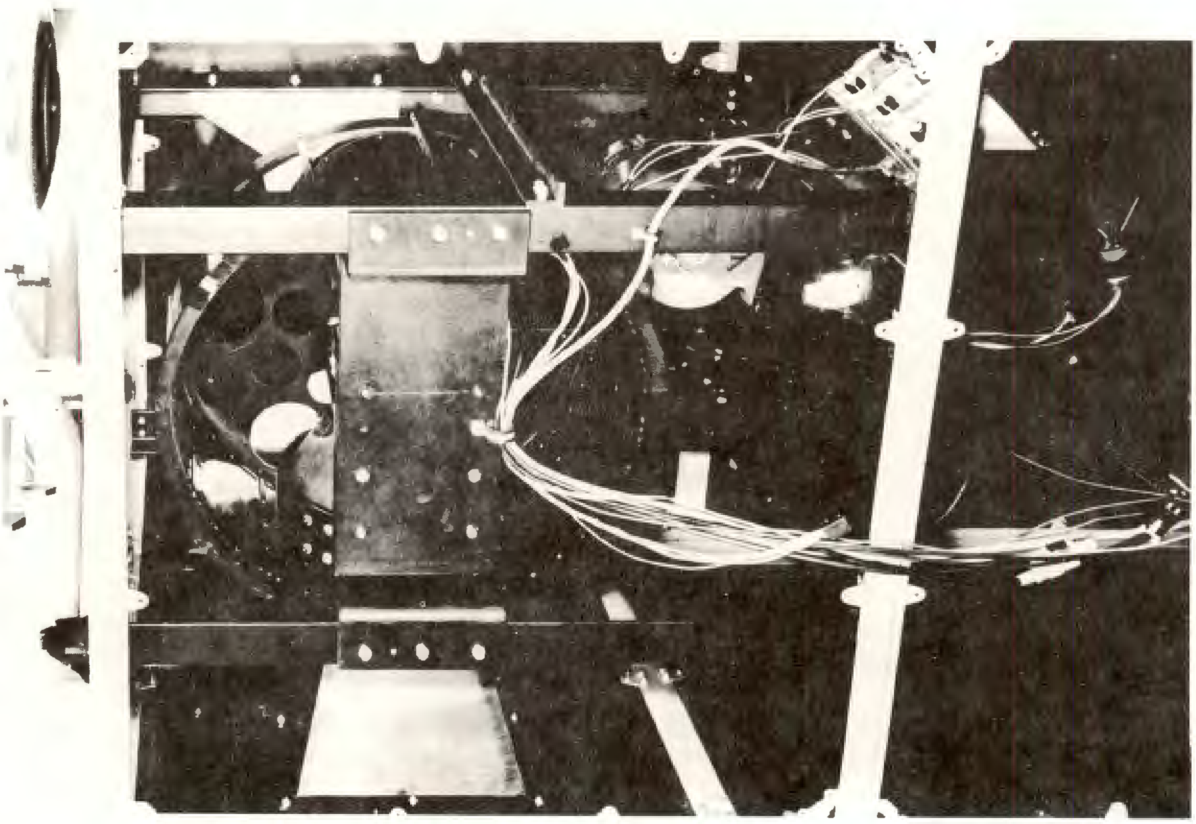
The third, the Deflection Interlock circuit, is a protection device which allows the high voltage to come up only if both deflection circuits are operating correctly. A relay also opens the cathode circuit of the picture tube.

The Focus Regulator and -150 supply is a high-gain, constant-current regulator which compensates for changes in line voltage, changes in focus coil resistance, etc.

The picture tube is mounted in an assembly which positions it with respect to the deflection yoke and focus coil. It is held rigidly against curved rubber pads by pressure exerted by tenite blocks attached to the deflection yoke mount. A detachable centering yoke is placed on the neck of the tube after assembly before the socket is affixed as an auxiliary raster centering aid. A ground spring connection attached to the tube mount is stretched across the dagging on the tube and clipped to the base of the assembly. The entire tube mount assembly is installed within the filter drum and tube replacement necessitates removal of the entire assembly. It is a heavy assembly and requires considerable care to avoid damaging either the tube or the filter drum. The filter drum, Fig. 6, consists of an open end drum having twelve rectangular apertures to permit viewing the raster of the picture tube. Mounted in each aperture is a Polaroid filter and a color filter in a sequence to be described later under Theory. Each filter has a heavy acetate base to avoid buckling due to rotation and humidity effects. The drum is driven by a 1/4-horse synchronous motor which has a Variac and extra capacitance in its starting circuit to permit it to reach synchronous speed. Control switches and the Variac control are located in the lower left side panel of the Viewer.

The Remote Control Box which contains the main power control switch also contains controls for the operation of the tube--raster brightness control, video contrast control, focus con-





trol and filter drum phasing switch.

The observer of the Stereo-Viewer is required to wear special Polaroid Viewing glasses.

Production of Color in the stereo-pair of images.

The ITV system has a field frequency of 180 fields per second. These fields are interlaced and may consequently be considered as pairs of odd-even interlace, a complete scan of the optical-electronic information and thereby a complete scan of the optical information at a rate of 90 times per second. A color drum superimposed on this in the camera introduces into the optical system a different color filter for each of three successive frames. The filters are of three primary colors for an additive color system. They differ between the camera and Monitor as the spectral sensitivity of the corresponding pick-up and picture tubes differ. By tandem operation through the electronic processing and control circuits the pick-up system reproduces a scene in color in the viewing system. Since the scene must be scanned by each color in each phase of the odd-even interlace, six successive fields are required to present a complete scan of the optical information in color. This electronic arrangement is essentially field sequential. It may be illustrated as a series of boxes which are alternately odd and even interlace:

Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	(Filters)
odd	even	odd	even	odd	even	odd	even	odd	even	odd	even	(Fields)
1st Frame						2nd Frame						

It is this symmetry which permits the development of stereo presentation at 45 frames per eye per second. (The above frame sequential set-up can be used to present stereo at a rate of 15 frame per eye per second.)

For Stereo pick-up in the present system the above schematic becomes:

Stereo Pick-up (Stereo-Attachment Plus Camera):

Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	(Filters)
odd	even	odd	even	odd	even	odd	even	odd	even	odd	even	(Fields)
Left lens		//////////		Left lens		/////////		Left lens		//////////		(Lens
/////////		Right lens		//////////		Right lens		//////////		Right lens		System)
1st Frame		2nd Frame		3rd Frame		4th Frame		5th Frame		6th Frame		(90/sec.)

Stereo-Viewer:

Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	(Filters)
odd	even	odd	even	odd	even	odd	even	odd	even	odd	even	(Fields)
++++++++		--------		++++++++		--------		++++++++		--------		(Polaroid)
1st Frame		2nd Frame		3rd Frame		4th Frame		5th Frame		6th Frame		(90/sec.)

Observer:

Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	Red	Blue	Green	(Filters)
1st Frame		2nd Frame		3rd Frame		4th Frame		5th Frame		6th Frame		(90/sec.)
Left ++++		/////////		Left ++++		/////////		Left ++++		/////////		(Polaroid
/////////		Right ---		/////////		Right ---		/////////		Right ---		Glasses)

Fig. 7

In the Stereo Pick-Up, accomplished by the dual optical system of the Stereo-Attachment, the blocks of 'Left' and 'Right' are sequentially arranged by means of rotating shutters having apertures equivalent to two fields, odd-even interlace, or 2 1/180ths of a second. The frame rate of the indicated 90/second is equivalent to 45 Frames per second per eye. The Rotating Shutter is arranged so that it may be phased electrically to mechanically shutter the primary image immediately behind the scanning beam, in the schematic, directly behind every even Field, as it sweeps the secondary image on the photocathode of the Image Orthicon.

The composite developed by the three elements of the Camera—the field scan frequency, the color filters and the rotating shutters—is presented in the Stereo-Viewer picture tube and differentiated by the Filter Drum. The Filter Drum contains Polaroid filters oriented as described by the solid blocks, +++ & ---, alternately ('L' pattern—horizontal and vertical axes of polarization) and color filters in super-position. The observer then views the picture tube through Polaroid glasses. It may be noted that the presentation described requires twelve successive fields corresponding to the segments of the Stereo-Viewer Filter Drum, and also that a cylindrical drum construction is used to achieve an orthogonal presentation of the Polaroid filters for maximum extinction and transmission as required to develop stereo sensation.

Camera Rotating Shutters: 12 fields per half rotation at 450 R.P.M.

Camera Color Drum: 12 fields in 2 rotations at 1800 R.P.M.

Stereo-Viewer Filter: 12 fields in one rotation at 900 R.P.M.

This sequence provides pick-up and presentation of 12 fields of video and color information required to complete one full frame of color-stereo information.

Operators of this equipment are expected to have normal stereopsis or binocular vision with fusion characteristics and color vision without anomalies. The operator, in using the Stereo-Viewer, should view the picture tube at a distance which will yield the same, or as nearly the same as convenient, perspective as seen at the Camera objective. Thus, the presentation will be more nearly orthostereoscopic and simultaneously the largest visual subtense of the picture will be obtained providing a direct aid to the maintenance of fusion.

In the analysis of the present 3D full-color T.V. system, the physical aspects of monocular and binocular considerations of the transducing system and the eyes are of prime importance. The interpretation of the data necessary for efficient handling of remote equipment then requires psycho-physiological considerations. A real three-dimensional scene converted into a pair of images on a two-dimensional screen must be viewed by the operator, whose mind must interpret the location of objects in space in correct perspective. Thus, in order to satisfy the monocular, binocular, and psycho-physiological components stated above, the physical characteristics such as image quality, transmission magnification, interaxial spacing of the camera lenses, nearness factor, depth range, stereoscopic window, field of view, and system resolution must be given careful consideration. After these determinations have been made on the present system, the permissible stresses on the accommodation-convergence mechanism of the eye and the psycho-physiological effects on the operator can be properly evaluated for best performance, i.e., maximum measurement accuracy of depth displacement, with minimum fatigue.

The Dual-Camera Lens System

Each of the two camera lens systems is similar in design except for the beam splitter which superimposes the left and right images in plane of the image orthicon. Figure 8 is a diagram of one of the pair of the lens systems. Light from an object at infinity is focused by the 75-mm. objective at I_1 forming a real image close to the second vertex of the field lens. This primary image is then relayed by a lens of 100 cm. focal length to form a second image at the image orthicon I_2 after three reflections caused by plano mirrors and a beam splitter placed between the relay lens and I_2. The color filters (red, green, and blue) intercept the light from the two camera lens systems at the last mirror sequentially, by means of a rotating cylinder.

The relay lens is a standard photographic objective which by virtue of its position has a magnification ratio of $I_2/I_1 = 1.83$. The image at I_2 is transmitted to the T.V. tube screen forming an image I_3. The magnification ratio = $I_3/I_2 = 5.7$. These magnifications are fixed.

For an object distance of 10 feet from the camera (first vertex) the magnification is $I_1/0 = 1/39$. The magnification ratio $I_2/0 = 1/21.3$, and the transmission magnification = $0/I_3 = 0.267$ for this same object distance. Table 1 shows magnification ratios for some selected object distances.

Table 1 (Magnification ratios for selected object distances)

Object distance from camera	$\frac{I_1}{0}$	$\frac{I_2}{I_1}$	$\frac{I_3}{I_2}$	Transmission Magnification $\frac{0}{I_3}$	Transmission Magnification $\frac{I_3}{0}$
15 ft. (180 in.)	1/59	1.83	5.7	0.1768	5.67 x
10 ft. (120 in.)	1/39	1.83	5.7	0.2674	3.74 x
8 ft. (96 in.)	1/31	1.83	5.7	0.3365	2.97 x
7 ft. (84 in.)	1/27	1.83	5.7	0.3863	2.59 x
6 ft. (72 in.)	1/23	1.83	5.7	0.4535	2.21 x
5 ft. (60 in.)	1/19	1.83	5.7	0.5490	1.82 x

Occlusion of Images

The left and right images are presented alternately to the left and right eye of the observer by the method of light polarization. Since the phosphor persistence of the television tube is 1 millisecond and the duration of occlusion by the polaroid filter is 5 milliseconds, occlusion is complete for each eye in this transmission system. The polaroid filters, shutters, and scanning beam, when exactly synchronized, can present only one image to the proper eye.

Leakage of light from the alternate screen-image to the non-corresponding eye is minimized by using HN32 Polaroid filters, selected to give 0.005 percent extinction. The axes of polarization are placed in the 90th and 180th meridians; thus, curvature of the polarizers at the

DIAGRAM OF CAMERA LENS SYSTEM (MONOCULAR)
THREE PLANO MIRRORS NOT SHOWN

RELAY LENS
MAGNIFICATION RATIO $= \frac{I_2}{I_1} = 1.83$

TV TUBE FACE (SCREEN) $= I_3$
MAG. RATIO $= \frac{I_3}{I_2} = 5.7$

$I_1 = 0.525'' \times 0.7''$ (CONJUGATE TO I_2)

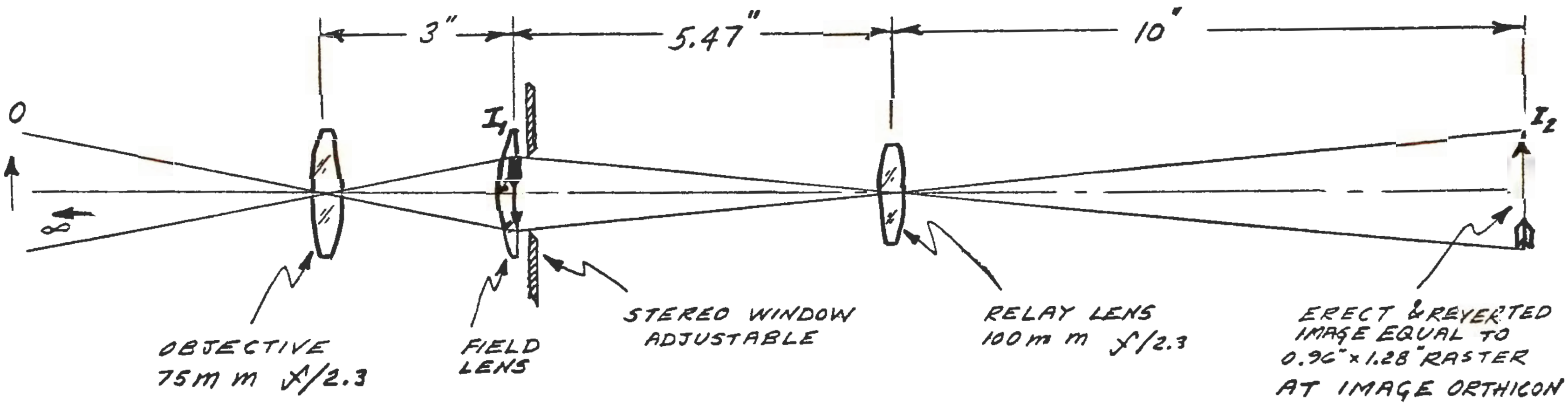
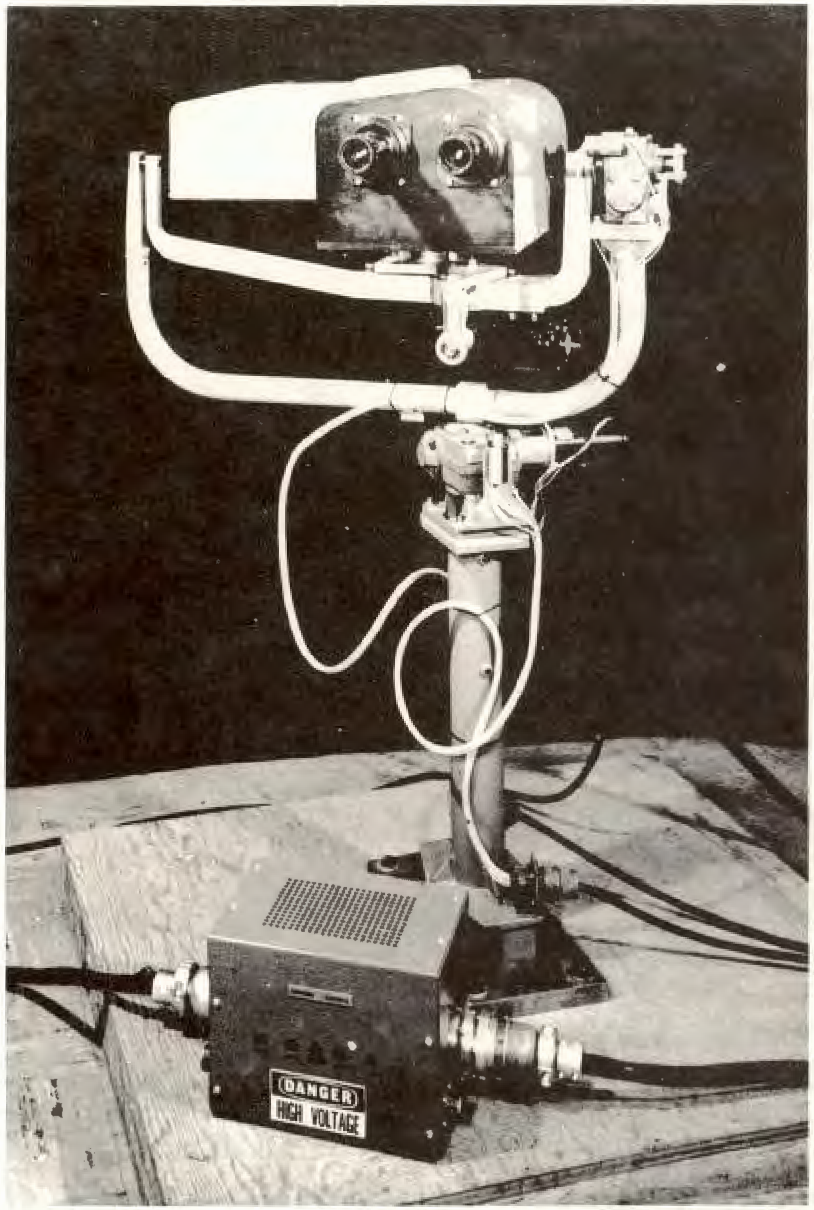
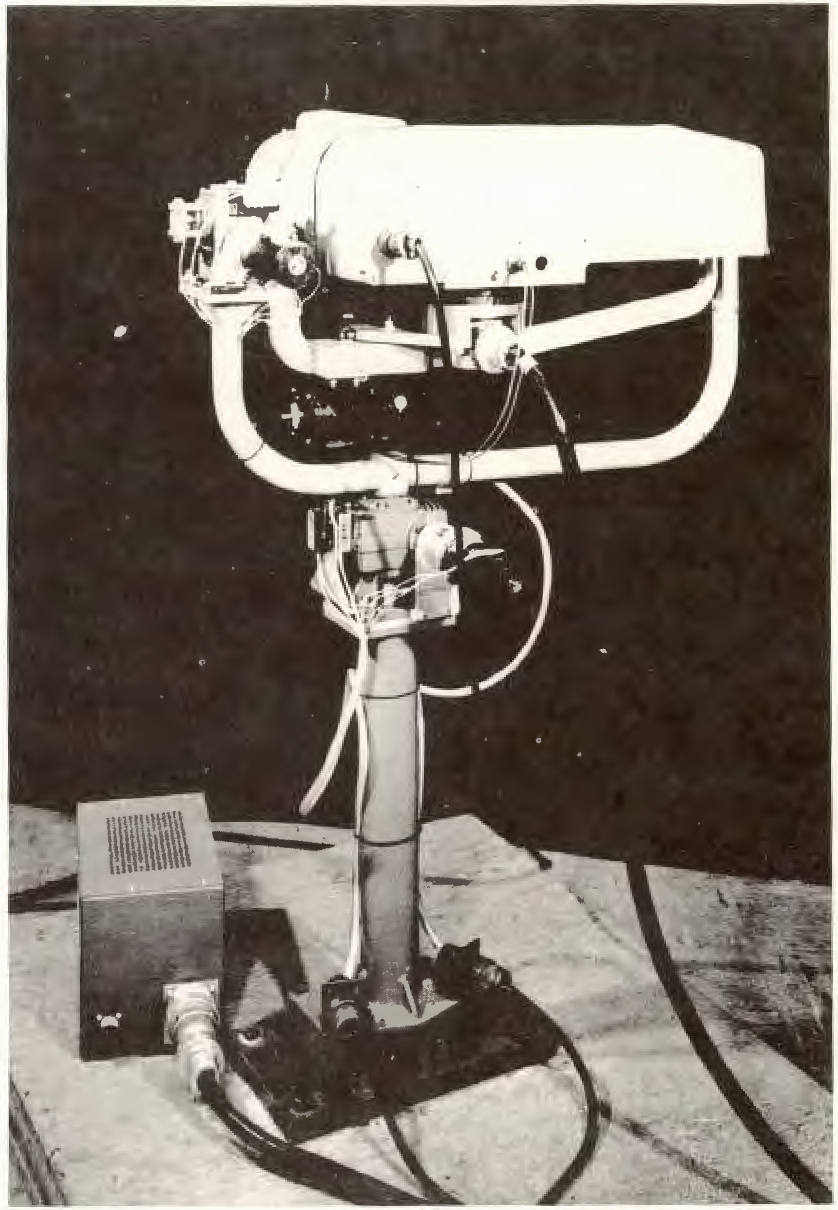
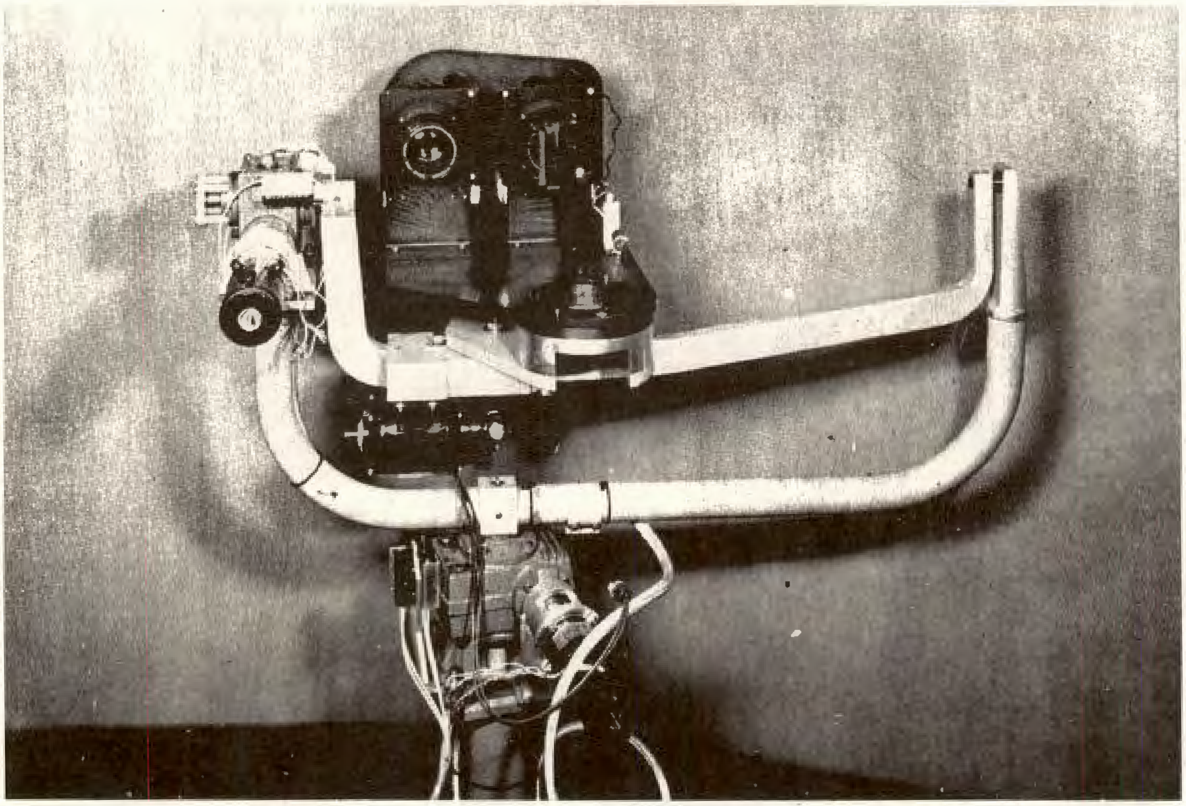
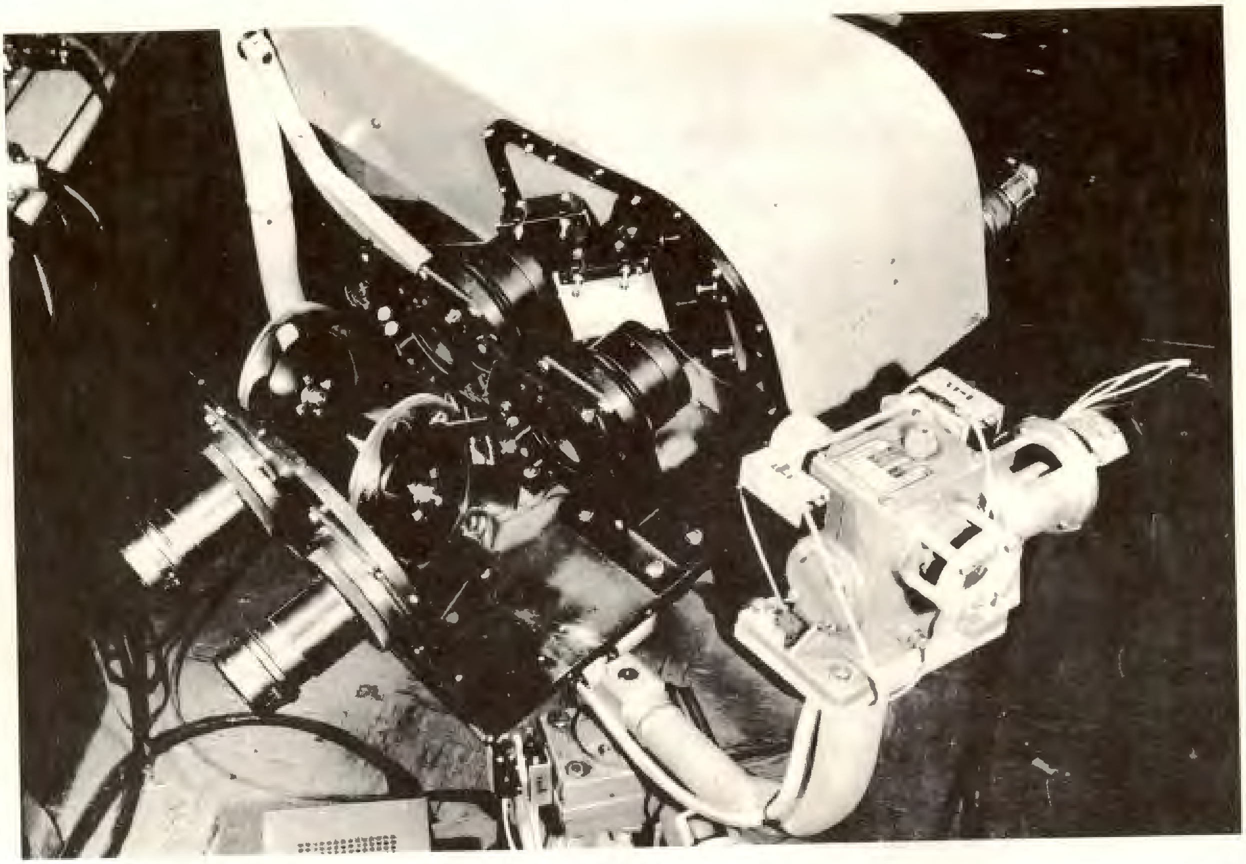


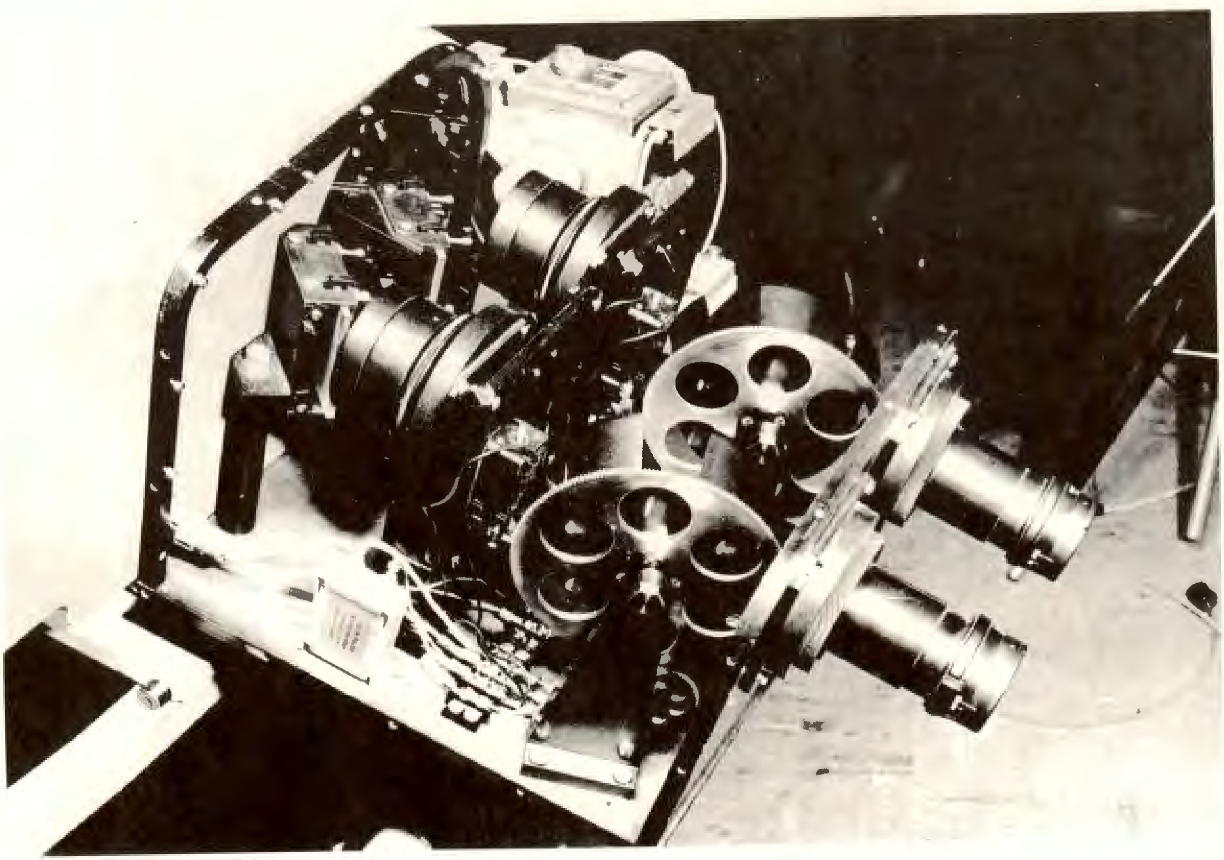
Fig. 8

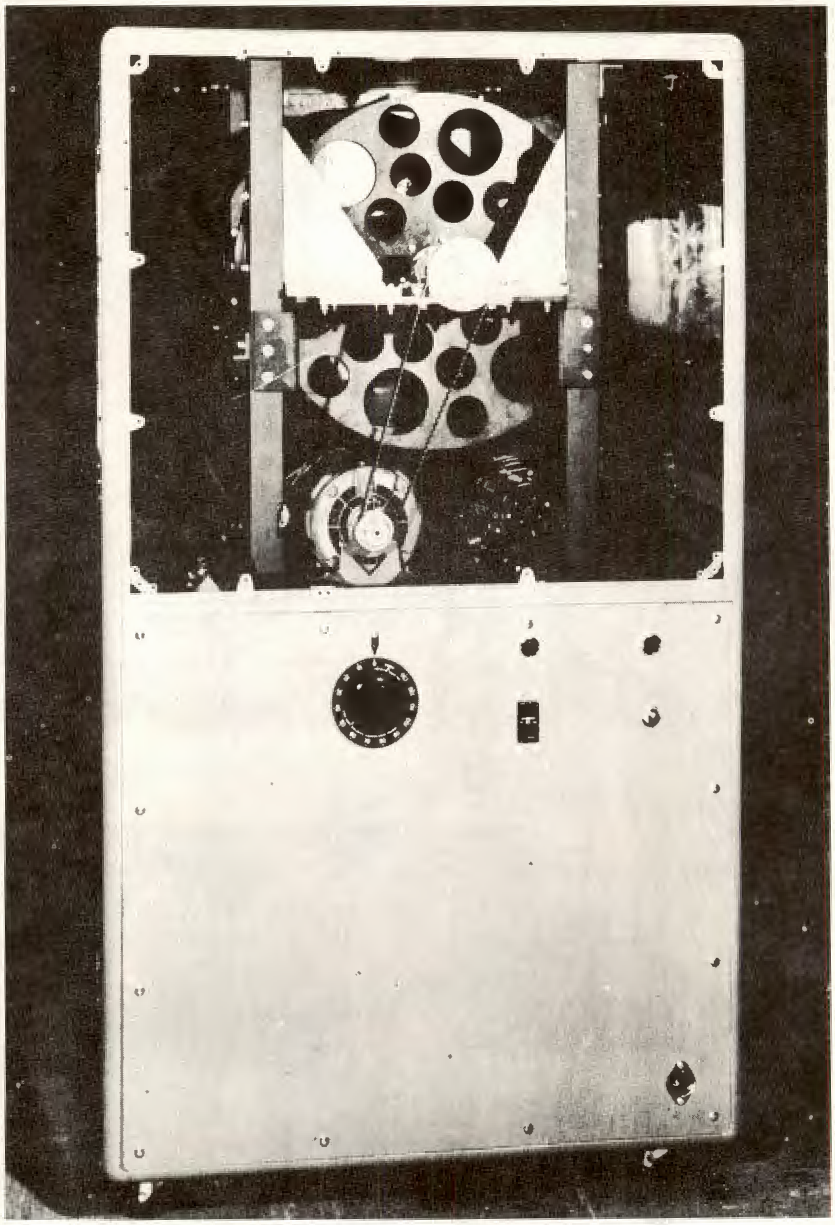

DANGER
HIGH VOLTAGE











drum will not cause light leakage from elliptical polarization which is otherwise encountered when the axes of polarization are obliquely crossed.

RESOLUTION (MONOCULAR)

In order to relate optical resolution with television resolution, the standard Snellen letters from an eye test chart are used as a criterion instead of the standard line resolution target. The reason for the choice was to avoid any lack of coincidence between horizontal lines of the target image and the scanning beam.

The minimum size letter that can be perceptibly reproduced by television is one which is covered by at least five scanning lines at the image orthicon (0.96 in. x 1.28 in. raster). A 4.45-mm. letter on the Snellen chart has a minimum gap of 1 mm. This size letter was resolved photographically at 10 ft. distance from the first vertex of the camera by both left and right lens systems, as well as target lines separated by 1 mm.

If the raster of 0.96 in. height is scanned by 441 lines, then 441/25.4 mm. = 17.4 lines/mm. Thus, two scanning lines are 0.057 mm. apart, approximately. For an object to be resolved by the television system, it must cover at least 5 x 0.057 = 0.285 mm. at the raster. This means that at the 10-ft. distance the object must have minimum height of 0.2850/1.83 x 39 = 6.0 mm. The smallest Snellen letter resolvable on the television display screen would therefore be 5.78 mm. (See Snellen Chart, Table 2.) Photographic tests with both lens systems, with and without the filters (in camera), demonstrated that the camera lenses alone were capable of resolving the 4.45-mm. letters at 10 ft. Though the optical system has not been specially corrected, and is afflicted with aberrations—particularly longitudinal chromatic aberration—the optical resolution is safely below the minimum resolution of the television system. At Idaho Test Station, after final adjustment of the television system, the 5.78-mm. Snellen letters were resolved at 10 ft. object distance.

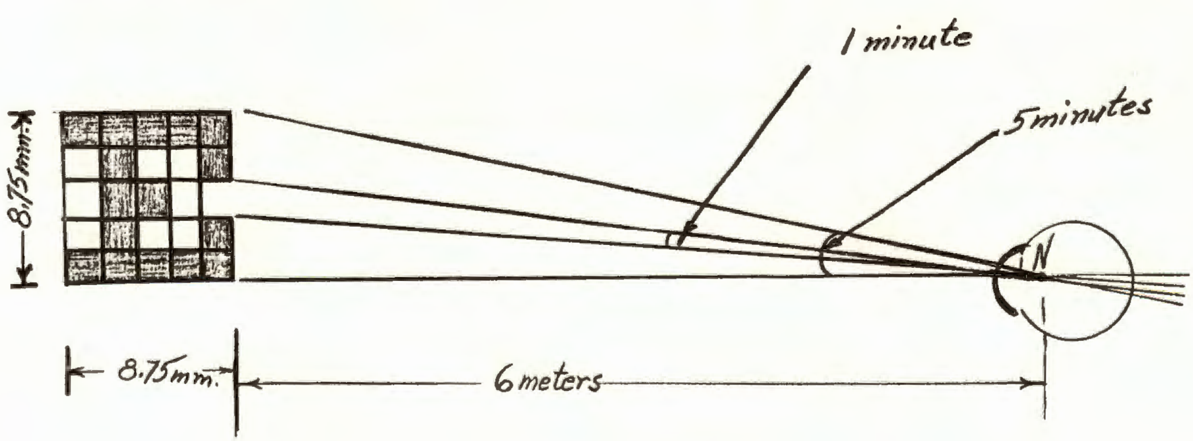


Fig. 13

The Standard Snellen Test Letters

Snellen letters are constructed such that they are enclosed in a square (see Fig. 13), the sides of which subtend 5 ft. at distance stated on the following chart. The letters are black, on a white background, and their minimum detail subtends one minute at the stated distances. The linear size of the limbs or spaces of the 20-ft. (6000 millimeters) letter is

$$x = 6000 \times 1 \text{ minute or } 6000 \tan 1'$$
$$= 6000 \times 0.000292$$
$$= 1.75 \text{ mm.}$$

The whole letter is thus 8.75 mm. in height since it subtends 5 minutes of arc.

Table 2

SNELLEN CHART

(Based on Visual Angle of 1 Minute)

	Distance in feet from eye or camera	Size Letter millimeters	Size Letter inches
E	200	89.0	3.504
FP	100	44.5	1.75
TOZ	70	31.1	1.224
LPED	50	22.2	0.874
PECFD	40	17.8	0.701
EDFCZP	30	13.34	0.525
FELOPZD	25	11.12	0.437
DEFPOTEC	20	8.9	0.3503
LEFODPCT	15	6.67	0.263
FDPLTCEO	13	5.78	0.228
PEZOLCFTD	10	4.453	0.175

RESOLUTION (STEREOSCOPIC)

The Geometry of Stereoscopic Vision

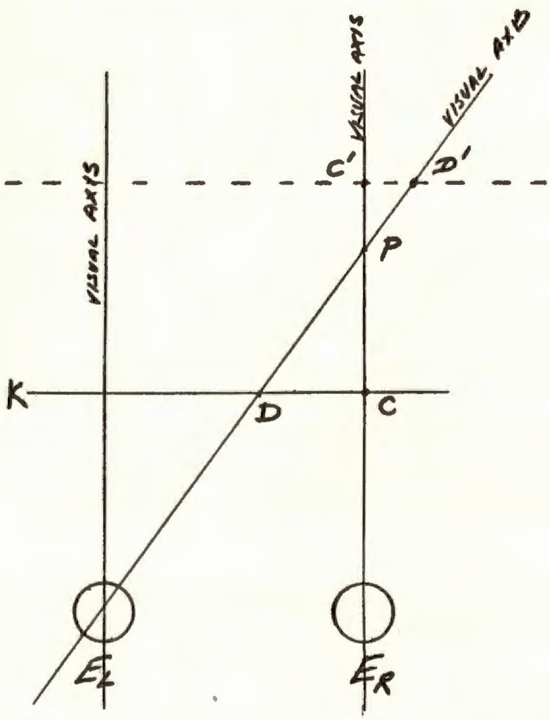


Fig. 14

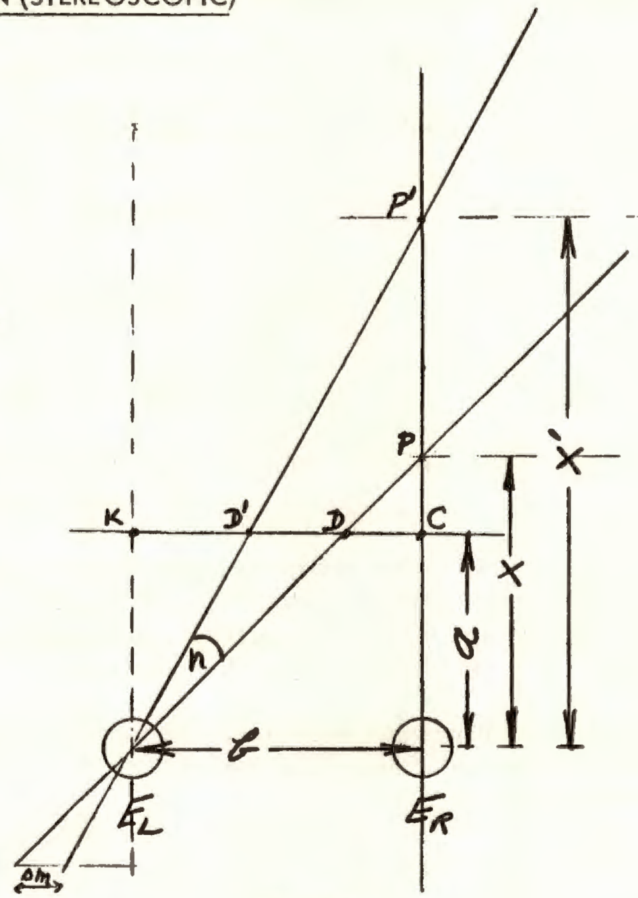


Fig. 15

E_L = left eye

E_R = right eye

Relation DK-D'K = D'D

Thus, $D'D = ab\left(\frac{1}{x'} - \frac{1}{x}\right)$

When point P is at infinity, the visual axes are parallel; and as P ⟶ C, D ⟶ C. (Figure 14.) Thus, a point at C on the screen KC seen only with the right eye, and a point at D seen with only the left eye, will be fused by the brain and seen at P. Actually points D and C need not be in the plane KC, but may be anywhere on the lines converging at P. If the screen is placed at KC the points D and C will be fused and appear at P beyond the plane of the screen (uncrossed disparity). If the screen KC is placed in a plane beyond the intersection of the visual axes and the point D' is presented to the left eye only, while C' is presented to the right eye only, the points C' and D' will be fused and will appear as a single point again at P, lying in front of the screen (crossed disparity).

If, in figure 15, a second point D' is introduced at the plane of a screen at KC it will be projected to P', to intersect the visual axis of the right eye. If the distance to the screen KC from the eyes is represented by the letter a, the distance of points P and P' from the eyes is represented by x and x', respectively, and the interocular distance is represented by b.

then $DK - D'K = D'D$

and $DK = \frac{ab}{x}$

$D'K = \frac{ab}{x'}$

and $D'D = ab\left(\frac{1}{x'} - \frac{1}{x}\right)$

$D'D = 2.5 \left(\frac{1}{x'} - \frac{1}{x}\right) a$

where b = base = 2.5 in. for average interocular distance

This means that the distance between spatial positions P' and P is a function of $\measuredangle$ n, the difference in convergence for the points P and P' or the binocular parallax difference. For simplicity, in Fig. 14 and 15, the right visual axis is fixed in one direction while the left eye is permitted to establish the angle of convergence.

If the minimum detectable binocular parallax difference for normal unaided eyes (trained) is about 30 seconds of arc = 0.000145 radian, then when a point D moves to D', so that the increment = Δ d,

then $\Delta d = na = 1.45 \times 10^{-4} a.$

Depth Displacement

Determination of movement of point P to P' with change of DD' = Δ d.

If the diagram (Figure 16) is rearranged so that the spatial points P and P' are between the observer and the screen to satisfy the correct viewing condition of the television screen, a is the distance from the observer's eyes (E_L and E_R); then P and P' are located at distances x and x', respectively, depending upon the image disparity d on the screen. The viewing screen is parallel to the base b, and distances x and x' are measured along perpendiculars to the base.

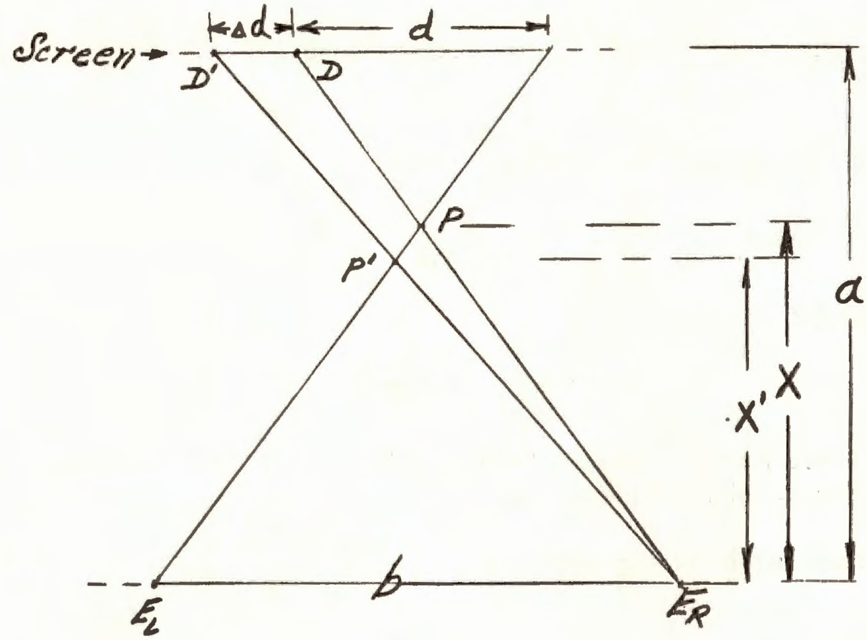


Fig. 16

<u>The depth displacement of P</u> is given the formula

$$\frac{x - x'}{a} = \frac{\frac{\Delta d}{b}}{(k + 1)(k + \frac{\Delta d}{b} + 1}$$

where k is some fraction or multiple of the interocular distance <u>b</u>.

The visual axes from E_L and E_R will be parallel, and point P will be an infinity when k = -1. And when k = +1, the point P will be half-way between the screen and the observer. Hence, the relative depth that can be perceived in projection is expressed by the perceptible displacement Δ d on the screen.

The difference in the two angles of binocular convergence at P and P' is the <u>binocular parallax difference</u>. (Same as angle <u>n</u> in Fig. 6.)

As stated above, if the minimum binocular parallax difference is 30 seconds of arc or 0.000145 radian

then $\Delta d = 1.45 \times 10^{-4} a$

= minimum perceptible lateral displacement on the screen.

Thus, if a point moves from D to D', a distance, Δd, equal to or greater than $1.45 \times 10^{-4}a$, an observer viewing a screen at a distance a will be aware of a displacement PP'.

For small displacement Δd compared with b

$$\frac{x - x'}{a} = \frac{d/b}{(k + 1)^2}$$

substituting for Δd

$$\frac{x - x'}{a} = \frac{1.45 \times 10 \quad a}{b\,(k + 1)^2}$$

If the normal interpupillary distance is taken as 2.5 in., then for a disparity of zero ($k = 0$) the point P will be in the plane of the screen.

the absolute depth displacement $x - x' = \dfrac{1.45 \times 10^{-4}a^2}{2.5\,(1)} = 5.8 \times 10^{-5}a^2$

Hence, for a screen distance a = 3 ft. = 36 inches

$$x - x' = 5.8 \times 10^{-5}\,(36)^2 = 4.5 \times 10^{-2}$$

Depth displacement of the stereo-image at the screen = 0.045 inches and

$$\Delta d = 1.45 \times 10^{-4}a = 1.45 \times 10^{-4}\,(36) = 0.0054 \text{ in.}$$

= the minimum perceptible lateral displacement at screen.

Thus, a point D must be displaced 0.0054 in. on the screen to show any displacement of the stereo-image.

For a stereo-image point half-way between the screen and the observer, the minimum depth displacement will be

$$x - x' = \frac{5.8 \times 10^{-5}\,(36)^2}{(2)^2} = \frac{4.5 \times 10^{-2}}{4} = 0.0011 \text{ in.}$$

For a screen distance a = 5 ft. = 60 in. (k = 0)

$$x - x' = 5.8 \times 10^{-5}\,(60)^2 = 20.88 \times 10^{-2}$$

Depth displacement of stereo-image at the screen = 0.2 in. or 5 mm.

and $\Delta d = 1.45 \times 10^{-4}\,(60) = 0.009$ in. or 0.23 mm.

= minimum perceptible lateral displacement at screen.

For a stereo-image point half-way between screen and observer (k = 1 or nearness factor = 2), the minimum depth displacement of the stereo-image will be

$$x - x' = \frac{5.8 \times 10^{-5} (60)}{(2)^2} = \frac{0.2}{4} = 0.054 \text{ in. or } 1.4 \text{ mm.}$$

Since the eye resolves two points when it subtends an angle of 1 min. approximately (monocular resolution), then for a screen at 36 inches this corresponds to a separation of

$$\Delta d = 3 \times 10^{-4} \times 36 = 108 \times 10^{-4} = 0.01 \text{ in.}$$

and for a screen at 60 inches

$$\Delta d = 3 \times 10^{-4} \times 60 \text{ in.} = 180 \times 10^{-4} = 0.02 \text{ in.}$$

or nearly twice the separation required to resolve two points in depth. (Compare with Δd = minimum perceptible lateral displacement for screen distances of 36 inches and 60 inches, respectively).

The following tables 3 and 4 are computed for minimum binocular parallax difference of 30 seconds of arc and 2 seconds of arc (extreme sensitivity of highly trained eyes).

Table 3

For 30 seconds of arc, minimum binocular parallax difference

	Observation distance from screen	
	3 ft.	5 ft.
Minimum perceptible lateral displacement at television screen	0.005 in.	0.009 in.
Depth displacement of stereo-image at television screen	0.045 in.	0.2 in.
Depth displacement of stereo-image at half-way (N= 2) from observer	0.001 in.	0.054 in.
Minimum perceptible lateral displacement at image orthicon	0.0009 in.	0.0015 in.

Table 4

For 2 seconds of arc, minimum binocular parallax difference

	Observation distance from screen	
	3 ft.	5 ft.
Minimum perceptible lateral displacement at television screen	0.00035 in.	0.00058 in.
Depth displacement of stereo-image at television screen	0.005 in.	0.0124 in.
Depth displacement of stereo-image at half-way (N = 2) from observer	0.0013 in.	0.0031 in.
Minimum perceptible lateral displacement at image orthicon	0.000023 in.	0.0001 in.

Strictly, the above resolution holds for good optical imagery as displayed by standard motion-picture projection. However, even though a television tube presents images that are inherently of lesser definition monocularly, the departure from these values need not seriously affect the precise location of the stereo-image when viewed binocularly, provided that "ghosts" and "irradiation" effects are held to the bare minimum.

Minimum Perceptible Disparity

The minimum perceptible displacement of left and right images at the image orthicon is considered for an observer whose minimum perceptible parallax difference is equal to 30 seconds of arc.

Referring to the above tables: — at the plane of the image orthicon, the minimum perceptible lateral displacement ($\Delta d'$) would be,

$$\Delta d' = \frac{d}{\text{magnification}} = \frac{1.45 \times 10^{-4} a}{m} = \frac{1.45 \times 10^{-4} (60)}{5.7} = 0.0015 \text{ in. or } 0.04 \text{ mm.}$$

when these images reproduced on the television display screen are viewed from a distance of 60 inches.

However, when viewed at a distance of 36 inches from the screen

$$\Delta d' = 0.0009 \text{ in.}$$

But, the minimum perceptible change in size* of an image at the image orthicon is equal to the distance between two scanning lines = 0.06 mm. Hence, at the television display screen, the minimum perceptible vertical change in size is 0.06 x 5.7 = 0.342 mm. (0.016 in.).

The disparity in image sizes due to inequality of the focal lengths of the camera lenses must not be greater than 0.06 mm. in the vertical meridians. Thus, the magnification difference between the left and right camera must not exceed 0.06 mm. in the vertical dimension.

In the horizontal dimensions, however, the images should be maintained equal within 0.1 percent since, in very sensitive eyes, a disparity over this amount is capable of producing aniseikonia.** Thus, while the camera lens system may be permitted to produce slight vertical distortions (within 0.06 mm. at the image orthicon) without becoming troublesome to the sensitive observer, the lenses must necessarily be paired for equal magnification within 0.1 percent* to accommodate the high stereo-resolution possible in the horizontal meridian. This is evidenced from the fact that an observer possessing a minimum binocular parallax difference of 30 seconds of of arc and viewing the display screen at a distance of 60 inches can discern a separation (disparity) between the left and right images of $\Delta d = 60 \tan 30$ in. = 0.009 inch. This corresponds to a separation of 0.0016 inch at the image orthicon. If the same observer views from a distance of 30 inches, then the minimum discernible image disparity $\Delta d = 0.0045$ at the screen. At the image orthicon this represents a disparity of $\Delta d' = 0.003$ inch. If the image at the image orthicon is taken as 1.28 inches, as is the case in the horizontal dimension, a disparity of 0.003 inch = 0.23 percent. For an observer possessing a minimum binocular parallax difference of 10 seconds of arc viewing the screen from a distance of 30 inches, the maximum image size difference permissible (disparity) at the image orthicon must be $\Delta d' = 0.001$ inch = 0.07 percent. Since the observer must maintain a viewing distance of not greater than 30 inches, for best stereo-resolution and measurement accuracy, as we will see later, the lens systems must be paired within 0.1 percent maximum.

Minimum Depth Displacement in the Object Space

The following discussion considers the object depth displacement (in the original scene) falling below the threshold of minimum perceptibility for observers at different viewing distances and possessing different levels of stereoscopic acuity.

In as much as the depth displacement is a function of the image disparity, the minimum perceptibility will vary from one observer to another. Therefore, for purposes of analysis, a minimum binocular parallax difference of 30 seconds of arc is used as that of the standard observer and is compared with the extreme case of a trained observer whose sensitivity is high enough to discern a stereoscopic angle of 2 seconds.

---

*This is true only in the vertical meridian of the image plane, and increases in the oblique meridians. In the horizontal meridians, the theoretical values for photographic imagery will apply (see previous page).

**Aniseikonia (literally: "not equal images") is a distortion of the binocular visual process whereby differences or distortions exist in the size and shape of the two retinal images. This term may be defined as any deviation relative to correct binocular stereoscopic localization of space. Physiological discomfort such as ocular fatigue, "burning" and "pulling" sensations, neurological symptoms, sensations of nausea, and functional disturbances may be experienced with this perceptual distortion.

For simplicity, Figure 17 shows a planned view of the left eye camera system, with the centerline Q'Q bisecting the interaxial distance (5 inches in this case).

The distance Δ d/2 is equal to one-half the incremental change due to the separation of the images at the television tube (I_3), and subtends an angle of $\theta'_3 - \theta_3$ at the eye (E) of the observer. The displacement Δ d/2 corresponds to a displacement Δ d'/2 at the image orthicon (I_2), which in turn corresponds to a depth displacement O'O in the original scene (object space). If $\theta'_3 - \theta_3$ is equal to one-half the minimum binocular parallax difference, then the distance O'O on the interaxial bisector Q'Q will be the minimum perceptible depth displacement. Since the principal axes of the left and right camera lenses are arranged to coincide at the image orthicon (or television tube), all axial object points (i.e., objects at infinity) must coincide at the image orthicon (and at the television tube), and the image separation will be equal to zero. Now, if an object point O on the line Q'Q is placed at a distance U = 15 ft. from the objective lens L_1, it will be displaced a distance h_o = 2.5 inches (for an interaxial distance of 5 inches) with respect to the principal axis of the objective. Then h_o subtends an angle θ_1 at the objective (L_1), which corresponds to an angle θ_2 subtending the displacement h_2 at the image.orthicon (I_2). The displacement h_2 (at I_2) corresponds to a displacement at the television tube (I_3) equal to h_k subtending an angle θ_3 at the eye of the observer. If θ_3 is the angular subtense at the eye, of the displacement $h_k + \Delta d/2$, this will correspond to an angle θ'_1 in the object space. It should be evident here that a minimum perceptible angular change $\theta'_3 - \theta_3$ (equal to one-half the total disparity) causes a linear change equal to Δ d/2 at the television tube, which in turn causes a corresponding change in depth displacement O'O = U - L. Note that the displacement Δ d/2 at the television tube = Δ d'/2 x magnification, where the magnification is equal to h_k/h_2. The transmission magnification $M_t = h_k/h_o$ = 0.1768 for an object 15 feet from the objective lens. (See table prior page).

If it is desired to know the minimum depth displacement for an object point located 15 feet from the camera that an observer will perceive if his minimum perceptible parallax difference is 30 seconds of arc, when viewing at a distance a = 5 feet from the screen (television tube), then

$$\text{Tan } \theta_3 = \frac{h_o (M_t)}{a} = \frac{2.5\,(0.1768)}{60} = 0.00737$$

and $\theta_3 = 25'\ 20.7''$

and since $\theta'_3 - \theta_3 = 15''$

then $\theta'_3 = 25'\ 35.7''$

and $\tan \theta'_3 = 0.00744$

hence $h_k = 60 \tan \theta'_3 = 0.4464$

and $$h'_o = \frac{h_k}{M_t} = \frac{0.4464}{0.1768} = 2.525''$$

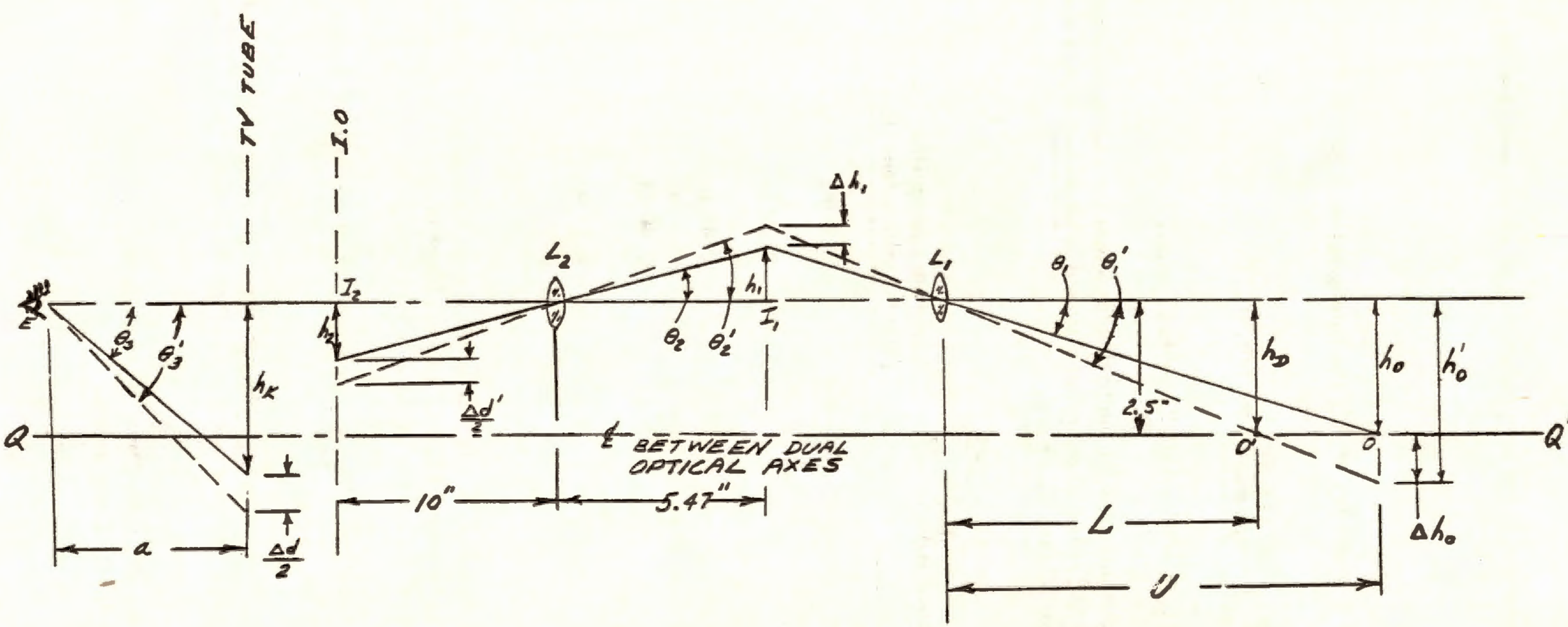

TV TUBE
I.O
L2
L1
I2
I1
h1
h2
hK
Δh1
θ1
θ1'
θ2
θ2'
θ3
θ3'
hD
ho
ho'
2.5"
Q
Q'
O'
O
℄ BETWEEN DUAL OPTICAL AXES
10"
5.47"
L
U
a
Δd/2
Δd'/2
Δho
E

Fig. 17

where h'_o is the displacement in the original object plane subtended by θ'_1. The object distance U = 15 ft.

By similar triangles

$$\frac{U}{h'_o} = \frac{L}{h_D}, \text{ where } h_D = 1/2 \text{ the interaxial} = 2.5''$$

and

$$L = \frac{U h_D}{h'_o} = \frac{180'' (2.5)''}{2.525''} = 178.2''$$

$$O'O = U - L = 180'' - 178.2'' = 1.8 \text{ inches.}$$

Tables 5, 6, and 7 show computations for depth displacement (U - L) in the object space for six different object distances (U). The observation distance is 60 inches with a minimum perceptible parallax difference of 30 seconds of arc.

Table 5

Object distance (U)	Minimum perceptible Depth displacement (U-L)
15 ft.	1.8 in.
10 ft.	0.72 in.
8 ft.	0.46 in.
7 ft.	0.40 in.
6 ft.	0.29 in.
5 ft.	0.17 in.

If the observer views the screen from a distance of 30 inches instead of 60 inches, then the minimum perceptible depth displacement for each of the object distances is shown in Table 8 for a minimum perceptible parallax difference of 30 seconds of arc.

For a minimum perceptible parallax difference of 2 seconds of arc at both 60 inches and 30 inches viewing distance (Table 9).

If the observer possessing a minimum perceptible parallax difference of 10 seconds of arc is to view the television screen from a distance not greater than 30 inches, then, as shown in Table 10.

Observers possessing stereo-acuity better than 10 seconds will obviously be capable of measuring correspondingly smaller depth displacements.

Table 6

Distance of Observer to T.V. Tube = 60 inches.
Minimum perceptible parallax difference = 30 seconds of arc.

h_o (1/2 inter-axial)	M_t Transmission Magnification Factor	Tan $\theta_3 = \frac{h_o M_t}{60}$	θ_3	θ'_3	Tan $0'_3$	h_k = 60 Tan θ'_3	$h'_o = \frac{h_k}{(M_t)}$	U (Object distance) (inches)	L= $\frac{2.5xU}{h'_o}$	U-L =Depth displacement= object distance - L (inches)
2.5	0.1768	.00737	25'20.7"	25'35.7"	.00744	0.4464	2.525	180 in.	178.20	1.8"
2.5	0.2674	.011125	38'16"	38'31"	..01121	0.6726	2.515	120	119.28	0.72"
2.5	0.3365	.01402	48'12.4"	48'27.4"	.01409	0.8454	2.512	96	95.54	0.46"
2.5	0.3863	.0161	55'20.7"	55'35.7"	.016173	0.9704	2.512	84	83.6	0.40"
2.5	0.4535	.0190	1° 5'18.6"	1° 5'33.6"	.019073	1.14438	2.510	72	71.71	0.29"
2.5	0.549	.02287	1°18'37.3"	1°18'52.3"	.022943	1.3766	2.507	60	59.83	0.17"

Table 7

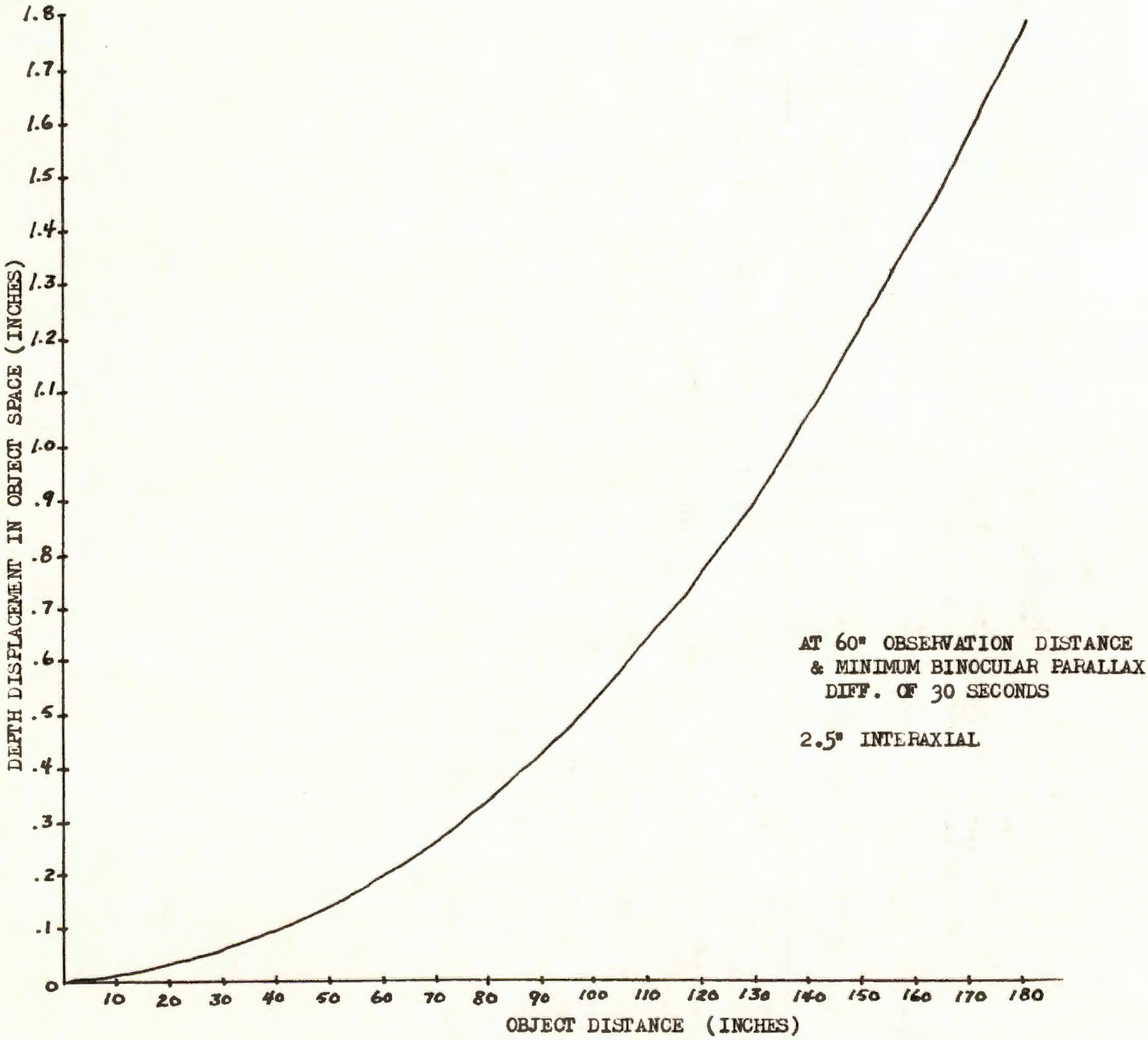

1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
DEPTH DISPLACEMENT IN OBJECT SPACE (INCHES)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
OBJECT DISTANCE (INCHES)
AT 60" OBSERVATION DISTANCE
& MINIMUM BINOCULAR PARALLAX
DIFF. OF 30 SECONDS
2.5" INTERAXIAL

Table 8

Object distance (U)	Minimum perceptible Depth displacement (U-L)
15 ft.	0.90 in.
10 ft.	0.36 in.
8 ft.	0.23 in.
7 ft.	0.20 in.
6 ft.	0.13 in.
5 ft.	0.07 in.

Table 9

Object distance (U)	Minimum perceptible depth displacement (U-L) at 60" viewing distance	30" viewing distance
15 ft.	0.140 in.	0.060 in.
10 ft.	0.048 in.	0.024 in.
8 ft.	0.031 in.	0.015 in.
7 ft.	0.027 in.	0.013 in.
6 ft.	0.019 in.	0.007 in.
5 ft.	0.011 in.	0.005 in.

Preliminary tests at Idaho Test Station with operators possessing 10 sec. of arc, and better, of stereo-acuity have substantiated 0.120 in. to 0.075 inch accuracies at an object distance of 9 ft. (Viewing distance was 30 inches)

With better imagery at the television display screen, higher stereo-acuity, closer viewing distance, and more experience, the operator is expected to approach correspondingly higher accuracies.

Image Distance Factor

The image distance factor is defined as the ratio of the screen viewing distance (a) to the image distance (x). Therefore, $N = a/x$.

Table 10

Object Distance (U)	Minimum perceptible depth displacement (U-L) at 30" viewing distance
15 ft.	0.30 in.
10 ft.	0.120 in.
8 ft.	0.075 in.
7 ft.	0.065 in.
6 ft.	0.035 in.
5 ft.	0.025 in.

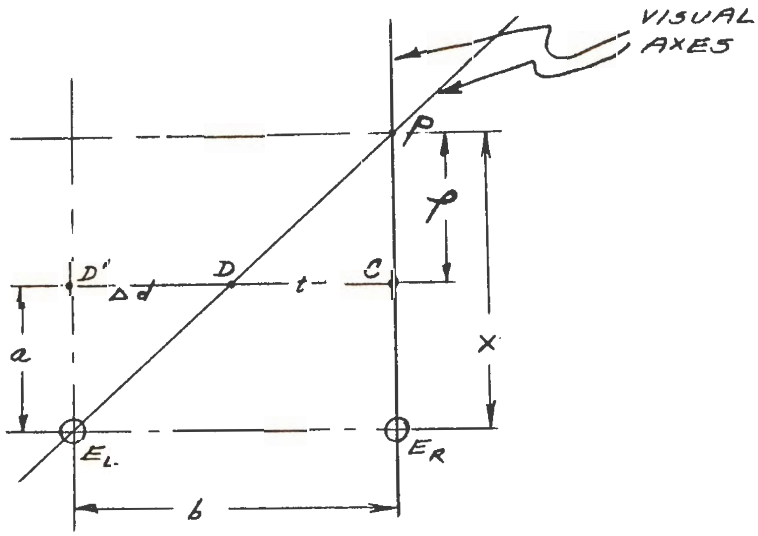


Fig. 18

In Fig. 18:

E_R = right eye

E_L = left eye

P = any point of intersection of the visual axes of E_R and E_L

D, D' and C are points on the viewing screen

t = DC = separation of image points D and C on viewing screen

Δd = DD'

ρ = distance of stereo-image point P from point C on the viewing screen

X = distance of stereo-image point P from the eye of the observer, perpendicular to base line

When DD' = Δd	0, stereo-image is at infinity	($X = \infty$),	N = 0
When DD' = Δd	1/2b, stereo-image is beyond the screen	(X = 2a),	N = 0.5
When DD' = Δd	b, stereo-image is at the screen	(X = 1/2 a),	N = 1
When DD' = Δd	1 1/2b, stereo-image is in front of screen	(X = a/1.5),	N = 1.5
When DD' = Δd	2b, stereo-image is half-way between screen and observer	(X = 2/a),	N = 2

When D is to the right of C, point P lies between the screen and the observer. In this case the image points are in the crossed condition. The term nearness factor is used as a special case of the term distance factor to apply to those stereo-image points lying between the screen and the observer. Hence, when the images are crossed and separated by an amount equal to the interocular distance, the nearness factor will be 2 and the stereo-image will be located half-way between the screen and the observer.

In the diagram (Fig. 9), the Distance ratio $= \frac{P}{a} = \frac{t}{b-t} = \frac{t}{d}$

When image point D lies between D' and C on the screen, the separation t between the left and right images is rendered positive (uncrossed condition), and when D lies to the right of image point C, t is rendered negative (crossed condition).

When the stereo-image point P lies berween the screen and the observer, the distance factor (in this special case, the nearness factor)

$$N = \frac{a}{a-p} = \frac{a}{x}$$

In this equation p is rendered negative for all stereo-image points P lying in front of the screen (i.e., between the screen and the observer) and positive for all points stereo-image P lying beyond the screen.

It should be observed that the distance factor (N) is equal to unity when left and right images are coincident at the screen, i.e., $t = 0$ or $\Delta d = b$. When the stereo-images are between the screen and the observer, N is greater than one, and, when the stereo-images are located beyond the screen, N is less than one; approaching zero when the stereo-image approaches infinity.

The discussion under image distance factor has been concerned with the geometry of the final image-space, i.e., from the imagery on the television screen as seen by the observer using the screen as the reference plane. The same discussion applies to the geometry of the object space, i.e., from the object position (in the original scene), to the camera, using the convergence point of camera axes to define the plane of convergence (reference plane, in this case).

Thus, all spatial object points about the plane of convergence in the object space will have corresponding image points about the television display screen in the image space. (See Fig. 19.) All dimensions in the object space and image space will correspond, differing only in magnification, in the ideal case. The transmission magnification defines the object-image scale and is itself defined as the ratio of a linear dimension of an image in the plane of the television screen to the corresponding dimension to the plane of convergence. Thus, for example, if an object 8 inches tall viewed by the camera in the plane of convergence (object space) measures 4 inches on the viewing screen, the transmission Magnification is 0.5.

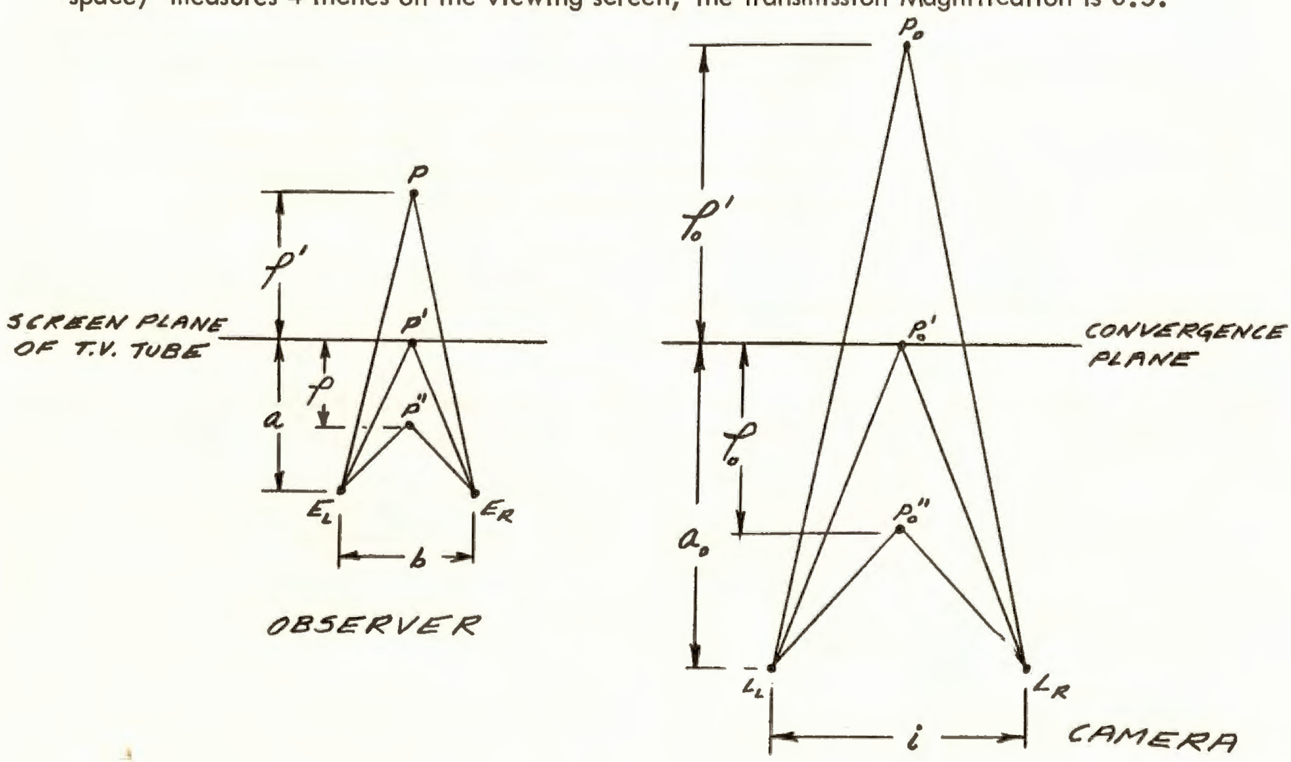


Fig. 19

In the present TV system, at 10 ft. camera distance, the images coincide when the interaxial distance of the camera is equal to 5" (zero separation at the image orthicon). By increasing the interaxial to 5-1/16", the image separation at the image orthicon becomes .063" in the crossed position. This means .063" x 5.7 = 0.36" separation at the screen; giving an image distance of

$$\rho = \frac{.36\ (60)}{.36 + 2.50} = 7.55\text{" in front of the television screen at 5' viewing}$$

distance and the nearness factor $= N = \frac{a}{a - \rho} = \frac{60}{52.45} = 1.14.$

The diagram (Fig. 20) shows the relative image displacement and orientation at the image orthicon for object points between infinity and 5 feet, based on the assumption that the principal axes are parallel, the interaxial distance is equal to 5", and all the lenses are optically centered, with the optical axis of each camera len s system directed at the center of the raster.

On first examination actual measurements of image displacements did not conform with calculated values. This indicated deviations in alignment of the mirrors and possibly of the lenses, in the vertical axes. Mirror alignment on the horizontal axes appeared correct since there was no indication of image tilt. Measurements, later taken at Idaho Test Station with the above "infinity" alignment, substantiated the mathematical computations, which will be shown tabulated after the following brief discussion.

The following tables and diagram show the separation of the left and right images at the image orthicon and television display screen, corresponding to several points in the object space. The location of the corresponding stereo-image points, given in percentage of the distance between the television screen and the observer, are shown together with the nearness factor. For convenience, the distances for the corresponding stereo-images when viewed from a distance of 30 inches have been included.

These computations are based on the assumption that the optical axes of the two camera-lenses are parallel and in the same horizontal plane and that the images at infinity coincide at the center of the image orthicon when the interaxial distance is equal to 5 inches. Thus, the plane of convergence is at infinity. The tables also indicate corresponding data for maximum and minimum interaxial distances.

When the plane of convergence is at infinity the images will coincide at the image orthicon. Thus, the images of infinitely distant objects will be imaged in the plane of the television screen (nearness factor = 1). All finite points in the object space will, therefore, be imaged between the screen and the observer (see Table 11). The stereo-field is 100% of the television screen width.

When the interaxial separation is increased to maximum (5-1/16") the images are crossed at the television screen. All stereo-images appear in front of the viewing screen and images of infinitely distant objects are separated 0.627 inch; thus, the projection plane, which

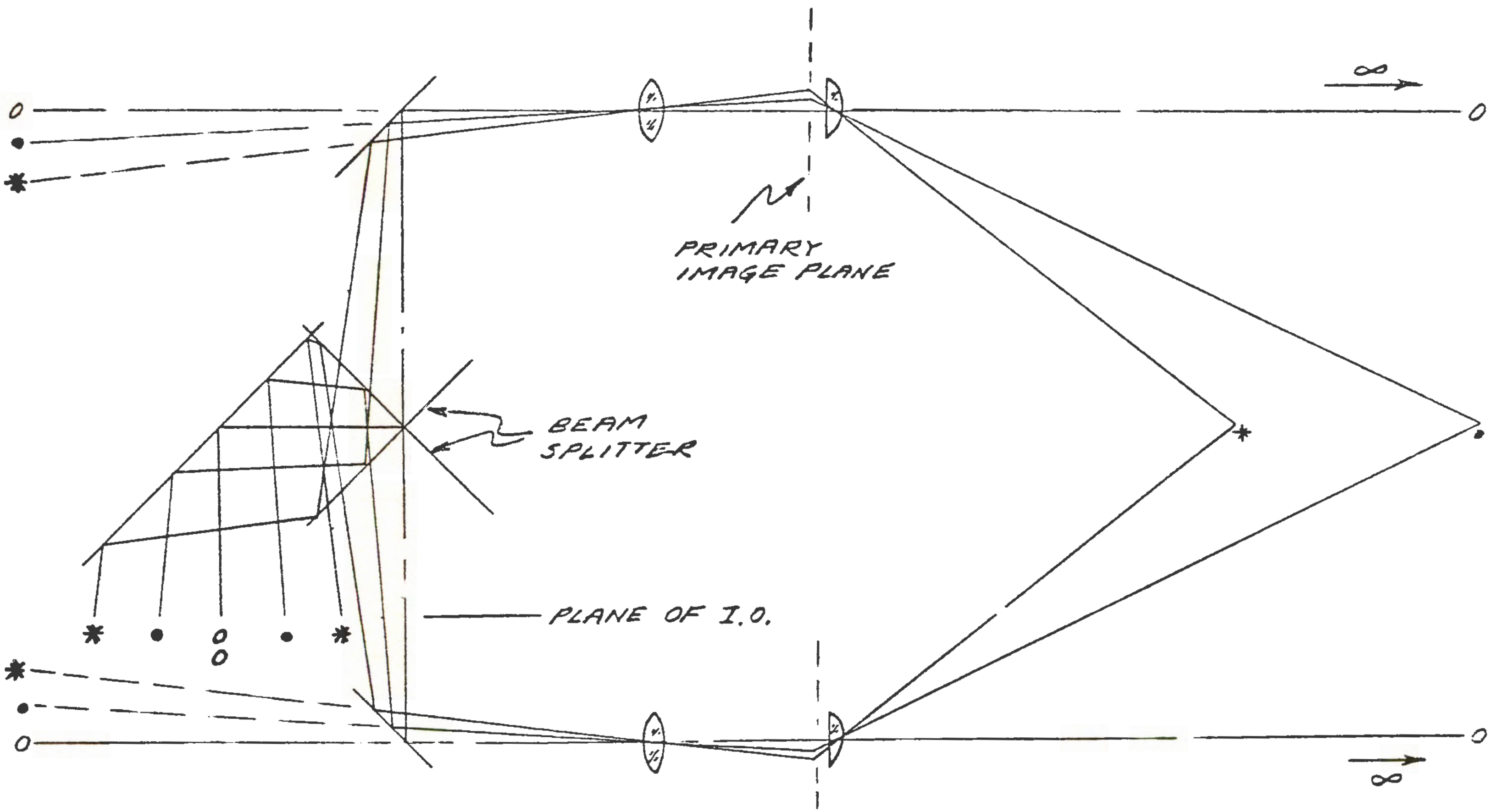


DIAGRAM INDICATING LOCATION OF IMAGE POINTS ON RASTER OF IMAGE ORTHICON FOR OBJECT POINTS BETWEEN THE NEAR POINT & INFINITY

Fig. 20

Table 11

(a)

5" Interaxial distance

30" Viewing for distance p

Object distance	Magnification $\frac{I_2}{O}$	Image separation at image orthicon Δd	Image separation at viewing screen Δd	P	Nearness factor N	Stereo-image location, Percentage of observation distance as measured from viewing screen.
		0	0			1
15 ft.	1/32.2	0.16" crossed	0.91"	8.0"	1.35	26.6%
10 ft.	1/21.3	0.234" crossed	1.33"	10.4"	1.53	34.7%
8 ft.	1/16.9	0.296" crossed	1.69"	12.1"	1.68	40.0%
7 ft.	1/14.8	0.338" crossed	1.93"	13.0"	1.78	43.3%
6 ft.	1/12.6	0.397" crossed	2.26"	14.2"	1.91	47.3%
5 ft.	1/10.4	0.480" crossed	2.74"	15.7"	2.09	52.3%

previously appeared at the screen is now forward of the screen by an amount of 20.8%, nearness factor = 1.25.(See Table 12) The stereo-field is also 100% at this slight increase in interaxial.

As the interaxial is reduced the image separation, in the uncrossed condition, increased with a gradual decrease in stereo-field, until, when at the minimum interaxial distance (4-1/2!), the stereo-field is reduced to about 10% of the total screen width. Here the separation is 5.21 inches (at the television display screen) and the images are located beyond the screen. At the same infinity setting, as the interaxial is shortened, the images separate progressively in the uncrossed condition. Table 13 shows that at minimum interaxial (with plane of convergence at infinity) that objects at 5 ft. distance will require 0.33° divergence of the eyes (from a viewing distance of 30 inches) while objects at 15 ft. require 3°40' of divergence for fusion. More distant objects require even greater divergence. For comfortable viewing the operator should not be required to diverge more than 1°. Note that the image separation is larger than the pupillary distance of the average observer for each object distance between 5 ft. and ∞ . If instead of decreasing the interaxial to minimum, it is adjusted to slightly below 5" so that all images are separated within the limit of divergence of the eyes for comfortable viewing, there would still be a limitation here in that the stereo-field decreases with decreasing interaxial. Thus, placing the plane of convergence at infinity is not satisfactory.

Recommendation

At this time it is recommended that the mirrors be adjusted for coincidence at 15 ft. object distance with interaxial at 5 inches. The interaxial can then be reset to place the convergence plane at eight or ten feet depending upon the desired working distance (see chart at back of report). Thus, if, for example, the images of a target 10 feet from the camera coincide at the television display screen, then all targets in front of this plane will be seen stereoscopically in front of the screen. Those targets placed beyond the reference convergence plane will be visualized as beyond the screen.

With this arrangement, the working distance (target distance) should be maintained in front of the reference plane; hence, the camera lenses should be focused for this distance. The stereoscopic image of the work will be visualized in front of the screen, giving the operator a more natural sense of proximity to the work with less minimum perceptible depth displacement per target distance. This will add to the accuracy and efficiency. Here the negative depth range (convergence plane to camera) is approximately 5 ft.

By adjusting the mirrors of the cameras, objects at 15 ft. distance can be imaged for coincidence at the image orthicon (or television screen), while the 5" interaxial distance is still maintained. With this optical alignment, the plane of convergence (coincidence at the screen) can be changed by decreasing the interaxial. This will tend to maintain maximum stereo-field. For example, by decreasing the interaxial to 4-29/32", the convergence plane will be 8 ft. from the camera. At 4-27/37" coincidence will be accomplished for objects at 6 ft. distance from camera. Here, at 6 ft. convergence plane a small forward displacement of the object causes doubling of the image (diplopia) to the observer.

Table 12

5-1/16" interaxial

30" viewing distance for distance p

Object distance from camera	Separation at image orthicon $\Delta d'$	Separation at television screen Δd	P	N	Stereo-image location, percentage of observation distance as measured from viewing screen
∞	0.115 crossed	0.656	6.25	1.26	20.8%
15 ft.	0.266 crossed	1.52	11.36	1.61	37.9%
10 ft.	0.304 crossed	1.73	12.25	1.69	40.8%
8 ft.	0.414 crossed	2.36	14.56	1.94	48.5%
7 ft.	0.458 crossed	2.61	15.32	2.04	51.5%
6 ft.	0.512 crossed	2.92	16.16	2.17	53.9%
5 ft.	0.602 crossed	3.43	17.35	2.37	57.8%

Separation at television display screen = Δd

$$= 2 \left\{ \left[(h_o + \Delta h_o) \frac{(0)}{(l_1)} + \Delta h_o \right] 1.83 \right\} \frac{l_3}{l_2}$$

Distance of stereo-image from screen = $p = \frac{a}{(1 + \frac{b}{\Delta d})}$

Table 13

4-1/2" interaxial

Object distance	Magnification $\frac{0}{I_1}$	Image separation at image orthicon $\Delta d'$	Image separation at T. V. tube Δd	Ocular divergence required to fuse left and right tube images at 30" viewing distance
85 ft.		0.914 uncrossed	5.21"	5° 10'
15 ft.	1/59	0.776 uncrossed	4.42"	3° 40'
10 ft.	1/39	0.700 uncrossed	4.00	2° 50'
8 ft.	1/31	0.65 uncrossed	3.7	2° 16"
7 ft.	1/27	0.61 uncrossed	3.48	1° 52'
6 ft.	1/23	0.556 uncrossed	3.17	1° 10'
5 ft.	1/19	0.484 uncrossed	2.76	0° 20'

Separation at television screen $= \Delta d = 2\left\{\left[h_o \frac{(0)}{(I)} + (2.50 - h_0)\right] \frac{H_2}{h_1}\right\} \frac{I_3}{I_2}$

Distance of stereo-image from screen $= p = \frac{a}{(1 + b/\Delta d)}$

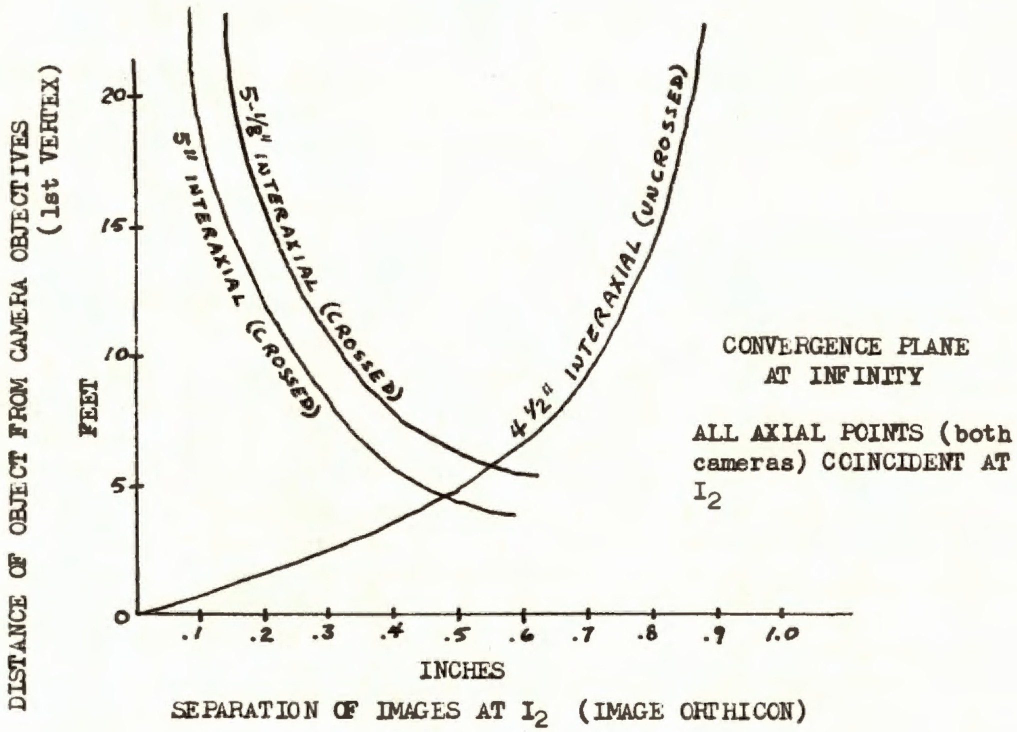
H_o = 1/2 interaxial

h_o = -1/2 change in interaxial

$\frac{0}{I_1}$ = Magnification ratio for conjugates at I_1 and I_2 (primary image plane and image orthicon, respectively)

$\frac{I_3}{I_2}$ = Magnification ratio (image orthicon and television screen)

Table 14


DISTANCE OF OBJECT FROM CAMERA OBJECTIVES (1st VERTEX)
FEET
20
15
10
5
0
5-1/8" INTERAXIAL (CROSSED)
5" INTERAXIAL (CROSSED)
4 1/2" INTERAXIAL (UNCROSSED)
CONVERGENCE PLANE AT INFINITY
ALL AXIAL POINTS (both cameras) COINCIDENT AT I2
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
INCHES
SEPARATION OF IMAGES AT I2 (IMAGE ORTHICON)

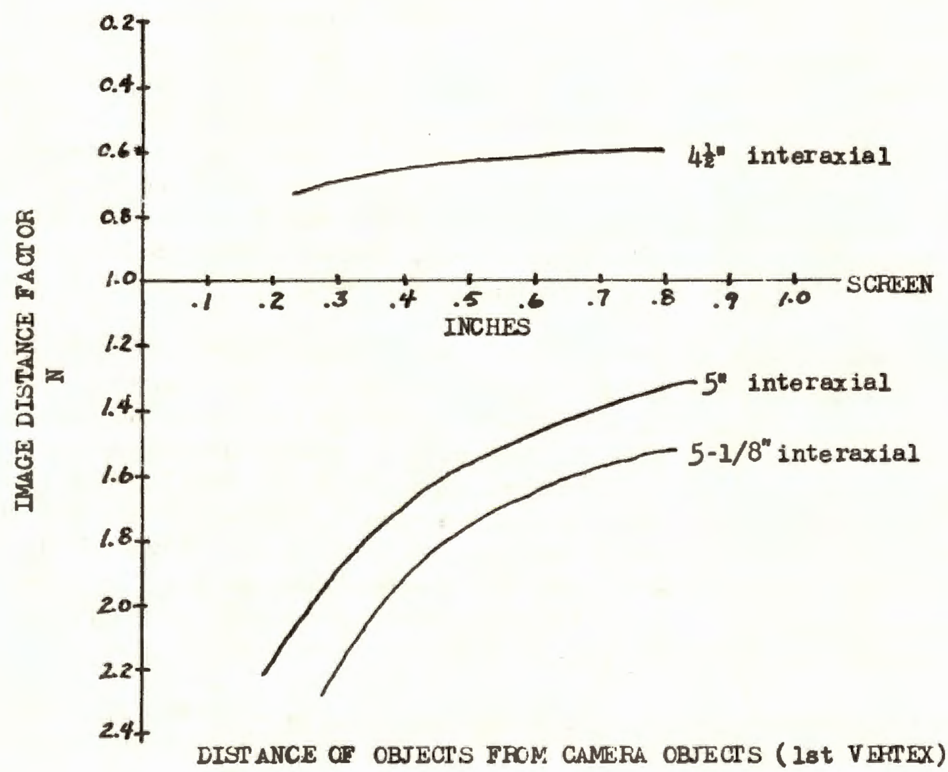


IMAGE DISTANCE FACTOR N
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
4½" interaxial
SCREEN
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
INCHES
5" interaxial
5-1/8" interaxial
DISTANCE OF OBJECTS FROM CAMERA OBJECTS (1st VERTEX)

Interim Summary and Discussion on the Quality of Monocular and Stereo Acuity

1. The resolving power of the camera lens system is greater than that of the television system. At 10 ft. distant target and 30 in. viewing distance the television system can resolve a 5.78-mm. Snellen letter and the optical system can resolve a 4.45-mm. letter.

2. Occlusion of left and right images is complete.

3. Left and Right image sizes should be kept within 0.1% in the horizontal meridians.

4. With the minimum perceptible binocular parallax difference taken as 30 seconds of arc ("conventional value"), the minimum perceptible image separation at the television screen and image orthicon and the corresponding depth displacement for two positions in the image space have been calculated. These calculations have been compared with similar determinations made for minimimum perceptible binocular parallax differences of 10 and 2 seconds of arc, where depth discrimination is obviously correspondingly higher. (See Tables 5 thru 10.)

5. Corresponding depth displacements in the object space for all conditions shown in (4) have been calculated and tabulated.

6. The nearness factor describes the location of the stereo image with respect to the observation distances from the screen. The stereo image location depends upon the separation of the left and right images, the interocular distance and the distance between the viewing screen and the observer. At zero separation (coincidence) the distance factor N = 1. If coincidence is maintained at the screen, the plane of the screen will then correspond to the convergence plane in space. All other object planes in front or beyond the convergence plane will be visualized as corresponding image planes in front of or beyond the viewing screen. It may be noted here that the stereo-window (which will be described later on in this report) can be so placed in the primary image plane (I_1) that it will appear at any pre-selected position in the final image space, including the plane of the television screen.

7. At the "infinity" setting, the left and right images of objects at infinity coincide at the television screen at both 5" and 5-1/8" interaxial distances. Hence, for all finite planes in the object space the left and right images are crossed, the accommodation is fixed at the screen while the convergence increases with nearness factor (N =2.09 and N = 2.37 at 5" object distance, see Tables 11 and 12). This is within the tolerable limits of dissociation of the accommodation-convergence mechanism of the eye. When images are in the uncrossed condition (4-1/2 interaxial and infinity setting), objects beyond six feet will require divergence of the visual axes from parallelism, greater than 1°. This would result in ocular fatique, and as the object becomes more distant fusion breaks and double images occur.

8. For specific location of stereo images in the image space (nearness factor), a displacement (X - X') corresponds to a separation (Δd) of the left and right images at

the television screen. This corresponds to a separation of the images at the image orthicon $= \Delta d' = \frac{\Delta d}{5.7}$. These separations in turn correspond to a depth displacement 00' in the object space.

When the eyes alternately view two images that are separated by an amount which is below the minimum monocular resolution, a stereo image will still be discernible and resolved in space. The extent to which "sub-monocular" resolution is possible will depend upon the minimum binocular parallax difference (or stereo acuity) that the observer is capable of appreciating, and the explanation can be analagous to the vernier acuity in man. Thus, two images that normally could not be resolved on photographic film or at the image orthicon or television screen monocularly become "depth resolved" when presented to the left and right eyes separately; again, the stereo image depth displacement depending fundamentally upon the stereo acuity of the individual observer.

Thus, the tables show the minimum separation discernible by observers with 30, 10, and 2 seconds of stereo acuity. The separations Δd and $\Delta d'$ are obviously below the monocular grating acuity in man, but correspond to definite discernible distances in the object space.

Monocular Acuity in man for 2 object points = 60 seconds to 80 seconds of arc and is dependent upon the width of a single retinal cone.

Monocular Vernier Acuity in man = 10 seconds and even as good as 2 to 4 seconds (coincidence setting of a broken vertical line) and is not Dependent upon the width of a single retinal cone.

Binocular (Stereo) Acuity = 10 seconds and even as good as 2 to 4 seconds. This acuity is dependent upon the geometrical disparity of the retinal images, the physiological and neurological components of the visual apparatus, and the psychological components for discrimination and interpretation.

Vernier Acuity or Contour Acuity

In the recognition of outlines or contours of objects and the detection of discontinuities in such, the eye is capable of extraordinary precision. Experiments have shown that the accuracy of contour acuity increases if the time allowed for the observation exceeds 1/10 second; and, furthermore, the contour acuity is greater for long lines than for short ones. These observations suggest that a movement of the image over the foveal cones is required and that large numbers of cones are concerned in this kind of vision.

Many attempts have been made to explain this high acuity. Anderson and Weymouth, 1923, offered a possible explanation. The mosaic pattern of the retinal cones disposes the photo-receptors in the neighborhood of the edge of the image of a line. Since the retinal cones are irregularly placed under the images of the line, they are stimulated to different extents as they lie in the region where the intensity falls gradually from the maximum to zero.

This fall in intensity is due to a spreading or irradiation of light over the surface of the retina whenever an isolated area of it is illuminated, which incidentally is of lesser extent in the dark races of mankind. The corresponding nerve impulses are integrated in the brain and a mean position of the edge of the line assigned therein. The accuracy with which a displacement of this mean position can be detected is therefore not limited by the dimensions of a single cone as is the case for monocular resolution of two image points.

Vernier Acuity vs. Stereo Acuity

Accordingly, if an observer possessing stereo acuity of 2 seconds of arc views the television screen from a distance of 3 ft., he could discern a minimum lateral separation of 0.00035 inch between the left and right image (Δ d) if the optical apparatus of the eye, television and camera were highly precise. (See Table 4) This corresponds to a lateral separation of 0.000023" at the image orthicon. This in turn corresponds to a minimum negative depth displacement of 0.024 inch (see Table 9). Similarly, an observer possessing stereo acuity of 10 seconds of arc will discern 0.120 inch of depth displacement (toward camera) at 10 ft. object distance; and, at 8 ft. object distance, the discernible depth displacement is 0.075 inch. Preliminary tests on operators trained to discern 10 seconds of arc stereoscopically have substantial 0.120-to 0.075-inch accuracies in depth displacement for a target 9 ft. from camera.

To achieve the theoretical measuring accuracies with stereo television, the following conditions would have to be satisfied:

1. The eyes must be devoid of aniseikonia; i.e., the images seen with either eye should be of the same size on the retinae.

2. There should be no anisometropia (refractive difference between both eyes).

3. No difference in magnification at the image orthicon. The camera lenses must be paired for all cardinal planes and equally corrected for all aberrations.

4. Television reception must be homogeneous throughout the viewing screen. Here errors are generally due to non-linearity of the sweep of the scanning beam and non-constancy of focus through the entire display screen.

5. The neurological apparatus from retina to visual area of the brain must allow faithful perception of two retinal images.

6. The brain must be capable of high stereo appreciation. A small amount of blur (small increase in blur circles on the retina) that is capable of decreasing monocular resolution would not affect the localization of objects in space provided the blur is equal in both eyes. Psychological components, however, would tend to create distortion of space localization. Therefore, the accuracy with which these parameters can be maintained will determine the extent to which the efficiency of binocular (stereo) performance can be related to the efficiency of monocular (vernier acuity) performance. Thus, while a letter may appear as a blurred patch (below monocular resolu-

tion), it can still be localized in image space when viewed binocularly, if it is within the radius of stereoscopic vision of the observer. Now since (as mentioned before) the fact that the eyes of the observer possess good fusion does not guarantee good stereopsis, and since in the ordinary act of vision the observer is not experienced in localizing blurred images of objects in space, stereopsis can deteriorate with increase in image blur. Hence, the personal equation of man can play havoc on his ability to perceive stereoscopically. Furthermore, the left and right images at the television screen will definitely be distorted because of inhomogeneities throughout the display. This has been noted theoretically and experimentally. Not only is the television resolution (monocular) inherently lower than the optical resolution of the camera but also the image definition varies with the position that the test image occupies on the television display screen. Hence, it cannot be inferred that stereo resolution is entirely independent of monocular resolution for efficient stereo appreciation; but it can be stated that stereo depth resolution can be many times greater than monocular acuity. In other words, the geometrical component of stereo perception is independent of monocular resolution, but the psychological components of vision may cause stereo deterioration because of lack of good monocular resolution.

FIELD OF VIEW

The fundamental requirement for stereoscopic appreciation is the common or binocular field of view, within which every object is seen by both eyes. The nerve connection from retina to the visual area of the brain provides that each object point is represented binocularly in the brain. The system of eye muscles and their central connections is such that the eyes move as a pair in a coordinated manner. Accurate binocular coordination depends upon the desire for the brain to maintain fusion of the retinal images. Thus, binocular fixation upon a single target ordinarily depends upon the power of fusion. The stimulus for fusion is the presentation of like (or slightly disparate) images to the left and right retinae.

Fusion is possible when two entirely different retinal images can be so combined mentally as to create a whole picture which is consistent with normal experience. Thus, if the right eye is presented with a stereogram of, say, a small triangle and the left eye with a stereogram of a larger circle, the observer possessing good powers of fusion will see a picture of a circle with a triangle within its perimeter. However, if the left and right pictures are very nearly alike except for some details which are grossly different at corresponding positions in the two pictures, a condition known as "horror fusionis" will be experienced when an attempt is made to obtain a single binocular visual impression. Thus, objects which are not common to both left and right monocular fields of view will tend to abolish fusion, making coordination of the two eyes either difficult or impossible; and, as is well known, without fusion stereoscopic vision is impossible. (It might be mentioned here that the ability for the eyes to fuse two retinal images does not guarantee stereopsis.) When fusion is broken up or abolished, one of two things will happen: either the observer sees double (diplopia) or else, in an effort for the brain to maintain single vision, one of the images is suppressed. In either case stereopsis deteriorates. Thus, for undistorted stereo appreciation, consideration must be given to the binocular or stereoscopic field of view with the 3D T.V. system beginning with the fundamental monocular field.

Monocular Field

The objective of each camera lens system has a focal length of 75 mm. with f/2.3 aperture, and a 23° field as specified by the manufacturer. The field of view required by the image orthicon raster is 13°20' and is therefore well within the design limits of the objectives. The relay and field lenses are infinity corrected and therefore by virtue their positions contribute to the aberrations of the lens system, principally longitudinal chromatic aberration and field curvature. The resulting aberrations, however, are below the minimum resolution of the television system, hence, are not deleterious to the final image.

Table 15 shows the horizontal and vertical field of view of the present T.V. system.

Table 15

Object Distance	Magnification $\frac{0}{I_1}$	Linear Field of View	Calculated	- Measured	Horizontal Stereofield 5" interaxial
15 ft.	1/59	Horizontal Vertical	41.3" 31.0	37.5 28.5"	36.3
10 ft.	1/39	Horizontal Vertical	27.3" 20.5	26.5 16.0	22.3
8 ft.	1/31	Horizontal Vertical	21.7 16.1	20. 14.	16.7
7 ft.	1/27	Horizontal Vertical	18.9 14.2	17.0 12.5	13.9
6 ft.	1/23	Horizontal Vertical	16.5 12.5	16.0 9.5	11.5
5 ft.	1/19	Horizontal Vertical	13.3 10.0	13.00 9.0	7.3

Non-Stereoscopic Edges of Binocular Field

In the diagram Fig. 21a and b, the right and left fields of the human eyes overlap so that the binocular field is essentially about 120°. About 30° of each monocular field does not contribute to the binocular stereo-field.

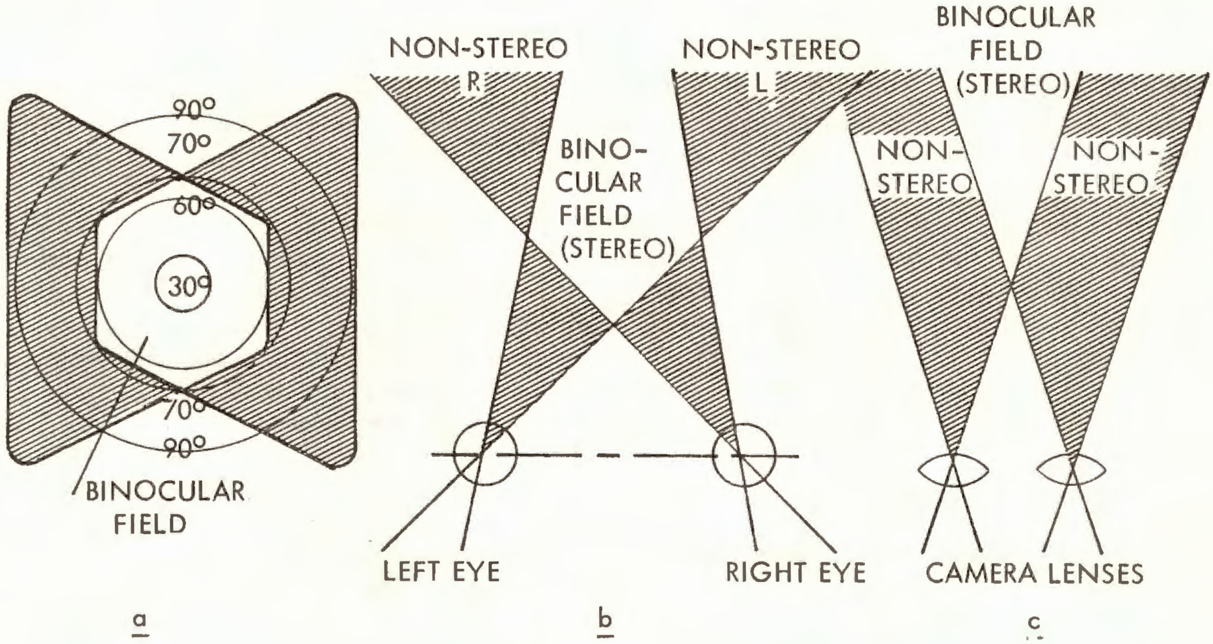


Fig. 21

Since, at any one time, the eyes fixate on only a small portion of the field (central field) the periphery of the binocular field is suppressed so that there are no disturbing effects on the person's stereo-ability, even though the non-stereoscopic edges exist. Shifting the gaze shifts the binocular field. In addition, the field angle of each eye is greater than obtainable with artificial optical instruments.

With the cameras, however, the situation is different since the whole left and right eye pictures are placed on a screen which subtend a relatively small angle at the eye. Thus, while the central portion of the pictures are properly superimposed for stereoscopic appreciation, the outer edges may not be common to both eyes for stereoscopic superimposition. See Fig. 12c. Objects that might be present near the margin of the scene would create an unnatural and confusing impression, because of lack of right and left eye duplication, consequently destroying stereopsis. Placement of stereo-window masks in the optical path to occlude the non-stereoscopic edges would obviously be desirable.

Stereo-images, which ordinarily should be visualized forward of the window, may appear to cling to the viewing screen either completely or partially thus creating a psychologic distortion. This distortion can be the result of lack of similarity between the field of view of the cameras and the observer's eyes. Where the fields do not match, there will be an unnatural effect at the left and right edges of the stereoscopic picture. Objects which appear in one of the two pictures but not in the other will create confusion and even fatigue. In general, whenever a fore-screen image of an object appears unnatural or difficult to visualize as consistent with natural phenomena, the image will tend to remain at the window and steropsis will be hampered.

Since the horizontal dimension of the raster (image orthicon) is 0.96", the horizontal linear field at 10 ft. is 27.3", and since the non-stereo edge is 5", the useful stereo field will be 22.5 inches. The sizes of the non-stereo edges are a function of the interaxial distance in the parallel dual-camera. The horizontal linear dimensions of the non-stereoscopic edges remain fixed for a given interaxial distance at all object distances but the linear binocular (stereoscopic) field increases with object distance. As has already been indicated, properly placed masks will occlude the non-stereo edges by cutting in on the outer field of view of each lens system.

In the present optical system, displacement of the objective lenses is accomplished independently of the relay lenses and causes the images to be displaced toward the outer edges of raster, so that, in some cases, as much as 50% of the desired images are shifted out of the frame of the raster. Shortening the focal length of the objective will improve this condition because points in the primary image I_1 will be displaced less relative to the principal axis of the relay lens. This decreases the axial displacement of I_1 (primary image) and, consequently, the axial displacement of the second image (at the image orthicon) is also decreased.

Decreasing the object distance also improves this condition. For example, at 10 ft. object distance the non-stereo edges cut out about 18% of the useful stereoscopic picture when the interaxial is equal to 5". Reducing the interaxial to 4-1/2" displaces the images off the raster and causes a loss of useful stereo-field of approximately 75%. With an object distance of 5 ft. the non-stereo edges cut out about 38% of the useful stereo-picture at 5" interaxial, while at 4-1/2" interaxial the non-stereo portion occupies about 56%.

The Stereoscopic Field

In the present 3D T.V. system a change in the interaxial distance is accomplished by an adjustment of the camera objectives only. The relay lens, mirrors, and image orthicon are in a fixed position. Thus, when the interaxial distance is changed from 4-1/2" (minimum) to 5-1/8" (maximum), the principal axes of the objectives are displaced, while the axes of the relay systems remain fixed at 5". Vertical adjustment of the images is also accomplished by vertical displacement of the objectives. When the interaxial distance between the objectives is set at 5", the optical axes of the objectives are in the vertical plane defined by the relay lenses; and when all mirrors are set at 45° to the optical axes, an object at infinity (all axial object points) will be imaged, by the left and right camera lenses, to superimpose at the image orthicon. Any vertical imbalance of the image is removed by vertical adjustment of the objectives, and image tilt does not exist when the mirrors and image orthicon are correctly aligned. With the "infinity" alignment as just described, the camera lenses can be focused independently for finite distances. However, with this "infinity" setting, the closer the object is located to the camera position, the greater will be the separation of the images at the raster, until finally the images will be displaced out of the raster area. Reducing the interaxial does not help much at this setting, and the overall effect at the finite planes as they approach the camera is a diminution of the stereo-field.

While the optimum setting will be shown later on, the following discussion indicates the effects of improper interaxial distance and/or mirror alignment per object distance on the stereo-field and stereo-perception.

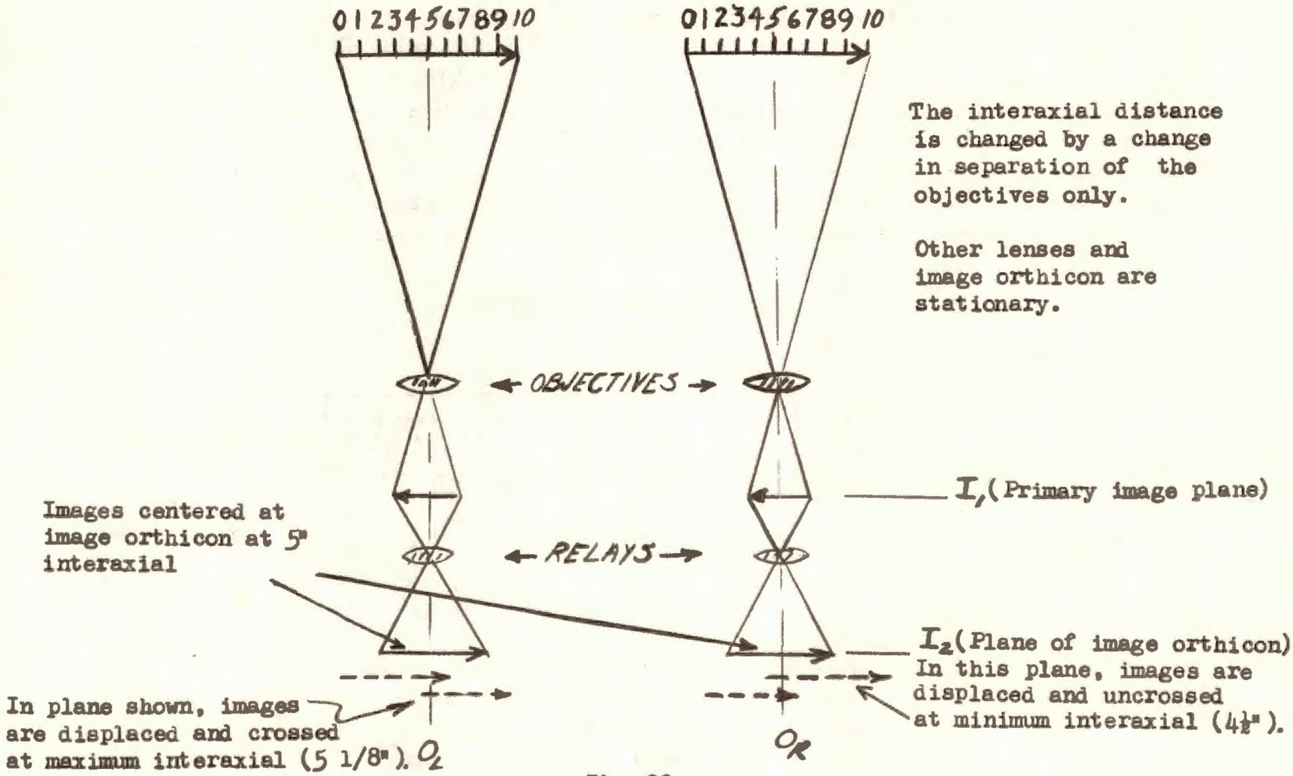


Fig. 22

In the drawing (Fig. 22), the single image orthicon is shown as two separate ones. This is shown in this manner for convenience only. Actually O_L and O_R will be coincident after the optical axes are deviated by mirrors and a beam splitter (not shown in the drawing).

At the "infinity" setting of the camera (5" interaxial, and mirrors set at 45° with principal axes), a 41.3" horizontal linear field in the plane 15 ft. from the camera objective just fills the raster of the image orthicon. This is equal to an angular field of 13°12'.

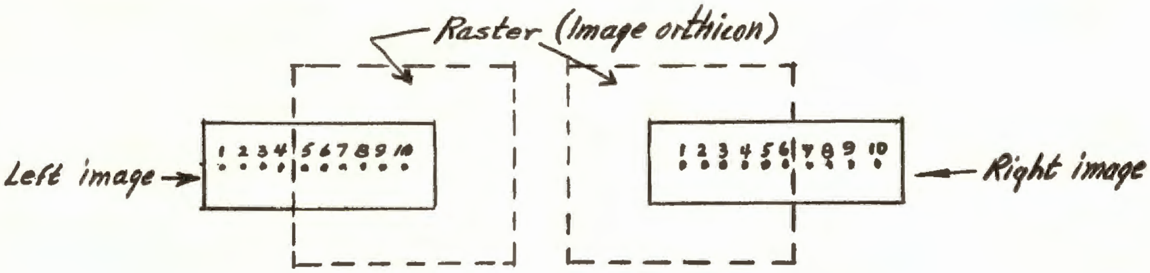
A decentration of the objective inward (toward minimum interaxial) of 0.5" = 12.5 mm.

$$\frac{\text{Power of lens} \times \text{decentration}}{10} = \text{Prism diopters} = \frac{+\ 13.33 \times 12.5}{10}$$

$$= 16.7 \text{ prism diopters or } 9.74 \text{ degrees}$$

This represents an image shift of 73%, due to the decentration or reduction of the interaxial to 4-1/2".

But before decentration (at 5" interaxial), only 37.05" of the 41.3" linear monocular horizontal fields or 85% of the total binocular image field is common to both left and right fields. Thus, at 4-1/2" interaxial, a loss of 73% of 37.05" due to image displacement at the image orthicon leaves 10" or 24% of the total)41.3"0 horizontal field. Of this amount only about 1/3 of the objects or points are common to both fields for stereoscopic appreciation. (See Fig. 23) Hence, only 8 to 10% of the total field-image can be useful for stereoscopy. Other portions of the scene at this screen would be non-stereoscopic and would tend to degenerate, or at least render unreliable, the measurement accuracy of the presentation. The stereoscopic portion of the scene increases with increase of interaxial distance from 4-1/2" to 5".



The points indicated by the numbers 5 and 6 (images in the stereo pair) are common to both images at the image orthicon. This represents a very small portion of the whole image or about 10%.

Fig. 23

Similarly, with the same optical arrangement as above except that the lenses are focused at a plane 5 ft. from the camera, the horizontal linear field is 13.3" and the images are crossed at maximum interaxial (5-1/8). The non-stereoscopic portion of the image is about 30%, leaving about 9.3" stereo-field (70%). Decreasing the interaxial to the minimum (4-1/2") shifts the images out of the raster so that the stereo-field occupies only 44% of the horizontal field. At minimum interaxial the images are uncrossed.

The following table shows the amount and type of image disparity for 3 selected distances when mirrors were adjusted for coincidence of the images at maximum interaxial, with the object plane at a distance of 15 ft. from camera lenses. This plane is the convergence plane and corresponds to the screen plane (T.V. tube) in the image space. Table 16 shows the interaxial distance required to establish the plane of convergence (or zero separation at screen) at 3 different object distances.

Table 16

Measured image separation (approx.) for 4-1/2" (min.), 5", and 5-1/16" (max.) interaxial distance.

Object Distance	Interaxial Distance	Image Separation at Screen (T.V. Tube)
15 ft.	5-1/16"	0
	5"	0.38" uncrossed
	4-1/2"	4.5" "
10 ft.	5-1/16"	0.125" crossed
	5"	0
	4-1/2"	4.5" uncrossed
5 ft.	5-1/16"	1.5" crossed
	5"	1.125" crossed
	4-7/8"	0
	4-1/2"	3" uncrossed

The Stereoscopic Window

The stereoscopic window is created by the limiting aperture of the stereo-transmission system. Usually this is the masking at the screen. The masking at the image orthicon is in the same position (coincident) for both left and right images; therefore, the stereo-window is in the plane of the television display screen. However, by placing the masks in the primary image plane (I_1) of each camera lens system, the stereo-window can be projected anywhere in the final image space, depending upon the separation of their conjugates at the image orthicon. This separation is effected by attaching the metal masks to each field lens. The width of each aperture can be varied and the whole aperture can be decentered by a simple adjustment of the metal slides. Since this device will separate the windows to the desired amount, placement of the stereo-window can be controlled to set in the plane of the nearest stereo-image.

The masks cut in on the useful portion of the total image, especially at minimum interaxial. However, for maximum interaxial, cutting off the external edges of the field by masking off the nasal portion of the primary image plane can occlude the non-stereoscopic edges without any additional reduction of the field of view.

Improper placement of the stereoscopic window will produce psychological effects which can distort or even destroy the sensation of stereopsis. Essentially, the window is a stereoscopic image of the smallest mask in the image plane of each camera. The disparity between the two masks determine the position of the stereoscopic window as it appears to the observer. If all images should appear to come forward of the window, towards the observer, then any unnatural representation of these two images will distort the sensation of stereopsis, causing the images to "stretch" or perhaps recede to the plane of the window.

Real objects interfering in the stereo-image space will also cause distortion. Hence, for performing remote-handling operations while viewing stereo-images between the screen and the observer, the masks should be so separated as to allow the stereo-window to appear in front of the nearest stereo-image. This will lessen the possibility of stereo-image deterioration which could be caused by some physical object that might be lurking at the margins of the final image space.

The only convenient location for the stereo-window is at the field lens. The size of the mask can be adjusted so that the stereo-image of the window will appear in front of nearest stereo-image (image factor = 2 in this case). Since the physical windows cannot be placed exactly in the plane of the primary image (1st conjugate of object), the final image will appear slightly blurred, but this is not seriously contra-indicated visually or stereoscopically.

The Stereo-Window, Image Distance Factor, and Accommodation

In general, for best performance, the following points should be remembered:

1. The stereoscopic window should always be in front of nearest stereo-image.

2. No physical objects should be permitted to stand between the stereoscopic window and television display screen, unless these objects are detached and totally within the window viewing area.

3. The pictures on the television screen must always be in sharp focus, with minimum fluctuation of image brightness.

4. Angular subtense of screen image is the same no matter where the converging eyes place the stereo-image in space. The stereo-image, however, will appear smaller in size as it comes forward of the screen, as a function of the binocular convergence.

5. The accommodation of the eyes is constant for a given observation distance but the convergence changes. Thus, dissociation of the accommodation-convergence reflex increases with increasing nearness factor. As long as observers are trained, the images can be brought forward of the television screen. But it must be remembered that normally, when viewing a motion picture screen at infinity (50' and more), the greater number of observers will feel more comfortable and see more easily if the images appear spread out beyond the screen, especially if it is itself the stereoscopic window. This is further facilitated by the fact that for spatial points at about "infinity" (slightly beyond and before the distant screen) the dissociation of the accommodation-convergence reflex is relatively small. In other words, it does not matter greatly whether the convergence is stressed while the accommodation remains fixed or vice versa; both are close to the relaxed condition. However, for a screen distance of 30 inches (as is the case for the present television screen size), the observer psychologically and habitually wants to converge, and, though he also wants to accommodate an equal amount, the desire for convergence is greater than that for accommodation. This is evidenced by the fact that as people grow older the effort of convergence is much easier than that of the accommodation.

In ordinary natural viewing, an accommodation-convergence balance is maintained. The accommodation is subconsciously adjusted to conform with the distance at which the eyes converge. However, when viewing a stereo-scopic screen-presentation the situation is different. The accommodation remains fixed for the screen distance while the convergence changes to localize the stereo-images in space. This kind of viewing breaks (dissociates) the normal accommodation-convergence reflex. At long distances from the screen (50 ft. or more), dissociation of the accommodation-convergence relationship is small and little concern need be given to this factor, even when the stereo-images are in front of the screen plane. However, in the present application the viewing screen will be close to the observer; thus, the eyes must converge on relatively closer points while at the same time focus (accommodate) on the more distant screen. This means that neurological effort must be applied to accommodate the close screen (about 3 ft.) and additional effort of the convergence to localize the stereo-images. Some observers have no difficulty adjusting to this new accommodative-convergence relationship, while others find it difficult. In general, however, everyone must train himself to maintain forescreen stereo-images. If the observer can fuse images at all, he can, with a little effort, soon adapt to the new relationship.

The average person is capable of dissociating his accommodation from his convergence to the extent of one diopter without much difficulty as shown by optometric tests, and some people show exceptional ability in this direction. But it is much easier for the normal observer to accommodate for a point more distant than his convergence point rather than to converge closer than his accommodation point. However, even though dissociation of the accommodation and convergence must be reckoned with, observers attempting to make stereoscopic determinations of spatial position of objects with a high degree of accuracy require training since the percentage of persons with high stereo-acuity is indeed very small.

RECOMMENDATIONS FOR BEST VIEWING PERFORMANCE WITH THE PRESENT 3D T.V. SYSTEM

1. Establish reference object plane at 15 ft. distance from camera (with 5" interaxial).

2. Establish Convergence plane by superimposing the screen images of a target placed 10 ft. from camera.

3. Target (working) distance should be between convergence plane and camera — at about 8 ft. distance.

4. Observation distance - 30 inches

   Target distance in inches x transmission magnification factor

   96 inches x .34 = 32 inches

5. Nearness factor = 1.6 (stereo-image distance from screen is approximately 40% of observation distance)

6. <u>Stereo window</u>, slightly closer than nearest image (N = 1.9)

7. Accommodation: 1.3 diopters (for emmetrope)

8. Convergence: 2.1 meter angles (dissociation 0.8 diopter)

9. With 8 sec. stereo acuity — Measurement accuracy 1/16"

As has been observed, the measuring accuracy is directly proportional to the stereo acuity of the operator and inversely proportional to the viewing distance. Closer targets (in the object space) will, of course, improve the transmission magnification ratio and resolution; but this will require increase of observation distance to maintain the ortho stereoscopic position.

Generally speaking, however, the measuring accuracy will depend upon the minimum perceptible parallax difference that the operator can perceive; and, in turn, this angular difference will correspond to smaller depth displacements in the object space for object points closer to the target. With proper adjustment of the convergence and best image quality, nearby object displacements of the order of a few thousandths of an inch are possible. The ortho-stereoscopic position need not be strictly adhered to.

For best perspective and resolution with the present system, the object to camera distance may be decreased.

object distance = 6 ft.

interaxial distance = 4-29/32 inches (superimposition at 8 ft.)

observation distance = 30"

nearness factor = 1.6
(Nearness of stereo-image 40% of observation distance)

accommodation: 1.3 diopters (for emmetrope)

convergence: 2.1 meter angles (dissociation 0.8 diopter)

stereo-window: N = 1.9

SUMMARY

Table 17 shows both the calculated and measured (where warranted) values concerning the corresponding object and image space geometry for several important object distances. In general, this report has discussed the necessity for geometrical correspondence between the original scene and the final image space, the way in which the present 3D T.V. system fulfills this demand, its flexibility and limitations, and the physiological and psychological entities which must be considered together with the best solution for optimum viewing performance and minimum fatigue. A brief summary of the more important points will be given here.

TABLE 17

GEOMETRY OF THE OBJECT AND IMAGE SPACE FOR SEVERAL OBJECT POSITIONS - VIEWED BY OBSERVER AT 30" FROM THE TELEVISION SCREEN

(AT 5" INTERAXIAL, MIRRORS ARE ADJUSTED FOR COINCIDENCE OF A DISTANT TARGET AT 15 FT. (INSTEAD OF INFINITY IN ORDER TO ACCOMMODATE 100% STEREO FIELD). ALL OTHER CONVERGENCE PLANES ARE ESTABLISHED BY CHANGING THE INTERAXIAL DISTANCE ONLY.

	15 ft.	10 ft.	8 ft.	7 ft.	6 ft.
A. CONVERGENCE PLANE (measured from first vertex of camera objective)	15 ft.(180")	10 ft.(120")	8 ft.(96")	7 ft.(84")	6 ft.(72")
B. INTERAXIAL DISTANCE to establish convergence plane	5"	4 59/64"	4 29/32"	4 28/32"	4 27/32"
C. VIEWING DISTANCE from television display screen (center of perspective)	29"	30"	31"	32"	33"
D. OBJECT SIZE (reference target in object space)	88 mm	88 mm	88 mm	88 mm	88 mm
E. IMAGE SIZE (left and/or right image corresponding to reference target) at television screen-(calculated)	15.6 mm	23.5 mm	29.6 mm	33.9 mm	48 mm
-(measured)*	17 mm	25 mm	32 mm	35 mm	45 mm
F. TRANSMISSION MAGNIFICATION FACTOR	0.1768 X	0.2674 X	0.3365 X	0.3863 X	0.4535 X
" " " -(reciprocal value)	5.67 X	3.74 X	2.97 X	2.59 X	2.21 X
G. RESOLUTION, MONOCULAR (minimum resolvable Snellen letter at center of perspective- (calculated)	11 mm	5.57 mm	5.5 mm	5.25 mm	4.5 mm
- (measured)*	11 mm	5.57 mm	5.5 mm	5.25 mm	4.5 mm
H. RESOLUTION, BINOCULAR (minimum resolvable Snellen letter at center of perspective- (measured)*	11 mm	6.5 mm	5.5 mm	6.2 mm	4.5 mm
I. LINEAR HORIZONTAL FIELD OF VIEW - MONOCULAR - (calculated)	41.3"	27.3"	21.7"	19"	16.5"
- (measured)*	37.5"	26.5"	20"	17"	16"
J. LINEAR STEREO FIELD (Percent of screen width) - at coincidence of left and right images (see 2)	100%	100%	100%	100%	100%
- at maximum interaxial distance (5 1/16")	95%	85%	80%	75%	75%
- " " " " " - crossed or uncrossed	crossed	crossed	crossed	crossed	crossed
- " " " " " - separation of images at screen	13 mm	19 mm	27 mm	35 mm	44 mm
- at minimum interaxial distance (4½")	10%	15%	30%	40%	45%
- " " " " " - crossed or uncrossed	uncrossed	uncrossed	uncrossed	uncrossed	uncrossed
- " " " " " - separation of images at screen	120 mm	113 mm	105 mm	102 mm	99 mm
K. MINIMUM PERCEPTIBLE DEPTH DISPLACEMENT IN OBJECT SPACE (measured from convergence plane toward camera) at observation distance of 30" from television screen - minimum perceptible parallax difference of 30 seconds	0.90"	0.360"	0.230"	0.200"	0.130"
- " " " " " 10 seconds	0.30"	0.120"	0.075"	0.065"	0.035"
- " " " " " 2 seconds	0.060"	0.024"	0.015"	0.013"	0.007"
L. MINIMUM PERCEPTIBLE SEPARATION OF LEFT AND RIGHT IMAGES (Binocularly) at the television display screen from observation distance of 30 inches - minimum perceptible parallax difference of 30 seconds	0.0045"	0.0045"	0.0045"	0.0045"	0.0045"
- " " " " " 10 seconds	0.0015"	0.0015"	0.0015"	0.0015"	0.0015"
- " " " " " 2 seconds	0.0003"	0.0003"	0.0003"	0.0003"	0.0003"
M. ABSOLUTE DEPTH DISPLACEMENT in the final image space - minimum perceptible parallax difference of 30 seconds - at the screen	0.040"	0.040"	0.040"	0.040"	0.040"
- at half-way between screen and observer (N = 2)	0.001"	0.001"	0.001"	0.001"	0.001"
- minimum perceptible parallax difference of 2 seconds - at the screen	0.035"	0.035"	0.035"	0.035"	0.035"
- at half-way between screen and observer	0.001"	0.001"	0.001"	0.001"	0.001"
N.**ACCOMMODATION at 30" observation distance (diopters)	1.3	1.3	1.3	1.3	1.3
O.**CONVERGENCE - at 30" observation distance (N = 1)	1.3	1.3	1.3	1.3	1.3
(Meter angles) - 20" observation distance (N = 1.5)	1.96	1.96	1.96	1.96	1.96
- 10" observation distance (N = 2.0)	3.9	3.9	3.9	3.9	3.9

*Where the measured values do not agree with the calculated, the errors are largely due to: (1) Lack of constancy of focus of electron beam at television tube screen. (2) Error in aspect ratio and non-linearity in cathode ray tube.

**For the emmetropic and orthophoric observer.

Calculations show that the center of perspective must be approximately 30 inches from the television screen. Since the monocular representation of the original scene is correct at this distance, then any increase of the interaxial distance of the dual camera over the interocular distance of the observer, will not contribute to distortion of the object-image space geometry, but rather will enhance stereoperception. This is not true for other observation distances, however. At the prescribed observation distance, and with proper adjustment of the nearness ratio, the stress on the accommodation convergence mechanism of the eyes is maintained at approximately 0.8 diopters of dissociation. This is within the normal capability of the average observer possessing good binocular vision.

The smallest resolvable Snellen letter with the present television system was calculated as 5.78 mm. for a 10 ft. target distance. The same size letter can be resolved from the prescribed viewing distance. Photographic tests on both left and right camera lens systems, with and without the filters demonstrated that the optics can resolve the 4.45 mm. Snellen letters at the same target distance of 10 ft. Hence the optical resolution is safely below that of the minimum resolution of the television system.

The calculated stereo-resolution for depth discrimination of 0.075 to 0.120 inch, at the camera distance of 9 ft. for an observer whose stereoactivity is 10 seconds of arc was substantiated by actual tests on the operators, when viewing black and white presentations. Color television was not used for tests because a "diffusion" effect was visible that created a white border at the edges of each image. While this border will not bother the non-discriminating observer, the trained observer would have difficulty in deciding exactly which point or edge of the comparison target should be used as reference. However, when a reference "edge" is selected for the observer, the stereo-acuity is as good as with black and white images.

The stereo-field is maintained at 100% for all finite object planes by maintaining correct adjustment of the mirrors and interaxial distance. Occlusion of left and right eye images is complete. However, when the mirrors and lenses are shifted to set the convergence plane beyond 20 ft.; light leakage or "ghosts" appeared. This may have been due to multiple reflection and/or depolarization effects.

The small amount of flickering which is observed even when viewing a black and white presentation does not appear to affect stereo-acuity. The flicker decreases somewhat when the brightness of the screen presentation is reduced. Flicker may be due to differences in transmission of the individual color or polaroid filters.

GENERAL DESIGN CONSIDERATIONS FOR VIEWING EFFICIENCY WITH STEREO-TELEVISION

Design considerations for optimum viewing efficiency in hot radiation laboratory operations through stereo-television should be aimed at achieving accurate quantative determinations of the relative spatial positions of the real objects by viewing the corresponding stereo images. The operator, though trained for high stereo-acuity and manipulatory dexterity, must ultimately depend upon the accuracy and reliability of the stereo-image presentation, the geometrical correspondence between image and object space, and the physiological and psychological comfort. In general, good stereoscopic presentation should have the following characteristics:

1. Good picture quality (high resolution) for images - large bright images if possible.

2. Good occlusion for left and right eye. The use of HN-32 crossed polarizers can reduce light leakage to 0.005%. There should be no depolarization effects due to shape, quality, or orientation of optical elements in the light path.

3. Nearness factor of not greater than 50% (factor = 2), with low applied accommodation.

4. Stereoscopic window for complete occlusion of non-stereo edges of the binocular field.

5. Observer's eye to subtend same angle from screen images as do the corresponding objects at the camera. The "Orthostereoscopic position" should be maintained. This is where both depth and width magnifications are equal to unity for geometrical correspondence between image and object.

6. Camera interaxial must be equal to interpupillary distance, if the center of perspective for the observer cannot be maintained. Variable interaxial (base line) should be provided.

7. Camera lenses should have large field of view and maximum depth of field.

8. Convergence of camera axes — automatically for different object planes. Convergence control which is calibrated and in synchronism with the focus control of the lens.

9. A binocular view-finder (stereo) and/or conventional flat view-finder.

10. Exact synchronization of shutters, filters, and television scanning beam.

11. Mirrors, beam splitters, prisms should be avoided in the optical path because

    a) they limit the use of wide angle lenses.

    b) there is a loss of light in transmission, thus effectively reducing lens speed.

    c) the use of "50%" transmission mirrors (beam splitters) requires some color correction which means that light reaching the image orthicon is effectively less than 50% of the scene brightness. Beam splitting mirrors are rarely neutral to color. Usually the reflected beam contains more blue and the transmitted beam more red light. For perfect color balance trimming filters are required in both beams and these further reduce the amount of light available. Unless these beam splitters can be installed in collimated light they may also cause shading of the image (unequal brightness in different areas) and aberrations such as astigmatism.

12. Filters that sequentially intercept the light path from the object space must have equal brightness transmission, and must be of good optical quality, i.e. no warping, and must be consistent with good optical design practice.

BIBLIOGRAPHY

A Methematical and Experimental Foundation for Stereoscopic Photography
by Armin J. Hill, October 1953, Journal of the SMPTE, Vol. 61

Resolution in Stereoscopic Projection
by Bernard G. Saunders, June 1953, Journal of the SMPTE, Vol. 60

Stereoscopic Perceptions of Size, Shape, Distance and Direction
by D. L. MacAdam, April 1954, Journal of the SMPTE, Vol. 62

The Theory of Stereoscopic Transmission
by Raymond Spottiswoode and Nigel Spottiswoode, Univ. of Calif. Press, Berkeley and Los Angeles, 1953

Mathematical Analysis of Binocular Vision
by Rudolph K. Luneburg, Princeton Univ. Press, 1947

The Effects of Base-in and Base-out Prisms on Stereo-acuity
by G. A. Fry and R. R. Kent, Amer. J. Optom., Monograph 4, Dec. 1944

The Geometry of Stereoscopic Projection
by John T. Rule, V. Opt. Soc. Amer. 31:-325-334, Apr. 1941

Visual Optics
by H. H. Emsley - London, Hatton Press. Ltd., 1944

Physiological Optics, Introduction to
by James P. C. Southall - Oxford University Press, New York

Physiological Psychology
by C. T. Morgan and E. Stellar - McGraw-Hill Book Co., Inc., New York, 1950

Mirrors, Prisms and Lenses
by James P. C. Southall - Macmillan Co., New York

Physical Optics, Fundamentals of
by F. A. Jenkins and Harvey E. White - McGraw Hill Book Co., New York