EARTH ORBITAL TELEOPERATOR
VISUAL SYSTEM EVALUATION PROGRAM

Test Report Number 3

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1.0 INTRODUCTION

The present report deals with empirical tests of range estimation and resolution via television. The tests reported here are part of a program of teleoperator technology development being pursued by NASA Marshall Space Flight Center. Within this development program considerable effort is being devoted to the characteristics, requirements, and design criteria for the visual system.

Since the teleoperator system exists to augment and extend man's capabilities, the man-machine interface of teleoperator systems is a primary consideration for design decisions. To derive man-machine interface requirements for the visual system, an extensive program of empirical testing and analyses has been conducted based on the visual task requirements for orbital remote manipulator system (RMS) performing satellite servicing and retrieval missions in conjunction with the Shuttle Transportation System (STS). This visual system test and evaluation program has been carried out based on a servicing and retrieval mission analysis (Malone, 1972). The mission analysis served to establish a set of visual tasks or operations which would be required in the course of RMS missions. To quantify system/operator performance in these operations, a series of laboratory visual system tests have been derived from the mission visual tasks. These tests have served to empirically provide a quantitative data base specifying system/operator visual capability in terms of speed and accuracy as functions of satellite and TV system parameters including:

- Target/background contrast
- Target marking
- Target shape

- Signal-to-noise ratio
- Horizontal resolution
- Transmission mode
- Field of view
- Frame rate
- Camera placement
- Number of cameras-including monoptic and stereoptic configurations.

The tests performed previously and the resulting quantitative data have been presented by Kirkpatrick, Malone, and Shields (1973) and by Kirkpatrick, Shields, and Malone (1974). The tests covered by these reports include:

- Minimum detection size
- Brightness discrimination
- Pattern recognition
- Size discrimination
- Distance estimation
- Solid target alignment
- Estimation of vertical
- Motion detection

The data base thus developed is intended to describe quantitatively the accuracy of performance of the various visual tasks by operators having specified levels of visual acuity. The variation in performance due to changes in target and system performance serve as an input to design trade-offs and design criteria. The results presented by Kirkpatrick et.al.(1973, 1974) include design feature recommendations and criteria based on quantitative performance measures as functions of target and system parameters.

The tests reported here deal with accuracy of range estimation and range resolution performance under monoptic and stereoptic viewing conditions. Range estimation refers to determination of camera to target range where a single target is being viewed. This visual task was studied using various reticles to aid monoptic range estimation. The primary application of this visual task to the orbital RMS is considered to be during the satellite approach/docking phases. These operations require that the operator control range rate and be able to maintain constant range for inspection during the process of approach/docking.

Range resolution refers to the detection of relative range between two target objects. This visual task was studied using a fresnel stereoptic system (Tewell, et.al., 1973) and a monoptic system. The task employed was one in which the operator controlled the camera-to-target range of a movable target and attempted to adjust its range to equal that of a fixed target. The fresnel system was tested to provide a comparison with the split-field stereoptic system tested earlier (Kirkpatrick, et.al, 1973, 1974). The range resolution task was considered to apply to visual feed back and estimation during x-axis control of a servicing manipulator system.

The range estimation data presented were collected to empirically quantify the analytical treatment of range estimation presented by Kirkpatrick et.al.(1974). The analysis of fresnel stereo system parameter relationships and optimization rationale presented in section 3 served as the basis for the empirical range resolution tests. These analytical efforts serve to generalize the empirical data to system parameter levels not included in the tests. The present analyses and results thus represent a continuation of investigation of system parameter effects on performance of RMS mission visual tasks.

2.0 RANGE RESOLUTION ANALYSIS

The visual task of range resolution requires that the observer detect a difference in range between two objects in the video field of view. This task is of considerable importance in servicing manipulator control since the manipulator tip must contact servicing targets with fairly precise range control. The task of range resolution also is a primary source of requirements for stereoptic television systems for remotely manned systems since the addition of parallax cues to the display would presumably facilitate the depth resolution task to a greater degree than it would other tasks identified, (Kirkpatrick, Malone, Shields, 1973).

The present section considers optimization of a stereoptic visual system with respect to the perceptual capabilities of the human operator.

2.1 - Fresnel Stereoptic Video System

The Stereoptic system considered here is one developed by Martin Marietta Corporation (Tewell, et.al., 1973) which has been constructed and is currently under evaluation at MSFC. The present section considers constraints on, and relations between, parameters of this class of stereoptic video systems.

The system currently being studied uses a stereo camera pair with variable baseline (distance between camera viewing axes) and convergence angle. The two images are displayed on two small monitors which are projected through two imaging lenses onto a fresnel display screen. The fresnel screen forms a separate exit pupil for each eye and retains the right-left field separation to permit parallax. The fresnel stereoptic system is described in greater detail in section 3.0.

2.2 - Relationship of Stereoptic System Cues to Direct Vision Cues

In direct viewing of an object, there are two basic parallax cues, convergence and retinal disparity. Convergence refers to the fact that the eyeballs converge such that the optical axes cross at the point in question. For near objects, the eyes must focus appropriately for a sharp image to be obtained on the retina. Since the contractive status of the muscles which produce convergence and accommodation are fed back to the brain, this feedback serves as a cue to absolute range (Graham, et.al,1966). This cue is not a visual one since it derives from muscle feedback. The necessary convergence angle for the eyes may, however, be considered a cue to absolute range. For ranges which are large relative to the interocular distance, the convergence angle (α) is given approximately by:

$$\alpha = \frac{a}{R} \qquad (2\text{-}1)$$

where

α = convergence cue (radians)
a = interocular distance
R = range from eye to point

For the case of two points whose separation in range must be determined, the difference in convergence angles gives rise to the concept of retinal disparity. This visual cue refers to the fact that the two points will be imaged at different points on the retina. Mathematically, the difference in convergence angles between the two points is the physical correlate of retinal disparity. Note that this does not imply that muscle feedback gives rise to retinal disparity. It is a visual cue which is a function of differences in convergence angle. Since convergence angles for two points, P_1 and P_2 are given by eq. 2-1, the retinal disparity is given by:

$$\Theta = \frac{a}{R_2} - \frac{a}{R_1} = a\left[\frac{1}{R_2} - \frac{1}{R_1}\right] \qquad (2\text{-}2)$$

Since the stereoptic video system provides right and left eye views of the points in the field of view, similar cue parameters may be calculated for the eyeball convergence and retinal disparity produced by the displayed images. The geometry is shown in Figure 2-1 and the terminology for the current section is presented in Table 2-1. The linear disparity d of the right and left views provides the basis for stereo cues. The parameter d is given by Tewell et.al.(1973) as:

$$d=(R\beta-B)\,\frac{M}{2R\tan\frac{\Omega}{2}} \tag{2-3}$$

or

$$d=(R\beta-B)\,\frac{K}{R} \tag{2-4}$$

where

d = disparity in display plane
R = range from camera to target
M = display dimension
B = stereo baseline
β = camera convergence angle (rad.)
K = video system constant

Based on Figure 2-2, the induced convergence angle depends on d, a, and the viewing distance L. Assuming that the monitor to fresnel screen optics are such that the right and left centerlines are superimposed, the induced convergence angle is:

$$\alpha \simeq \frac{a-d}{L} \tag{2-5}$$

Where α = induced convergence in radians and a-d is assumed to be small relative to L. Upon substitution of eq. 2-4 in eq. 2-5:

$$\alpha \simeq \frac{a}{L}-\frac{(R\beta-B)\,K}{LR} \tag{2-6}$$

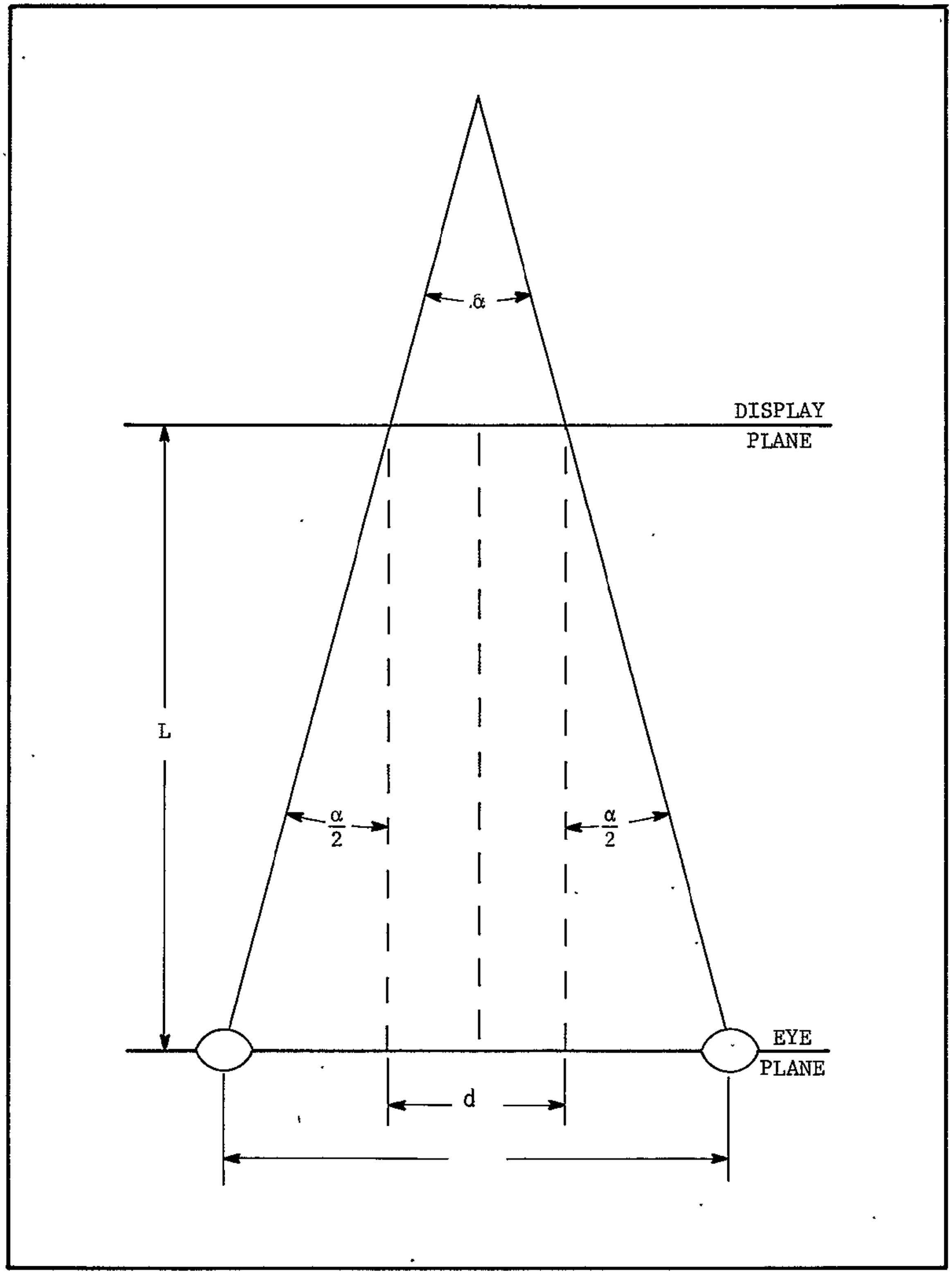

Figure 2-1. STEREOPTIC DISPLAY GEOMETRY

TABLE 2-1

TERMINOLOGY FOR RANGE RESOLUTION ANALYSIS

a = INTEROCULAR DISTANCE

R = CAMERA-TO-TARGET OR EYEBALL-TO-TARGET DISTANCE

α = EYEBALL CONVERGENCE ANGLE

d = DISTANCE IN DISPLAY PLANE BETWEEN RIGHT AND LEFT IMAGES OF POINT IN THE FOV

β = CAMERA CONVERGENCE ANGLE

B = CAMERA BASELINE

L = VIEWING DISTANCE

M = MONITOR DIMENSION

Ω = FOV ANGULAR DIMENSION

$$K = \frac{M}{2 \tan\left(\frac{\Omega}{2}\right)}$$

Θ = RETINAL DISPARITY ANGLE

E_α = CONVERGENCE EXAGGERATION RATIO

E_θ = DISPARITY EXAGGERATION RATIO

θ_t = THRESHOLD OF RETINAL DISPARITY ANGLE

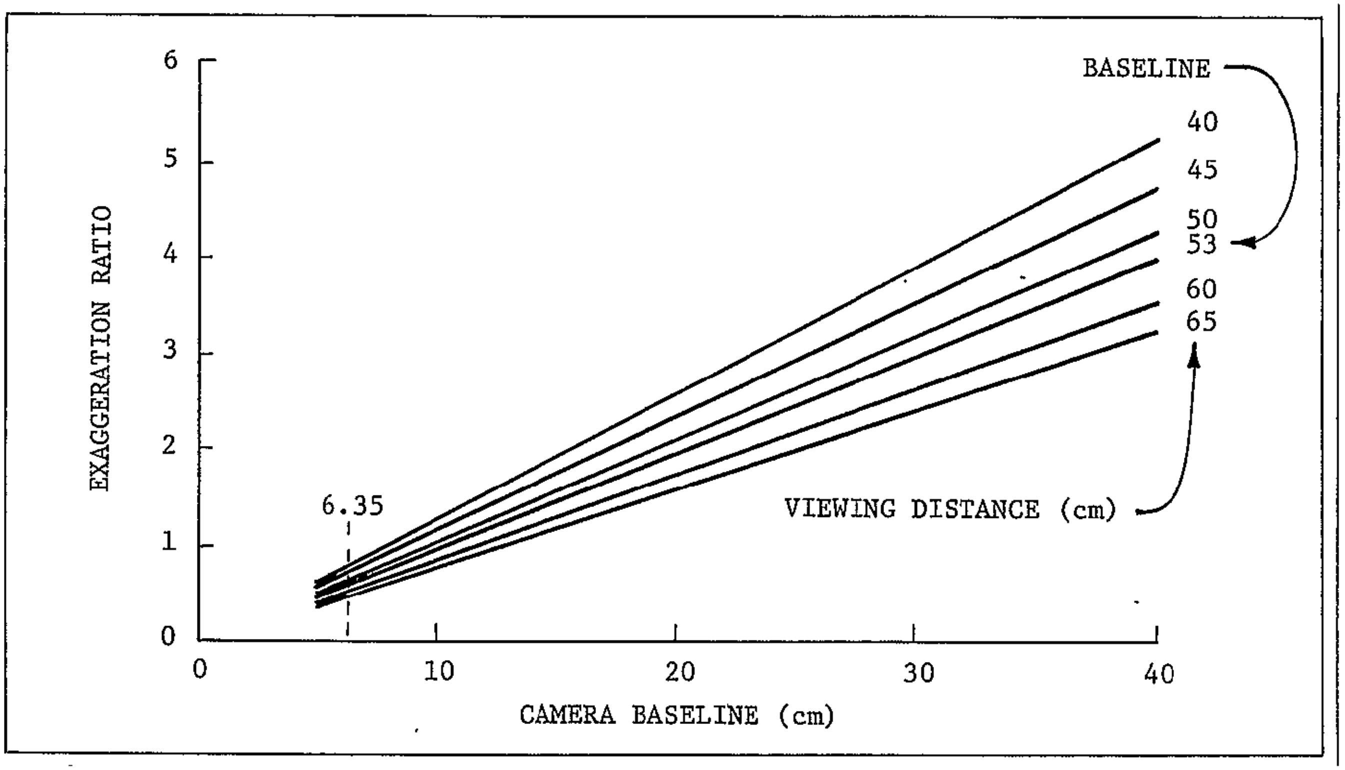

Figure 2-2. EXAGGERATION EFFECTS DUE TO CAMERA BASELINE AND VIEWING DISTANCE

For the case where two points are imaged by the system, the retinal disparity is given by the difference between convergence angles.

$$\theta' = \alpha_1 - \alpha_2 = \frac{(R_1\beta - B)K}{LR_1} - \frac{(R_2\beta - B)K}{LR_2} \qquad (2\text{-}7)$$

Rearranging eq. (2-7):

$$\theta' = \frac{BK}{L}\left[\frac{1}{R_2} - \frac{1}{R_1}\right] \qquad (2\text{-}8)$$

2.3 Parameter Constraints for Natural Stereo

To make the stereoptic view using the stereoptic system correspond as closely as possible to normal direct viewing, the parallax cues should be equal for the two viewing cases. This state of affairs will be called "natural stereo". It is obtained when:

$$\alpha' = \alpha \text{ and } \theta' = \theta$$

In the above constraint, α and θ refer to direct vision convergence and retinal disparity cues which would be obtained if the eyes were viewing the scene from the camera plane. To relate the retinal disparity constraint to system parameters, eqs. 2-2 and 2-8 may be equated yielding:

$$\frac{BK}{L}\left[\frac{1}{R_2} - \frac{1}{R_1}\right] = a\left[\frac{1}{R_2} - \frac{1}{R_1}\right] \qquad (2\text{-}9)$$

All ranges may be cancelled from eq. 2-9 leaving:

$$\frac{BK}{L} = a \qquad (2\text{-}10)$$

Equation 2-10 expresses a system parameter constraint necessary to provide natural retinal disparity. In eq. 2-10, K is dependent on monitor (fresnel screen) size and the tangent of one-half of the angular field of view of one camera. (See Table 2-1)

To obtain natural convergence cues, eq. 2-10 is assumed to hold and eq. 2-1 and 2-6 may be equated yielding:

$$\frac{a}{L} - \frac{(R\beta - B)K}{LR} = \frac{a}{R} \tag{2-11}$$

Rearranging eq. 2-11:

$$a - (R\beta - B)\frac{K}{R} = \frac{aL}{R} \tag{2-12}$$

Expanding eq. 2-12:

$$a - K\beta + \frac{BK}{R} = \frac{aL}{R} \tag{2-13}$$

Assuming eq. 2-10 holds and substituting for a:

$$\frac{BK}{L} - K\beta + \frac{BK}{R} = \frac{BK}{R} \tag{2-14}$$

Simplifying eq. 2-14

$$\beta = \frac{B}{L} \tag{2-15}$$

Therefore, natural stereo will be obtained if eqs. 2-10 and 2-15 hold.

For a fixed parameter system, viewing distance will be constrained by seating/console relationships and by the requirement that the right and left eyes be located within their respective exit pupils for stereoptic values of K and L, the requirement placed on B, the stereo baseline is determined by eq. 2-10 and the camera convergence angle is determined by eq. 2-15. It should be noted that exaggerated stereo does not necessarily result when B>a. Theoretically, any baseline value can result in natural stereo if compensated for via eq. 2-10.

2.4 Range Resolution With Natural Stereo

The argument for use of natural stereo is that positive transfer of practice in range resolution and estimation using direct vision should occur. The observer should be able to apply his experience directly and not have to learn new range/cue value correlations in utilizing the system. The disadvantage of natural stereo is that it yields a fixed range resolution function. If range resolution is expressed as a proportion of range, the relationship of this resolution measure to range may be determined from eq. 2-8 since retinal disparity is the appropriate paralax cue for relative range (Graham, et.al., 1966). Eq. 2-8 may be rewritten as:

$$\theta' = \frac{BK}{L}\,\frac{R_1 - R_2}{R_1\;R_2}, \tag{2-16}$$

Letting $\Delta R = R_1 - R_2$ and substituting in eq. 2-16:

$$\theta' = \frac{BK}{L}\,\frac{\Delta R}{R_2\,(R_2 + \Delta R)} \tag{2-17}$$

Assuming ΔR to be negligible with respect to R_2 or R_1:

$$\theta' \simeq \frac{BK}{L}\,\frac{\Delta R}{(R_2)^2}. \tag{2-18}$$

Letting ΔR represent the range increment which is just detectable at range R, ΔR depends on the threshold retinal disparity θ'_t. This measure is a least detectable disparity angle and depends on diffusion in the ocular media, and the resolving power of the retina. Empirically, this value may be as small as 2 arc seconds and as large as 2 arc minutes depending on individual acuity and other factors (Graham et.al., 1966). The lower reported values, however, appear questionable. Since "normal" visual acuity is often taken as the ability to resolve objects separated by one arc minute, it is difficult to see how the retinal disparity threshold can be less.

The disparity threshold for viewing with television would be expected to exceed the direct vision value. Kirkpatrick et. al. (1973) found angular separation requirements five to twenty times those for direct vision using a television system subject to noise, bandwidth limiting, etc. The empirical determination of θ'_t for the observer of a stereoptic video system is discussed in sections 7 and 8. It is sufficient here to note that eq. 2-18 may be rearranged to yield:

$$\frac{\Delta R}{R}=\frac{L\theta' t R}{BK} \qquad (2\text{-}19)$$

However, under the constraints of natural stereo, eq. 2-10 holds so that:

$$\frac{\Delta R}{R}=\frac{\theta' t R}{a} \qquad (2\text{-}20)$$

Thus, range resolution is proportional to R under natural stereo and the constant of proportionality is fixed by the disparity threshold and inter-ocular distance. If the degree of range resolution afforded by natural stereo is insufficient, exaggeration or enhancement of stereo cues will be required.

2.5 Exaggerated Stereoptic Cues

If greater range resolution is required than is afforded by natural stereo, the available cues must be magnified or exaggerated to provide above threshold retinal disparity. To examine this departure from natural stereo, exaggeration ratios for convergence and retinal disparity may be defined. The exaggeration ratio for retinal disparity is:

$$E_\theta = \frac{\theta'}{\theta} \qquad (2\text{-}21)$$

Substituting eqs. 2-2 and 2-8 in eq. 2-21:

$$E_\theta = \frac{BK}{La} \qquad (2\text{-}22)$$

E_θ is a cue magnification factor for retinal disparity relative to natural stereo. If $E_\theta = 1.0$, eq. 2-22 reduces to eq. 2-10. The purpose of exaggerated stereo is to increase range resolution capability. Substituting eq. 2-22 in eq. 2-19:

$$\frac{\Delta R}{R} = \frac{\theta' t R}{a E_\theta} \qquad (2\text{-}23)$$

Thus, range resolution capability is proportional to E_θ.

Since convergence to a single point may serve as a cue to absolute range, a measure is also required for convergence exaggeration. The convergence exaggeration is:

$$E_{\alpha} = \frac{\alpha'}{\alpha} \qquad (2\text{-}24)$$

Substituting eqs. 2-1 and 2-6 in eq. 2-24:

$$E_{\alpha} = \frac{R}{a}\left[\frac{a}{L} - \frac{(R\beta - B)K}{LR}\right] \qquad (2\text{-}25)$$

Expanding eq. 2-25:

$$E_{\alpha} = \frac{R}{L} - \frac{R\beta K}{aL} + \frac{BK}{aL} \qquad (2\text{-}26)$$

Substituting eq. 2-22 in eq. 2-26:

$$E_{\alpha} = R\left[\frac{1}{L} - \frac{\beta K}{aL}\right] + E_{\theta} \qquad (2\text{-}27)$$

Eq. 2-27 is linear in R. The exaggeration of convergence equals disparity exaggeration plus a term which is proportional to R. This variable depth enhancement would presumably be difficult to learn and might produce visual disturbances. The effect can be eliminated if the bracketed term in eq. 2-27 equals zero. This will be true if:

$$\beta = \frac{a}{K} \qquad (2\text{-}28)$$

Equation 2-28 expresses a constraint on camera convergence angle which will yield equal enhancement of depth and relative depth cues. The enhancement of convergence cues will be independent of range if eq. 2-28 is satisfied. Equation 2-28 further shows that convergence angle does not necessarily vary with baseline if enhanced stereo is required. If as before, it is assumed that <u>K</u> and <u>L</u> are fixed, convergence angle may then be selected via eq. 2-28. Then by eq. 2-27, the convergence and retinal disparity exaggeration ratios will be equal. Natural stereo will be obtained for only one value of baseline which is given by eq. 2-22 with eq. 2-28 assumed to hold:

$$E_\theta = \frac{B}{L\beta} \quad \text{if} \quad \beta = \frac{a}{K} \tag{2-29}$$

Rearranging eq. 2-29, natural stereo will result if $B = L\beta$ and $\beta = \frac{a}{K}$. To illustrate, a system may be considered having parameters shown in Table 2-2.

Table 2-2 Hypothetical Stereoptic System Parameters

Camera field-of-view	Ω = 30 deg.
Monitor dimension	M = 18 cm. (7.1 in.)
Viewing distance	L = 53 cm. (20.9 in.)
Video System Constant	K = 33.59 cm. (13.2 in.)

The average value of the interocular distance may be taken to be a = 6.35 cm. (2.5 in.). The required camera convergence angle for equal retinal disparity and convergence exaggeration is then given by eq. 2-28 as .189 radians or 10.8 degrees. The exaggeration ratio for this system may be calculated from eq. 2-22. The ratio of K to a must be constant to achieve $E_\alpha = E_\theta$. This ratio is 5.29. Therefore, substituting in eq. 2-22:

$$E_\theta = E_\alpha = \frac{5.29\ B}{L} \tag{2-30}$$

In the previous discussion, L has been assumed fixed due to the requirement that the eyes correspond to the exit pupils. In fact, some variation in L could be allowed. Figure 4-2 shows exaggeration ratios for various values of L as a function of B. Notice that the equality of E_α and E_θ is not disturbed by variation in L so long as eq. 2-28 is satisfied. Note that β is constant although the camera baseline varies. Equations 2-22 and 2-28 thus show that increased range resolution may be obtained subject to the constraint that retinal disparity and convergence cues are equally exaggerated by increasing the baseline while keeping camera convergence constant. A second means of obtaining increased range resolution is to decrease the field-of-view by means of zoom lenses. This requires that camera convergence be changed along with field of view so that eq. 2-28 can be satisfied. The camera angular field of view must exceed the convergence angle to retain an infinite stereo range. Furthermore, the convergence angle for a particular field of view is given by eq. 2-28. Substituting the definition of K in eq. 2-28:

$$\beta = \frac{2a \tan \frac{\Omega}{2}}{M} \tag{2-31}$$

Assuming the tangent approximation applies to Ω as it approaches β:

$$\beta \simeq \frac{a}{M} \Omega \tag{2-32}$$

Equation 2-32 shows that β required to satisfy eq. 2-28 is linear with respect to Ω so that Ω will be less than β producing a finite stereo field only if:

$$\frac{a}{M} < 1.0 \tag{2-33}$$

Equation 2-33 thus places a lower limit on display dimension if an infinite stereo field and constant exaggeration ratios are to be maintained. This lower limit is the interpupilary distance which is not a particularly stringent constraint in the current context (it might become stringent if a head-mounted display technique were considered).

To obtain parametric effects of field of view on the exaggeration ratio, the relevant equations are 2-22 and 2-28. Figure 2-3 shows the relationship between camera baseline and field of view for various values of

$\underline{E_\theta}$. The values of convergence angle necessary for $E_\alpha = E_\theta$ are shown as the upper abscissa. Exaggeration Ratio is the curve parameter in Figure 2-3. The range of enhancement available to a particular zoom range as well as absolute enhancement level may be seen to depend on camera baseline. Figure 2-3 also makes evident the slow increase in camera baseline with field of view for a unity exaggeration ratio. Notice that if the baseline were fixed at 20 cm. or so, a very large angular field of view would be required for natural stereo.

A desirable feature of a stereoptic system would appear to be the capability to produce natural stereo at some combined level of its variable parameters. Since it is difficult to see how depression of stereo cues (exaggeration ratio less than unity) would be to advantage, the system should produce natural stereo at the minimum baseline and/or maximum zoom settings. Variation in these parameters would then produce exaggerated stereo. Of the two parameters, baseline would probably be the easiest to vary since convergence angle need not change with baseline but must change with field-of-view to maintain equal convergence and disparity exaggeration ratios.

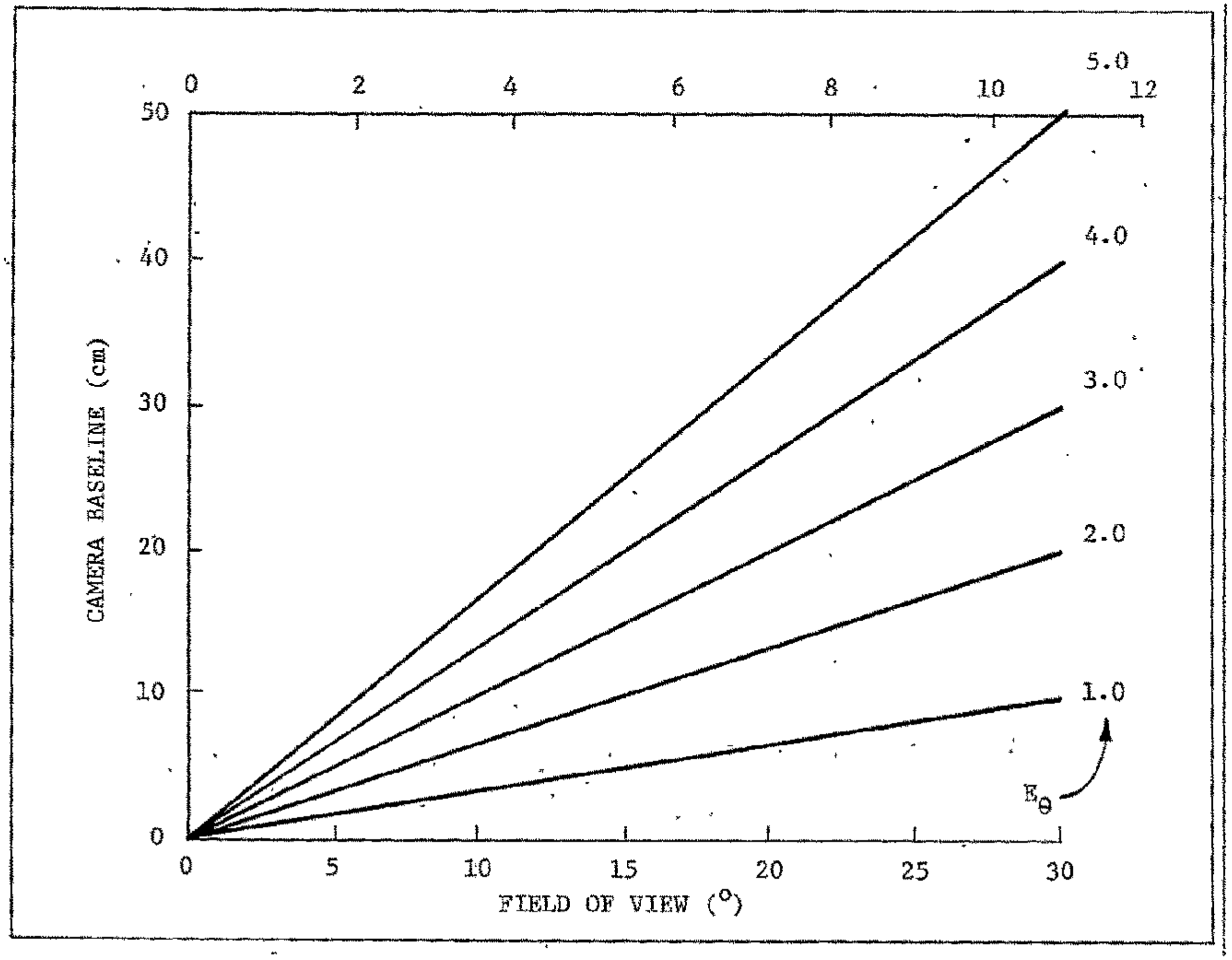

Figure 2-3. EXAGGERATION EFFECTS DUE TO FIELD-OF-VIEW AND CAMERA BASELINE

3.0 VISUAL SYSTEM EVALUATION LABORATORY

The Teleoperator Visual System Evaluation Laboratory at Marshall Space Flight Center's Astrionics Laboratory has been the focal point for the collection of human performance data using television scene feedback of remote tasks. The laboratory has come to offer an ever increasing range of system parameters and task conditions under which human performance can be investigated and analyzed. The basic laboratory is illustrated in Figures 3-1 and 3-2, although the configuration can be altered in order to accomodate unique testing requirements.

The Visual System Laboratory has been operated using both stationary (static) targets and moving (dynamic) targets with the aid of the Target Motion Generator (TMG, Fig. 3-3). With the introduction of TV system peripheral equipment, target objects can be displayed under a wide range of conditions, specifically:

- Black and white transmission
- Color transmission
- Monoptic and Stereoptic video systems
- 1 or 2 camera/monitor configurations
- Variations in monitor sizes
- Target sensitivity calibration
- Variable field of view
- Variable frame rate display
- Analog signal format 4.5 MHz
- 4 bit digital signal format 4.5 MHz
- Analog signal format 1.0 MHz
- Variable signal to noise ratio 32 db, 21 db, 15 db
- Moveable electronically generated Curser overlay
- Fixed, electronically generated Reticle overlay
- Variable target/camera geometries
- Variable target/background contrast conditions
- Variable target brightness

The selection of test conditions, formats, and parameters employed in any test are specified in each of the individual test reports which follow.

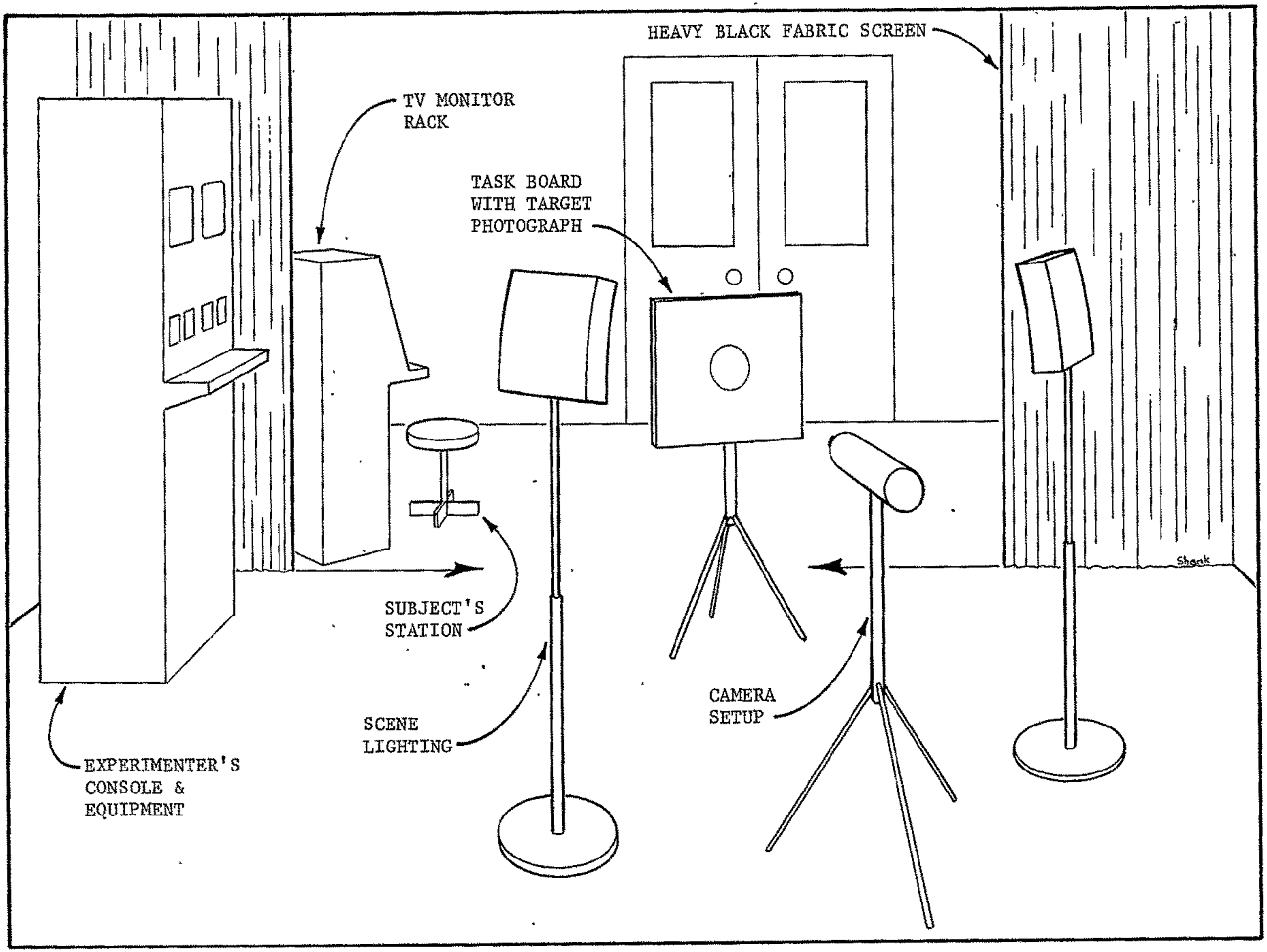

Figure 3-1. VISUAL SYSTEM LABORATORY ARRANGEMENT FOR RANGE ESTIMATION EXPERIMENTS

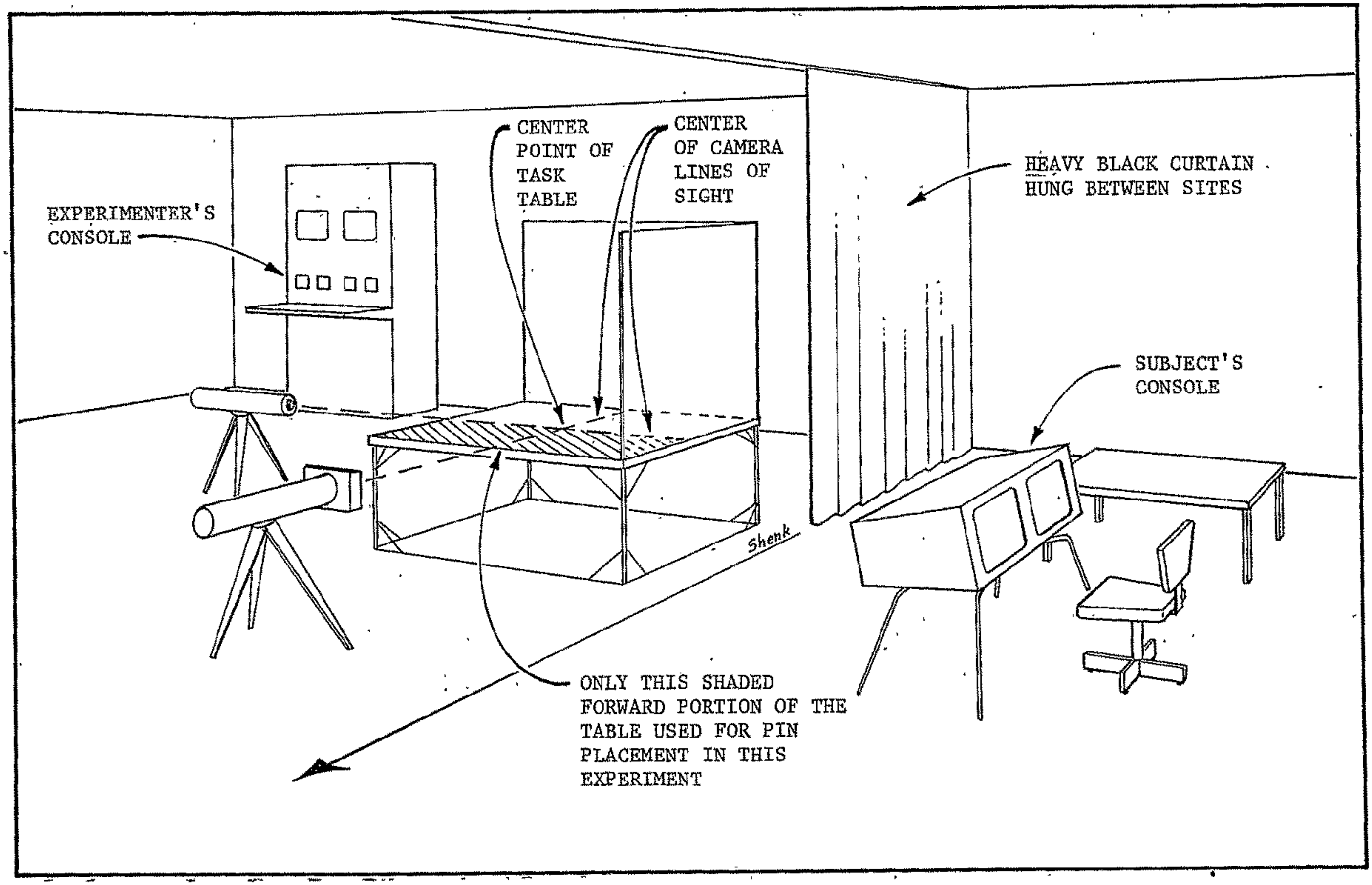

Figure 3-2. VISUAL SYSTEM LABORATORY LAYOUT

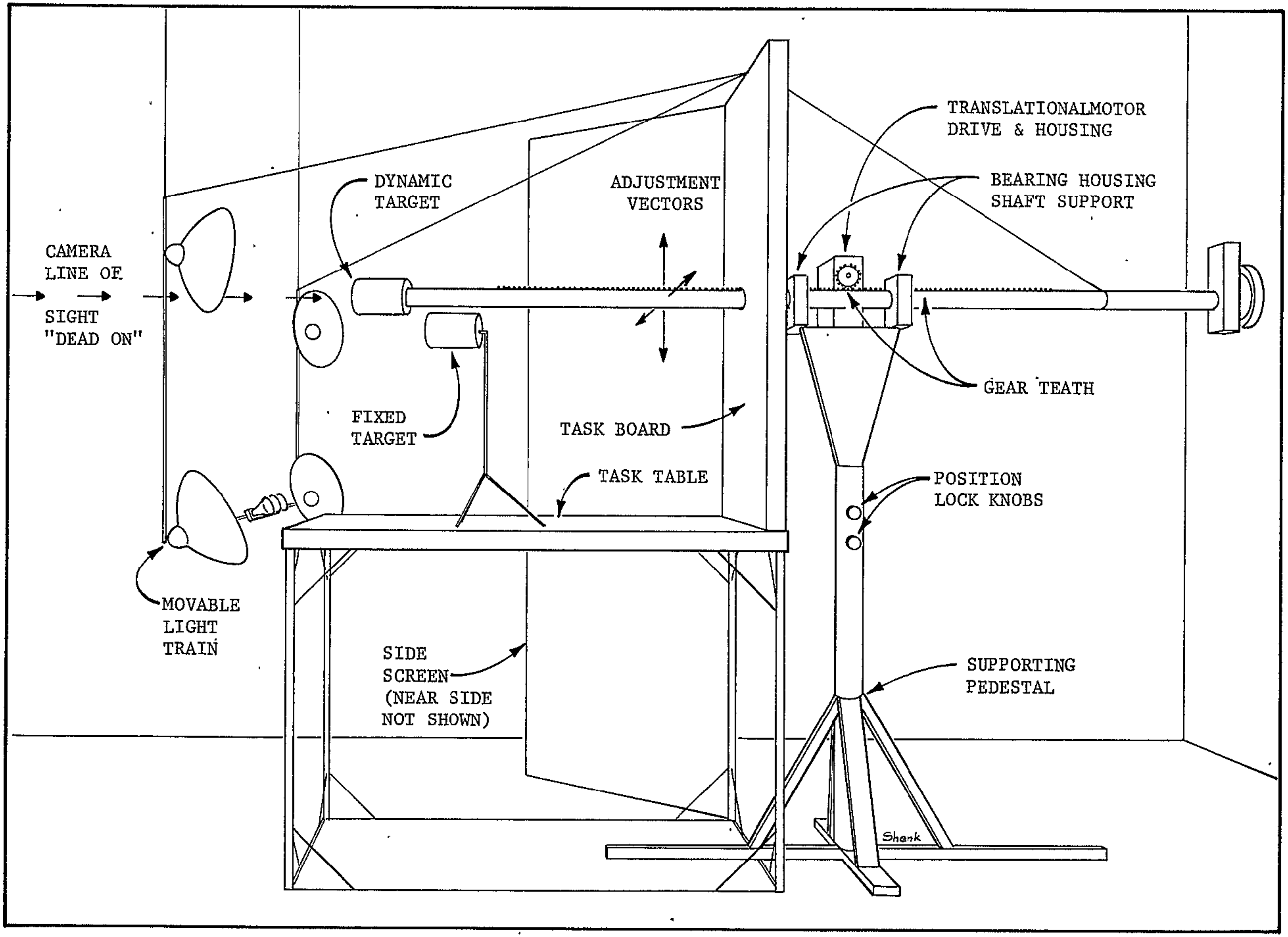

Figure 3-3. TMG APPARATUS

One of the current approaches being taken in the visual system laboratory is an investigation of human performance using a unique stereoptic video system which employs a Fresnel lens at the display. This Fresnel Stereoptic System is illustrated in Figures 3-4 and 3-5 and a discussion of its capability preceed the specific Fresnel test reports.

Table 3-1 provides an overview of the levels of specific variables which were exercised during experimentation.

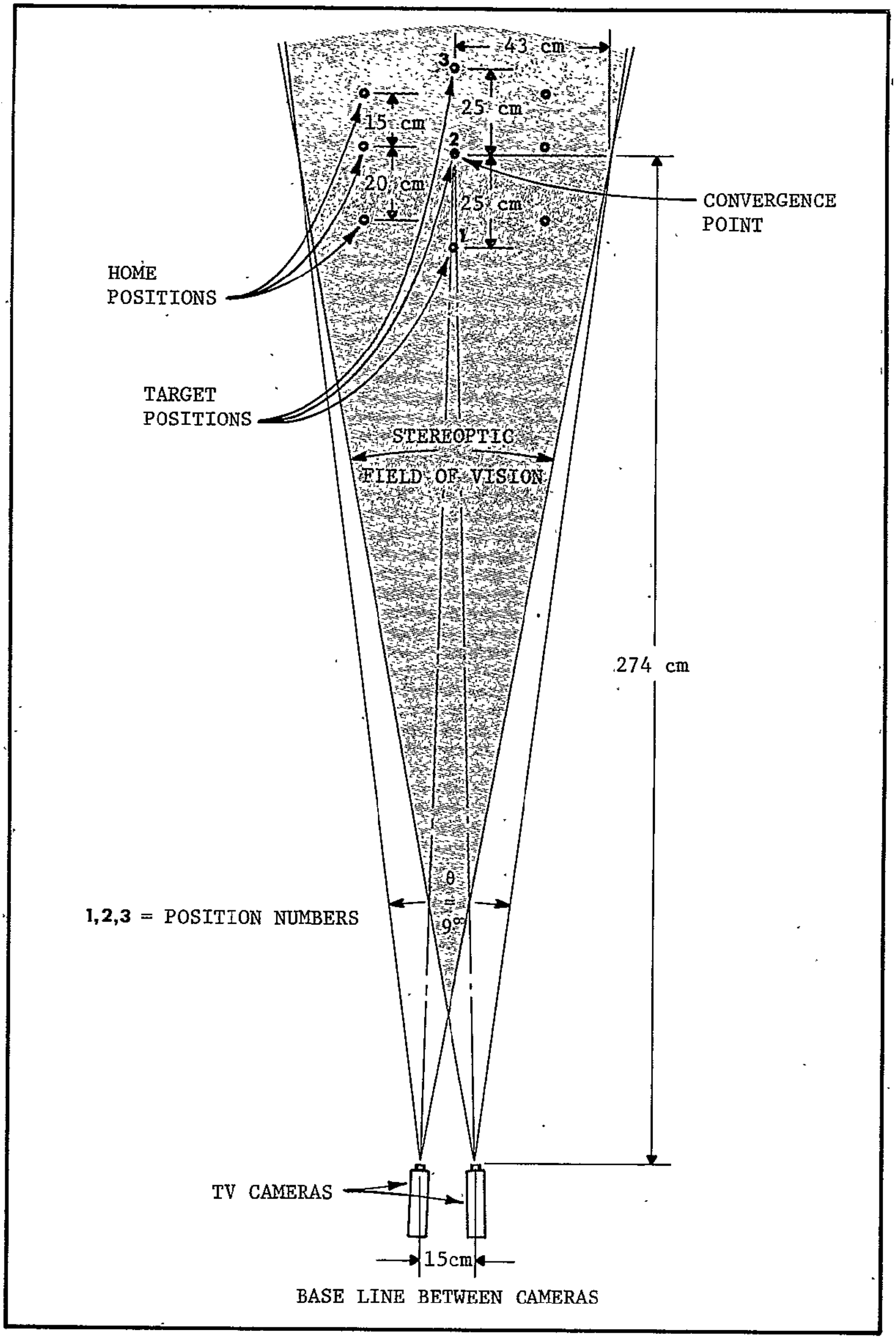

Figure 3-4. FRESNEL STEREOPTIC CAMERA ARRANGEMENT UTILIZED IN TARGET ALIGNMENT TASKS

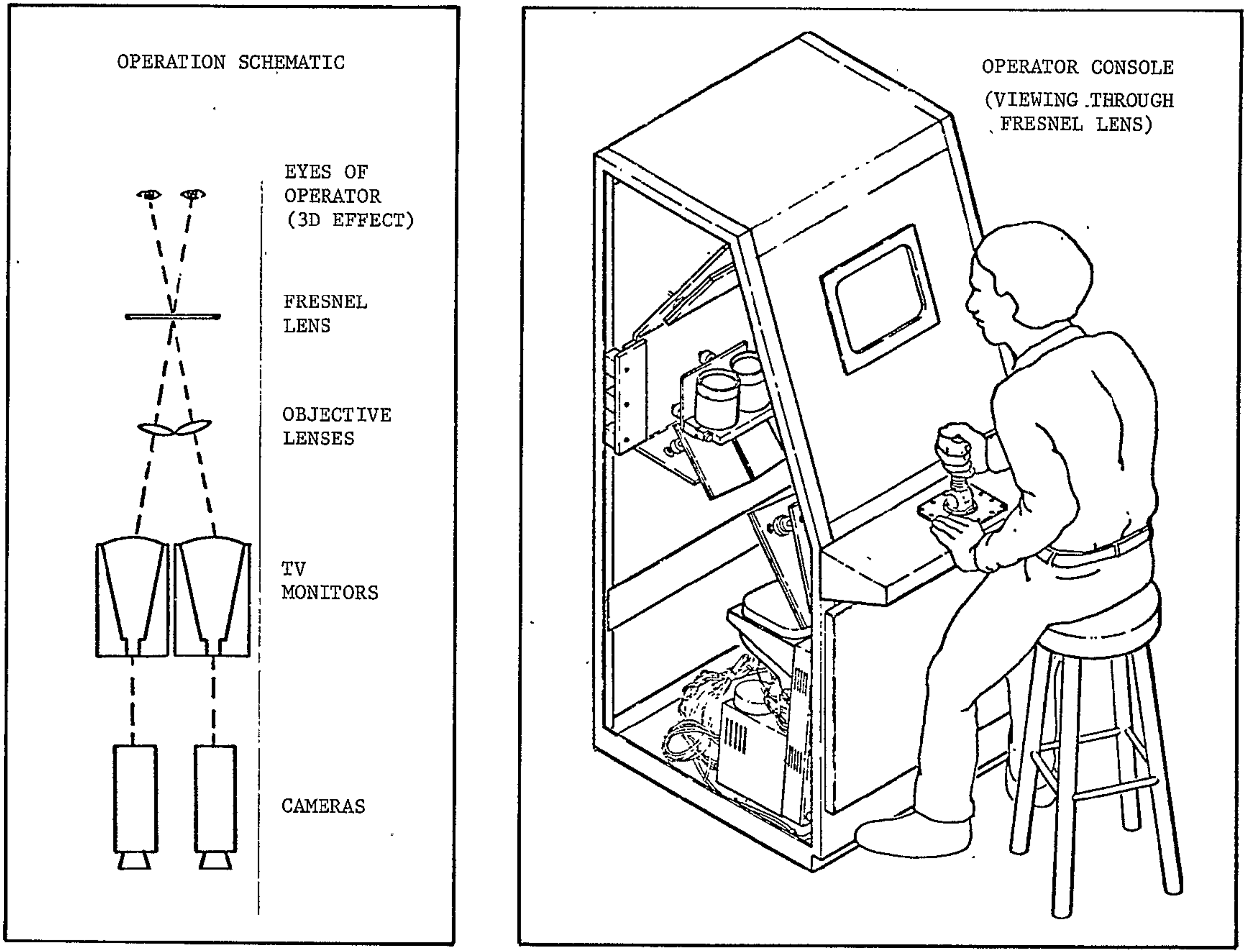

Figure 3-5. STEREO TV SYSTEMS -- LABORATORY MODEL

Table 3-1 PARAMETERS AND LEVELS INVESTIGATED IN RANGE ESTIMATION AND STEREOPTIC ALIGNMENT OF TARGET OBJECTS

PARAMETERS	RANGE ESTIMATION TEST	TARGET ALIGNMENT 1	TARGET ALIGNMENT 2
Signal Format	1. Analog 2. 4 Bit Digital	1. Analog	1. Analog
Signal to Noise Ratios	1. 32 db 2. 21 db } rf Random Noise 3. 15 db	1. 32 db	1. 32 db 2. 21 db } rf Random Noise 3. 15 db
Bandwidth	1. 4.5 MHz *2. 1.0 MHz	1. 4.5 MHz	1. 4.5 MHz 2. 1.0 MHz (Left Channel Only)
Target Parameters	1. 9 sizes	1. Variable	1. Variable
Target/Background Contrast	1. .1/.9 2. .9/.1	1. .5 & .7 on Black (.1) 2. .7 & .7 on Black (.1)	1. .5 & .7 on Black (.1) 2. .7 & .7 on Black (.1)
Number of Cameras Number of Monitors	1. One Each	1. 2 Cameras/Stereo 1 Camera/Mono	1. 2 Cameras with output combined on one Fresnel Screen
Direction of View	1. Normal	1. Normal	1. 45° Offset to Left
Field of View	1. Fixed	1. Fixed	1. Fixed
Depth of View	1. Two Dimensional	1. Two Dimensional 2. Three Dimensional (Two Camera/Fresnel)	1. Three Dimensional (Two Camera/Fresnel)
Viewing Aids	1. Static Reticles 2. Dynamic Reticles		

* Not Used With The Digital Format

4.0 OPTICAL RANGE ESTIMATION OF A TARGET

4.1 Introduction

Range and range rate are felt to be important parameters in remotely controlled orbital docking operations and this experimental effort was conducted to determine the human operator's ability to judge target range using an aided television system.

4.2 Apparatus

The target objects used in range estimation were developed by photographing a 7.6 cm target cylinder with an albedo of .9 on a nonreflective black felt background (.1). Nine positive prints were made from the master negative yielding a set of targets with absolute sizes of .75 cm., 1.25 cm, 2.00 cm, 3.5 cm, 5.00 cm, 6.50 cm, 8.00 cm, 9.50 cm, and 11.00 cm. Then a set of 9 negative prints were made such that the target was black (.1) and the background bright (.9). The target sizes for this second set were the same as for the first.

Two types of reticle conditions were employed, each electrically generated and made composit with the video signal output. The first reticle was a concentric arc type which displayed seven concentric arcs radiating out from the monitor center point and with the arcs oriented in four positions: 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock. This reticle was generated by using a 35 mm. reticle slide with a standard optiliner attached to a General Electric closed circuit TV camera. The concentric arc reticle was known as the static reticle in view of the fact that there was no controlled movement associated with it. On the other hand, a hairline verticle cursor, or dynamic reticle, incorporated subject controlled lateral movement. The dynamic reticle utilized two vertical cursors which were the full monitor face in height. Subject control of the cursors was by way of two Vernier dials on a panel located in front of the subject's TV monitor. Circuitry from the dials was connected to a Hewlett Packard digital display such that the separation of the two cursors could be read directly from the panel in intensive unit readout. Range data was estimated using one or the other of these reticles.

The target and reticle combinations were set up at the experimenter's console where any one of the two sets of 9 photographs could be displayed to a Cohu model 2000 TV camera. After target selection and positioning, the experimenter could select the appropriate reticle and mix this with the TV signal. The target/reticle combination set up by the experimenter comprised the basic information displayed to the subject. Variability in this format could be introduced by manipulating certain of the TV system parameters which were controlled at the experimenter's console. (Fig. 4-1)

Base Line Format		Variable Format
4.5 MHz	or	1.0 MHz
32 db S/N	or	15 db, 21 db S/N
Analog	or	4 bit digital

The system format could be presented under 9 conditions, each controlled from the experimenter's console using a Computer Lab A/D converter and a Computer Lab D/A converter for digital transmission, a Gerneral Radio Co. Random noise generator to vary signal-to-noise ratios, and a narrow band pass filter for transmission at 1.0 MHz.

The system was separated from the experiment site by a heavy black felt drape and was in a portion of the laboratory which had maximal control of extraneous variables.

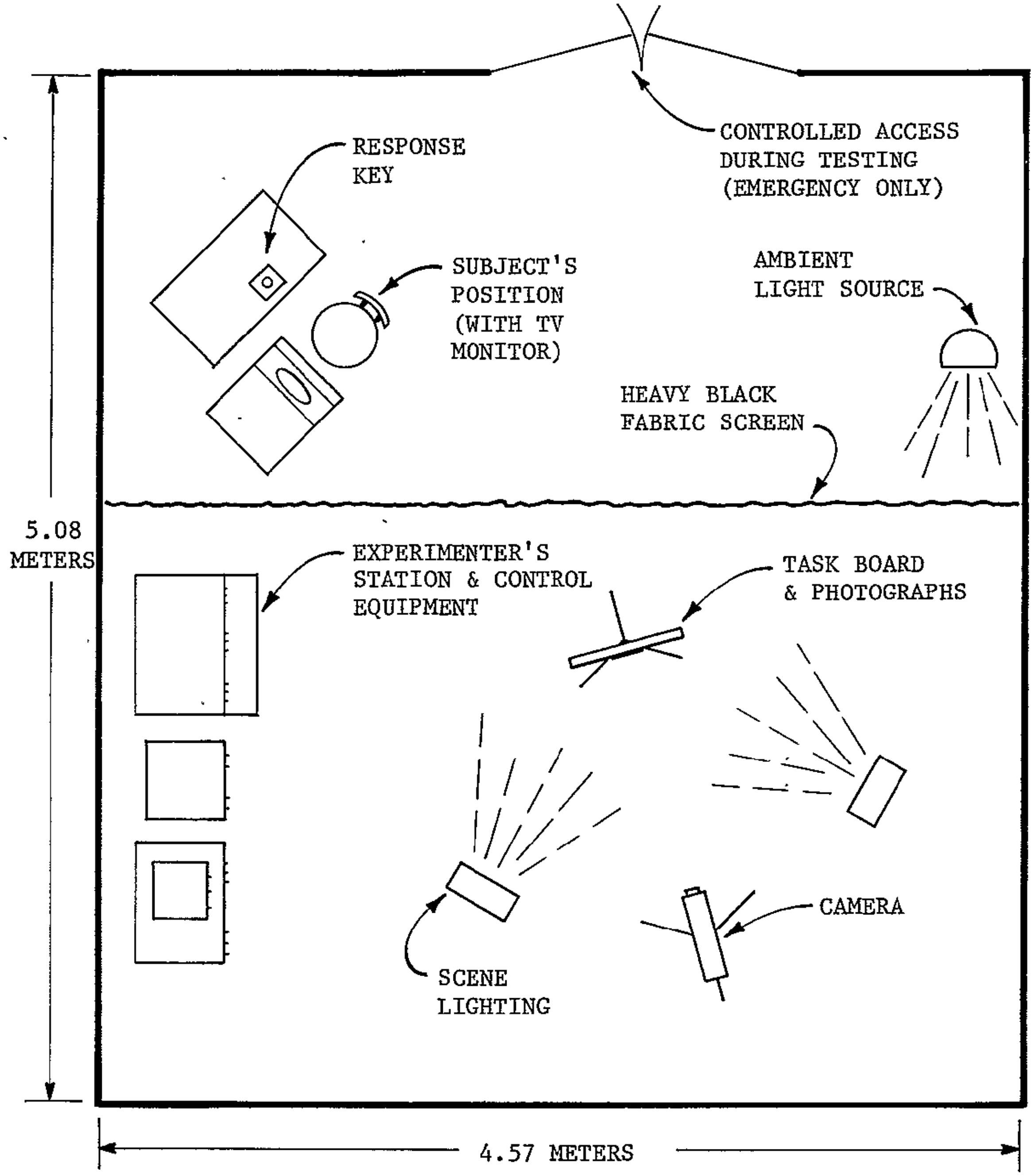

Figure 4-1. VISUAL SYSTEM LABORATORY ARRANGEMENT FOR RANGE ESTIMATION EXPERIMENTS

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The subject's station was equipped with a 19.7 cm. (7.75 in.) Conrac monitor, in front of which the subject was seated and viewed the task at a distance (eye to monitor) of 53.3 cm. (21 in.) and at an angle 15° below the horizon. Each subject used this signal monitor to view the displayed range estimation task with the appropriate parameters introduced with the signal.

Lighting was controlled so that no direct or indirect light was reflected from the subject's monitor. Available ambient light was controlled to a level of 1 footcandle in order to avoid eye strain and fatigue.

Below, and in front of, the TV monitor were the two Vernier dials used to control the verticle cursors at the subject's monitor. To his right, the subject had a response key which he pressed when he had completed his range estimation task. This response key, when depressed, terminated the subject's view on his TV monitor and stopped the recording clock in the experimenter's station.

4.3 Experimental Design

Five independent variables were manipulated in this experiment. They were the reticle conditions, either dynamic cursors or static arcs; signal-to-noise levels of 15 db, 21 db, and 32 db; transmission modes of 4.5 MHz analog, 4.5 MHz 4 bit digital and 1.0 MHz narrow band; two target-background contrasts, one .9/.1 and the other .1/.9 for each of 9 displayed image sizes, .75 cm, 1.25 cm, 2.00 cm, 3.50 cm, 5.00 cm, 6.50 cm, 8.00 cm, 9.50 cm, and 11.00 cm.

The variables subject to control were set at the following levels: illumination level of the target was 70 footcandles, the eye to monitor distance was 53.3 cm (21 in.) with a viewing angle of 15° below the horizontal plane, and the maximum viewing time allowed was limited to 60 seconds.

Each of five subjects was screened for normal vision using the Standard Orthorator Visual Tests. Each subject received all combinations of conditions, and all combinations were randomized for each subject for a total of 324 trials per subject. The experimenter recorded the time to respond and the accuracy of the subject's response.

4.4 Procedure

All laboratory equipment was activated and allowed to warm up. After reaching a stable level, the equipment was calibrated. Ambient light level at the task site was set at 70 footcandles, T.V. camera target sensitivity was set using a standard white chip with an albedo of .8, and the brightness and contrast ratios at the subject's monitor were set and locked.

After setting up the system parameters as predetermined by the data sheets, the experimenter initiated the trial by pressing the circuit button which activated his digital clock and transmitted the televised target image to the subject's monitor.

Under the dynamic reticle condition, the subject then manipulated the rotating dials so that the outer edge of the target image was subtended by the two verticle hair line reticles. When he had completed this, he pressed his response key which removed the image from his TV screen. He then verbally reported to the experimenter the reading of range from the digital panel. The experimenter recorded the time of the trial and the subject's response on his data sheets. The subject was given a maximum time limit of 60 seconds to respond and if he could not do so within that time limit, the experimenter automatically terminated the target image transmission.

Under the static reticle condition, the concentric arc reticle was displayed along with the target image. The subject was told during his initial instructions that each arc represented 10 "units" such that the progression for range determination was 10, 20, 30, etc. with between arc ranges being determined by the subject, 35, 72, etc. These figures were used to report range estimations, with smaller numbers indicating increased range. In real time situations this could be reversed so that ranges for a particular satellite size could be read directly from the display. The instruction to subjects is presented in Table 4-1.

4.5 Results

The raw data from the range estimation test were errors in estimation of displayed image size. While these error data are sufficient to determine range estimation error, they are not range estimation as such. The accuracy of estimation available depends primarily on accuracy of image size estimation. The range estimation error itself obviously depends on the range involved but there is a fixed relationship between percent error in range and percent error in image size. The latter measure is the most general parameter since image size errors may be converted to range error for any TV system under consideration by means of the system's image size equation. The dependent measure used for the present analysis was therefore percent error values or absolute error. Mean signed error is a measure of bias or constant tendency to over-estimate or under-estimate. Mean absolute error measures variable error. Both variables were calculated for the present data by the relationships:

$$\mathrm{PSE} = \frac{I' - I}{I} \times 100$$

$$\mathrm{PAE} = \left|\frac{I' - I}{I}\right| \times 100$$

TABLE 4-1
RANGE ESTIMATION TEST
SUBJECT'S INSTRUCTIONS

Your task is to judge the range of targets. Initially, your TV monitor will be blank. After I give you a verbal "ready", a round target will appear on your screen, along with <u>either</u> two vertical hairlines <u>or</u> a series of concentric arcs along the vertical and horizontal axis of your monitor screen. If the hairline reticles appear, you are to align the right line with the right edge of the target and the left line with the left edge of the target by <u>approaching the target from outside the target area</u>. That is, if the hairlines are inside the round target, move them outside the edges of the target and then return them to the edges to get your range reading. The range will be the number which appears in the lighted display after the hairlines are aligned. The hairlines are moved by turning the two knobs located below this lighted range display.

(Try each knob)

If the concentric arcs appear you are to estimate the range by counting the number of arcs across the target, from the cneter of the screen, along the horizontal axis, and multiplying by 10. That is, if two arcs cover the target, and the edge is aligned with the second arc, you will report the range to be 20. If 2 arcs cover the target and the target edge extends one half the distance between arcs 2 and 3, then you will report 25 as the range. Each arc unit represents 10 distance units.

(Any Questions?)

As soon as each range is determined, either by use of the verticle hairlines or the concentric arcs, depress the foot pushbutton and call out your estimated range figure.

The targets will be presented under different TV conditions. At times it will be very snowy, at other, it will be very clear and crisp. These conditions are normal. However, if you experience "flop-over" or similar difficulties, please call out that there are non-normal TV problems.

(Any Questions?)

where PSE = percent signed error

PAE = percent absolute error

I' = subject's estimated image size

I = true image size

Thus, a positive value of PSE indicates overestimation of image size and, consequently, underestimation of range.

Both percent error measures were subjected to six-way analysis of variance using a repeated measures model with all factors fixed except subjects. The results of the analysis of variance of percent absolute error appear in Table 4-2. As indicated in Table 4-2, reticle type ($\alpha<.01$), signal-to-noise ratio ($\alpha<.05$), contrast ($\alpha<.01$) were found to exert significant main effects. Reticle type was also found to interact with signal-to-noise ratio ($\alpha<.05$), contrast ($\alpha<.01$), and target size ($\alpha<.01$). The contrast by target size interaction was also found to be significant at the .01 level. In addition, several higher order interactions involving reticle type, target size, contrast, and signal-to-noise ratio.

The main effects of reticle type, target size, and the interaction of these variables is illustrated in Figure 4-2. It may be noted that the movable cursor produces markedly reduced error relative to the fixed reticle and that the difference between reticle types depends on target size. The main effect of reticle type arises from an over-all mean percent error of 2.3 percent for the movable cursor as opposed to 6.9 percent for the fixed reticle. It may also be noted that image size errors in the range of 1-2 percent were achieved for the image sizes from 3.5 through 11 cm. using the movable cursor. Since image size error and range error are closely related, range errors on the same order of magnitude would be expected using the movable cursor.

TABLE 4-2 ANALYSIS OF VARIANCE OF PERCENT ABSOLUTE IMAGE SIZE ESTIMATION ERROR

SOURCE	DF	SS	MS	F
MEAN	1	3.491709	3.491709	109.8552
RETICLE (R)	1	.8574548	.8574548	24.3104**
TRANS. MODE (X)	2	.1981745-02	.9908723-03	.3311
S/N RATIO (N)	2	.1022227	.5111137-01	5.2941*
CONTRAST (C)	1	.1651771-01	.1651771-01	5.6821
TARGET SIZE (T)	8	3.223887	.4029858	31.5217**
SUBJECTS (S)	4	.1271368	.3178421-01	
RX	2	.9028473-02	.4514236-02	2.0962
RN	2	.7586319-01	.3793159-01	6.4440*
XN	4	.1615150-01	.4037876-02	1.3683
RC	1	.4067245-01	.4067245-01	59.4199**
XC	2	.2120266-02	.1060133-02	.3707
NC	2	.1684006-01	.8420028-02	2.1186
RT	8	1.339360	.1674200	23.2276**
XT	16	.5141846-01	.3213653-02	.8637
NT	16	.7107956-01	.4442472-02	1.1875
CT	8	.7475311-01	.9344139-02	4.5264**
RS	4	.1410834	.3527084-01	
XS	8	.2393825-01	.2992282-02	
NS	8	.7723648-01	.9654560-02	
CS	4	.1162819-01	.2907047-02	
TS	32	.4091046	.1278452-01	
RXN	4	.3534326-02	.8835816-03	.3914
RXC	2	.3550810-03	.1775405-03	.1292
RNC	2	.9350815-02	.4675407-02	2.0793
XNC	4	.1836689-01	.4591722-02	2.1171
RXT	16	.8070022-01	.5043764-02	1.6579
RNT	16	.8367187-01	.5229492-02	1.5270
XNY	32	.1419989	.4437466-02	1.1047
RCT	8	.1807944	.2259930-01	11.0661**
XCT	16	.4521004-01	.2825627-02	1.0778
NCT	16	.1009105	.6306906-02	4.3969**
RXS	8	.1722820-01	.2153525-02	
RNS	8	.4709259-01	.5886574-02	
XNS	16	.4721847-01	.2951155-02	
RCS	4	.2737889-02	.6844723-03	
XCS	8	.2288063-01	.2860079-02	
NCS	8	.3179375-01	.3974218-02	
RTS	32	.2306525	.7207889-02	
XTS	64	.2381369	.3720889-02	
NTS	64	.2394186	.3740916-02	
CTS	32	.6605942-01	.2064357-02	
RXNC	4	.1225857-01	.3064642-02	.8390
RXNT	32	.9941131-01	.3106604-02	.9825
RXCT	16	.1130489	.7065554-02	2.3260**
RNCT	16	.1349036	.8431472-02	3.9083**
XNCT	32	.1038821	.3246317-02	.9930
RXNS	16	.3611389-01	.2257118-02	

TABLE 4-2 (Con't)

SOURCE	DF	SS	MS	F
RXCS	8	.1099113-01	.1373892-02	
RNCS	8	.1798828-01	.2248535-02	
XNCS	16	.3470055-01	.2168784-02	
RXTS	64	.1946951	.3042111-02	
RNTS	64	.2191855	.3424773-02	
XNTS	129	.5141626	.4016895-02	
RCTS	32	.6534988-01	.2042184-02	
XCTS	64	.1677786	.2621541-02	
NCTS	64	.9180099-01	.1434391-02	
RXNCT	32	.2267462	.7085819-02	2.2968**
RXNCS	16	.5844704-01	.3652940-02	
RXNTS	128	.4047406	.3162036-02	
RXCTS	64	.1944052	.3037581-02	
RNCTS	64	.1380698	.2157340-02	
XNCTS	128	.4184582	.3269205-02	
RXNCTS	128	.3948834	.3085027-02	

DF Degrees of Freedom

SS Sums of Squares

MS Mean Square

** $p < .01$

* $p < .05$

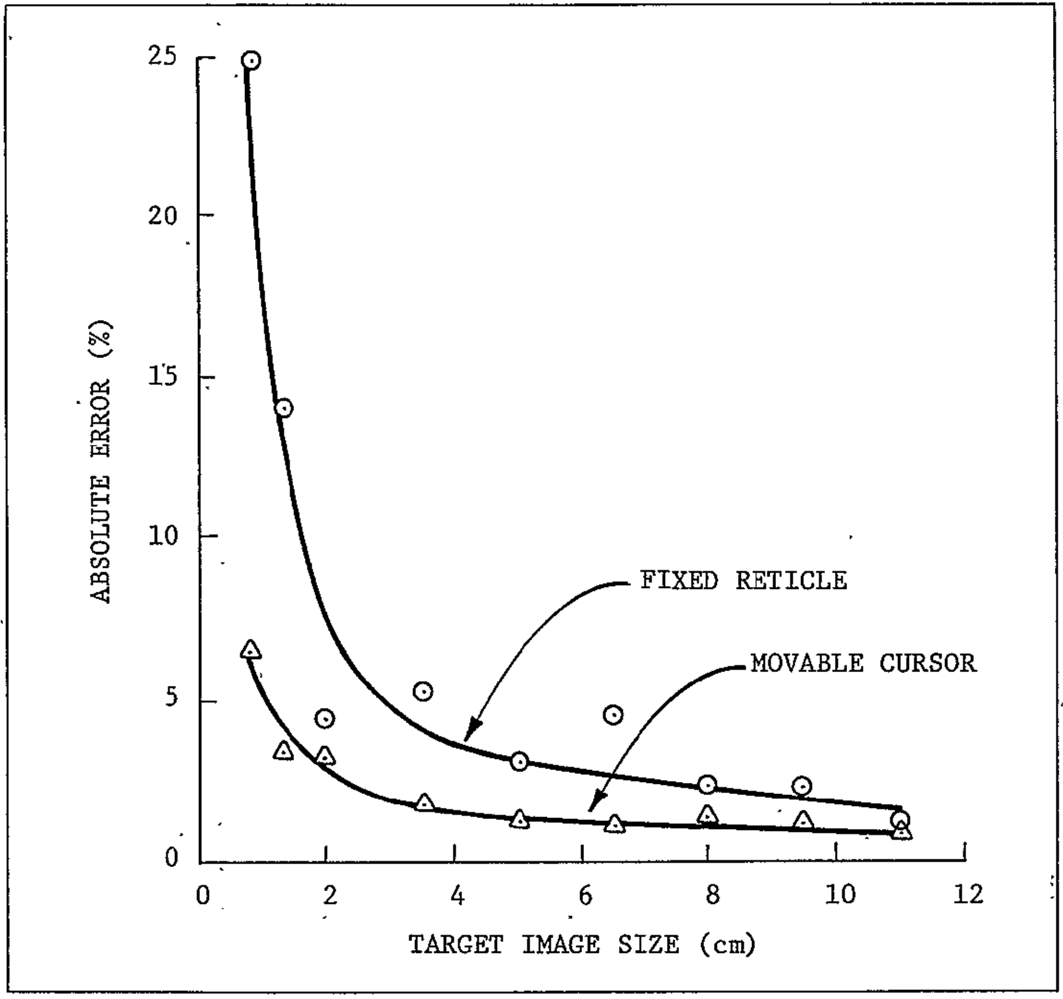

FIGURE 4-2. PERCENT ABSOLUTE ERROR AS A FUNCTION OF TARGET IMAGE AND SIZE

The joint effects of signal-to-noise ratio and reticle type are illustrated in Figure 4-3. The main effect of reticle type is evident in Figure 4-3. Furthermore, the movable cursor is less sensitive to variation in signal-to-noise ratio than is the fixed reticle. In fact, performance using the movable cursor appears to be quite insensitive to variation in signal-to-noise ratio as low as 15 db. This result is striking in comparison with previous results (Kirkpatrick, et.al., 1973,1974) where considerable performance decrements were noted when signal-to-noise ratio was reduced to 15 db.

The interaction of reticle type by contrast is illustrated in Figure 4-4. It appears that the movable cursor error rate is not strongly influenced by direction of contrast. The fixed reticle, however, shows a slight increase in percent error for negative as opposed to positive contrast.

The interaction of contrast and target size was found to be due to the results obtained for the smallest target size (1 cm.). At this level of target size, positive contrast resulted in smaller percent error than did negative contrast. At the other target sizes, no contrast effect was apparent.

The remaining significant interaction effects involved small percentage differences for the majority of target sizes. The high order interaction which are significant in Table 4-2 all involve target size and this was found to be due to interactive effects of reticle, contrast, signal-to-noise ratio, and transmission mode at the smallest level of target size. It appears that with the movable cursor, little effect of signal-to-noise ratio, transmission mode, or contrast appears. For the fixed reticle, however, signal-to-noise does influence performance. This effect being most notable for narrow band transmission and positive contrast.

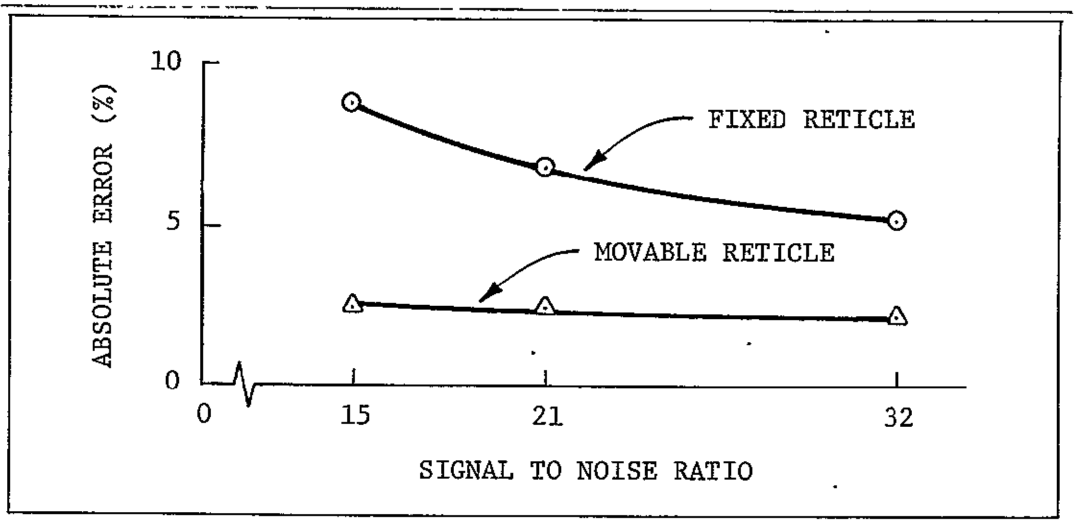

Figure 4-3. PERCENT ABSOLUTE ERROR AS A FUNCTION OF SIGNAL-TO-NOISE RATIO AND RETICLE TYPE

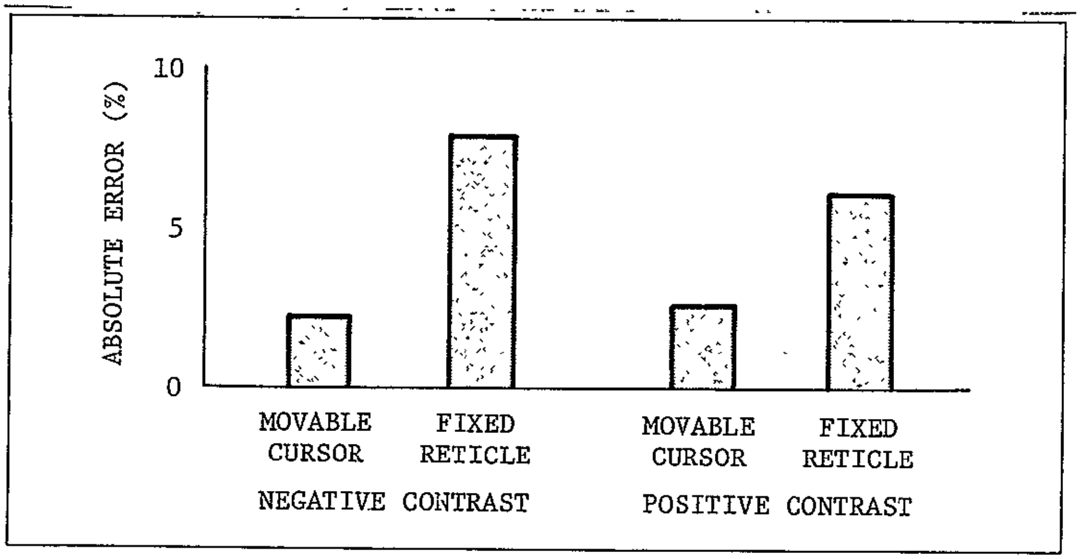

FIGURE 4-4. PERCENT ABSOLUTE ERROR AS A FUNCTION OF CURSOR TYPE AND CONTRAST

Percent Signed Error

The results of the analysis of variance of percent signed error appear in Table 4-3. The significant level for the difference between the grand mean and zero ($\alpha < .05$) shows a general tendency towards positive bias, the mean being +1.73 percent. The direction of bias, however, depends on the type of reticle used. Significant main effects were isolated for reticle type, contrast, and target size-all of which reached the .01 significance level. Reticle type was also found to interact with contrast ($\alpha < .05$) and with target size ($\alpha < .01$). The contrast by target size interaction was also significant ($\alpha < .01$).

The joint effects of reticle and target size are illustrated in Figure 4-5. The general trends are similar to those for the PSE data in that error increases for the smaller target sizes but the effect is much greater for the fixed reticle than for the movable cursor. For target sizes of 6.5 cm. (2.6 in.) and greater, the percent signed error values for the two reticle types are similar in magnitude but opposite in sign. The target size tends to be underestimated with the movable reticle and overestimated using the fixed reticle. The remaining significant interactions in Table 4-2 show similar effects to those of the PAE data. The effects of contrast, signal-to-noise ratio, and transmission mode being confined to the smallest target size employed and the fixed reticle condition.

TABLE 4-3 ANALYSIS OF VARIANCE OF PERCENT SIGNED ERROR

SOURCE		DF	SS	MS	F
MEAN		1	.4848035	.4848035	8.3853*
RETICLE	(R)	1	1.555120	1.555120	49.7207**
TRANS. MODE	(X)	2	.1536802-01	.7684011-02	1.2512
S/N RATIO	(N)	2	.1017535	.5087677-01	3.8625
CONTRAST	(C)	1	.2042624	.2042624	63.5703**
TARGET SIZE	(T)	8	2.068247	.2585309	17.4362**
SUBJECTS	(S)	4	.2312628	.5781570-01	
RX		2	.4219313-02	.2109656-02	.3777
RN		2	.4942718-01	.2471359-01	1.4139
XN		4	.1142315-01	.2855787-02	.7751
RC		1	.4560104-01	.4560104-01	8.7148*
XC		2	.9789982-02	.4894991-02	.6803
NC		2	.4941244-02	.2470622-02	.2175
RT		8	2.845957	.3557446	23.0932**
XT		16	.1258780	.7867374-02	.9309
NT		16	.1745230	.1090769-01	1.1216
CT		8	.3526166	.4407707-01	5.4014**
RS		4	.1251074	.3127685-01	
XS		8	.4913154-01	.6141443-02	
NS		8	.1053737	.1317171-01	
CS		4	.1285271-01	.3213177-02	
TS		32	.4744733	.1482729-01	
RXN		4	.7828750-02	.1957188-02	.3599
RXC		2	.2779205-01	.1389603-01	4.9504*
RNC		2	.1464704-01	.7323522-02	.5744
XNC		4	.1172642-01	.2931604-02	.7145
RXT		16	.7250625-01	.4531641-02	.5567
RNT		16	.9774811-01	.6109257-02	.7636
XNT		32	.3393109	.1060347-01	1.6373**
RCT		8	.1539236	.1924046-01	1.7895
XCT		16	.2596905	.1623066-01	2.6339**
NCT		16	.8359176-01	.5224485-02	.7489
RXS		8	.4468933-01	.5586166-02	
RNS		8	.1398321	.1747902-01	
XNS		16	.5894867-01	.3684292-02	
RCS		4	.2093037-01	.5232591-02	
XCS		8	.5756012-01	.7195015-02	
NCS		8	.9087784-01	.1135973-01	
RTS		32	.4929669	.1540522-01	
XTS		64	.5408960	.8451500-02	
NTS		64	.6224389	.9725609-02	
CTS		32	.2611401	.8160629-02	
RXNC		4	.1573952-01	.3934879-02	.5617
RXNT		32	.3712170	.1160053-01	1.3972
RXCT		16	.1268011	.7925071-02	1.2790
RNCT		16	.1206325	.7539530-02	.7459
XNCT		32	.2847150	.8897342-02	1.7268*
RXNS		16	.8700592-01	.5437870-02	

TABLE 4-3 (Con't)

SOURCE	DF	SS	MS	F
RXCS	8	.2245624-01	.2807031-02	
RNCS	8	.1019977	.1274971-01	
XNCS	16	.6564743-01	.4102964-02	
RXTS	64	.5209985	.8140602-02	
RNTS	64	.5120263	.8000412-02	
XNTS	128	.8289514	.6476183-02	
RCTS	32	.3440564	.1075176-01	
XCTS	64	.3943951	.6162424-02	
NCTS	64	.4465039	.6976623-02	
RXNCT	32	.2990735	.9346046-02	1.7389*
RXNCS	16	.1120876	.7005472-02	
RXNTS	128	1.062749	.8302726-02	
RXCTS	64	.3965619	.6196279-02	
RNCTS	64	.6469446	.1010851-01	
XNCTS	128	.6595178	.5152483-02	
RXNCTS	128	.6879602	.5374689-02	

** $p < .01$

* $p < .05$

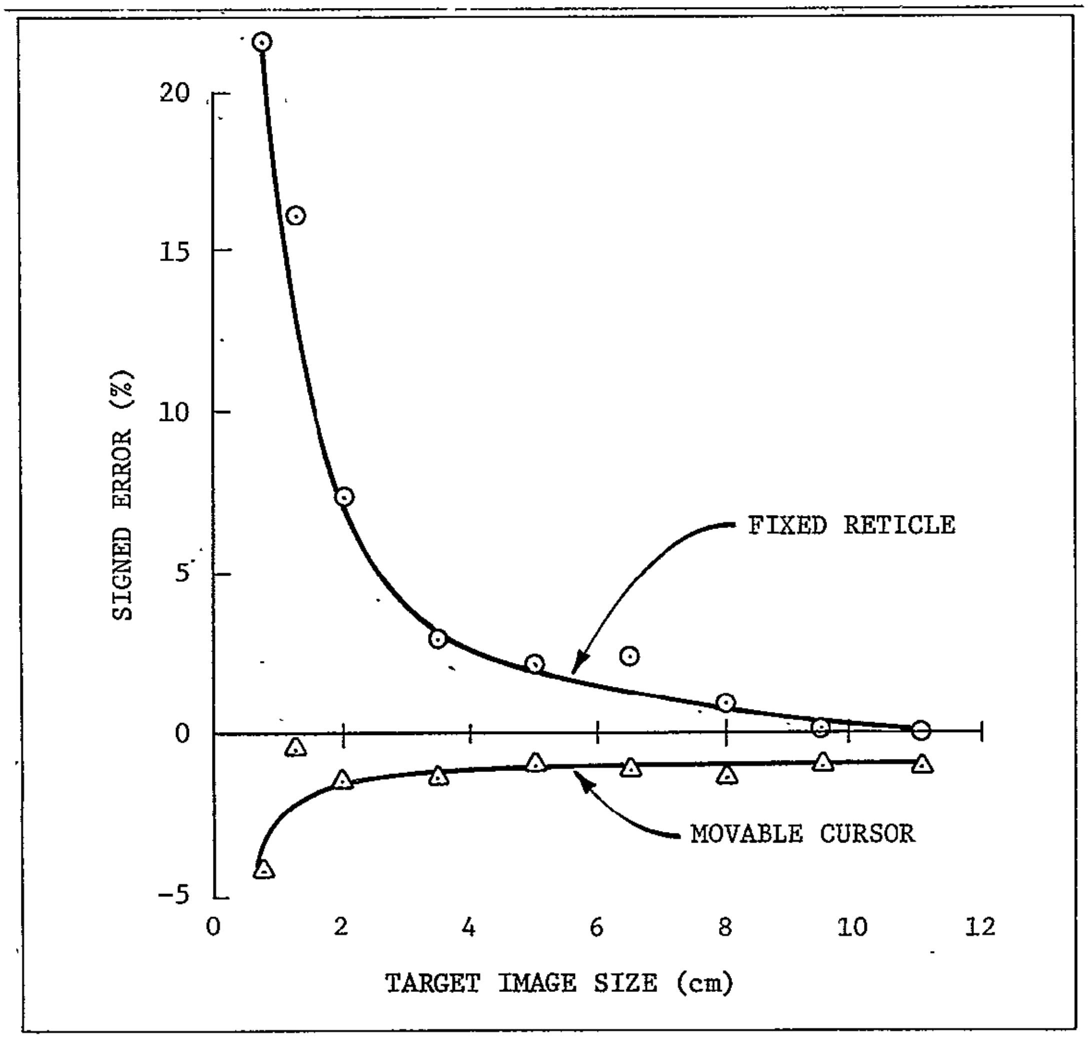

Figure 4-5. PERCENT SIGNED ERROR AS A FUNCTION OF TARGET SIZE AND RETICLE TYPE

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Response Time

In considering the fixed and movable reticles, it appeared that the control adjustment feature of the movable cursor might require a greater amount of time to complete the measurement than would the perceptual estimate required by the fixed reticle. Consequently, the response time data were subjected to a six-way analysis of variance having the same model and assumptions as the percent error analysis. The results showed most of the first and second order interactions to be significant at the .01 level. The main effects of reticle type, signal-to-noise ratio, and target size were also significant at the .01 level. While the independent variables thus significantly influenced response time in a complex fashion, the effects were generally found to be of little practical significance. Aside from the reticle type and target size main effects, the effect parameters obtained were on the order of a few tenths of a second. The grand mean for all trials was 4.84 seconds with a total standard deviation of 2.16. The primary difference in response time was that between reticle types. The mean times were 4.06 seconds for the fixed reticle and 5.62 seconds for the movable cursor. This represents a difference of 1.56 seconds and a percent increase in response time of 38 percent for the movable cursor relative to the fixed reticle. Since the corresponding percent decrease in absolute error ranged from 50 to 80 percent depending on target size for the movable cursor, the tradeoff appears to favor the movable cursor.

5.0 RANGE RESOLUTION - BASIC

5.1 Introduction

The objective of the first range resolution test was to determine the operator's capability to position a variable target at the same range as a fixed target utilizing monoptic television and a fresnel stereoptic system. The test was designed to provide a comparison of range resolution performance using the fresnel system with performance using monoptic systems and previously studied stereoptic systems. The test reported here differs from previous tests (Kirkpatrick, et.al., 1973,1974) in that the operator exercised active control over the variable target range rather than judging range separation in a static scene. The present task was considered to more adequately represent the servicing manipulator situation than would a passive judgment test.

The data from the present test are intended to provide empirical parameter values for the analytical expressions of section 2.0. These data and analysis results will thus serve to support design decisions concerning stereoptic system parameter selection. Based on the camera to target ranges employed and the nature of the task, the data are considered applicable to the servicing and manipulation phases of RMS operation. The data apply directly to these phases since they serve to quantify range errors during fine positioning in the x-axis.

5.2 Apparatus

The testing of range resolution capability was performed in the Visual System Evaluation Laboratory at MSFC. The general laboratory configuration is discussed in section 3.0. The laboratory components included:

- Operator station
- Experimenter station
- Target motion generator (TMG)
- Fresnel television system

Operator Station - The operator station contained the fresnel stereoptic display. The display was mounted in a console containing the two 23 cm. (9 in.) (diagonal) Conrac monitors and the associated optical train composed of mirrors and lenses as described in section 3. The fresnel display viewed by the subject was a 23 cm. (9 in.) unit. To the right of the display console was a control unit for the TMG. The control box contained a two position travel direction switch and a knob which controlled the rate applied by the direction switch. The commanded rate was indicated by a vernier dial. A separate momentary switch was included which was used by the operator to signal completion of the task.

Experiment Station - The experimenter station contained a pair of repeat monitors showing the individual rosters of the stereo camera pair. The video control equipment included a techtronix wave form monitor, signal processing and conditioning equipment and associated controls, and a digital timer. A TMG control box was included to permit the experimenter to initially position the variable target prior to the trial. The components of the experimenter station are described in section 3.0.

Target Motion Generator - The TMG is an apparatus which provides target motion in one translational and one attitude degree of freedom. The TMG is illustrated in Figure 5-1. The TMG contains a translation motor with gear drive and a rotation motor with belt drive. Only the translation degree of freedom was used for the present test. The TMG was positioned with the shaft translating longitudinally above a task table as shown in Figure 5-1. The shaft axis was aligned with the line bisecting the triangle formed by the lines of regard of the stereo pair.

The targets employed were two wooden cylinders with length and diameter of 8 cm. (3.1 in.). The variable target was mounted on the end of the TMG

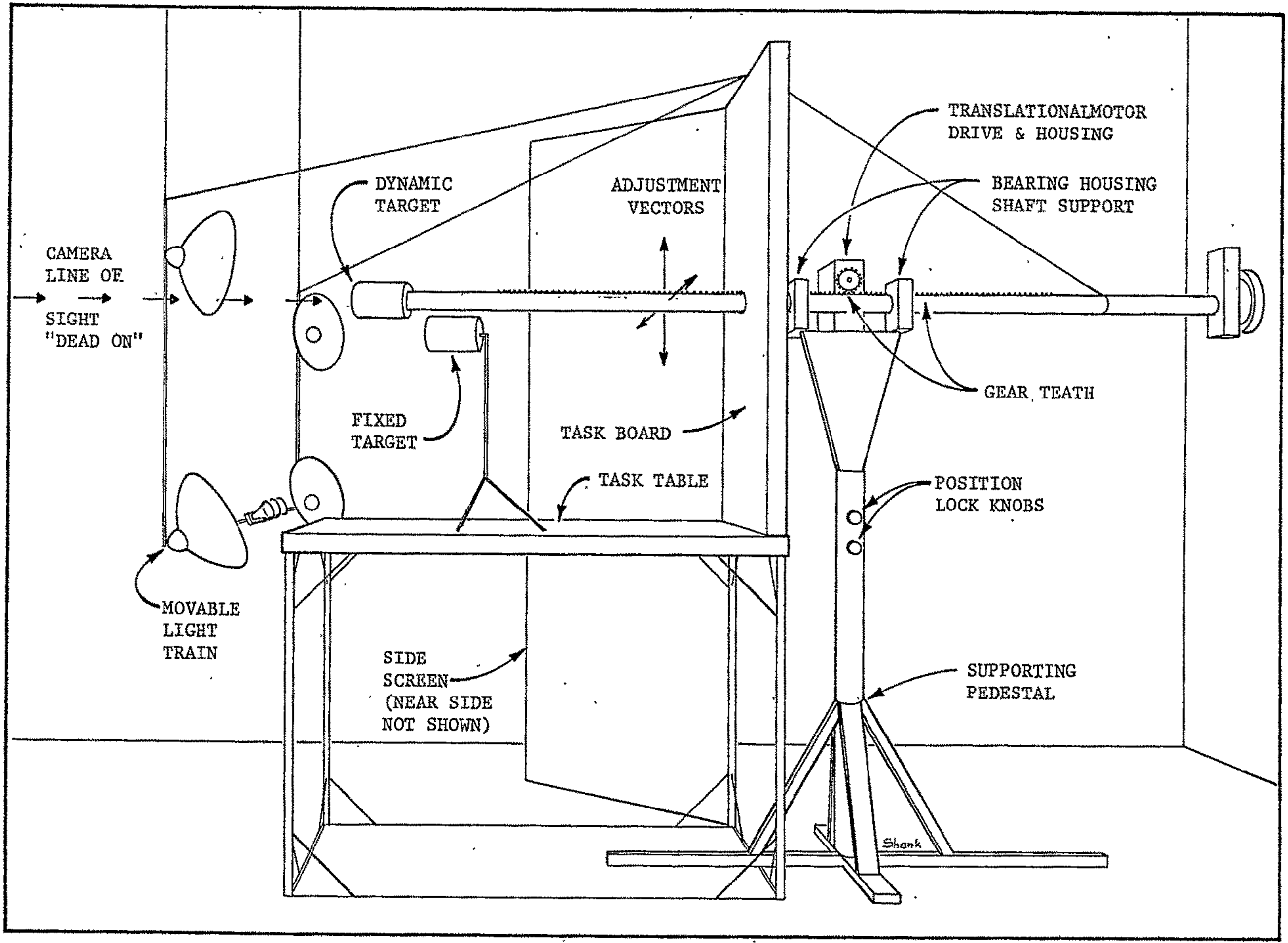

Figure 5-1. TMG APPARATUS

shaft with the circular face toward the cameras. The fixed target was mounted on a stand and could be positioned on the task table. The task table and rear panel was covered with black non-reflective felt so that the video image contained only the two targets against a black background.

Fresnel Television System - The video system consisted of a pair of COHU Mod 2000 cameras located 274 cm. (108 in.) from the center of the task table. The geometry of the targets, the TMG, and the cameras is shown in Figure 5-2. The camera lens centers were separated by a baseline of 15.24 cm. (6 in.). The convergence angle between camera lines of sight was .05556 radians. The zoom lenses were adjusted to provide a horizontal field-of-view of 35 degrees. The two camera video channels were processed through the experimenter station and then input to the video console at the operator station.

5.3 Experimental Design

The independent variables manipulated during the test were:

- Target/background contrast - target surface albedo of .5 or .7 on black background.
- Lateral fixed target placement - right or left of the variable target.
- Fore/aft placement of fixed target - 25 cm. (10 in.) in front of the camera convergence point, at the point of convergence, or 25 cm. (10 in.) behind the convergence point.
- Initial position of variable target - 20.3 cm. (8 in.) behind the convergence point, 5 cm. (2 in.) behind the convergence point, or 15.2 cm. (6 in.) ahead of the convergence point.
- Video system mode - stereoptic display versus monoptic display using the output from a single monitor.

The geometric relationships between the fixed target, the variable target, and the camera pair are shown in Figure 5-2.

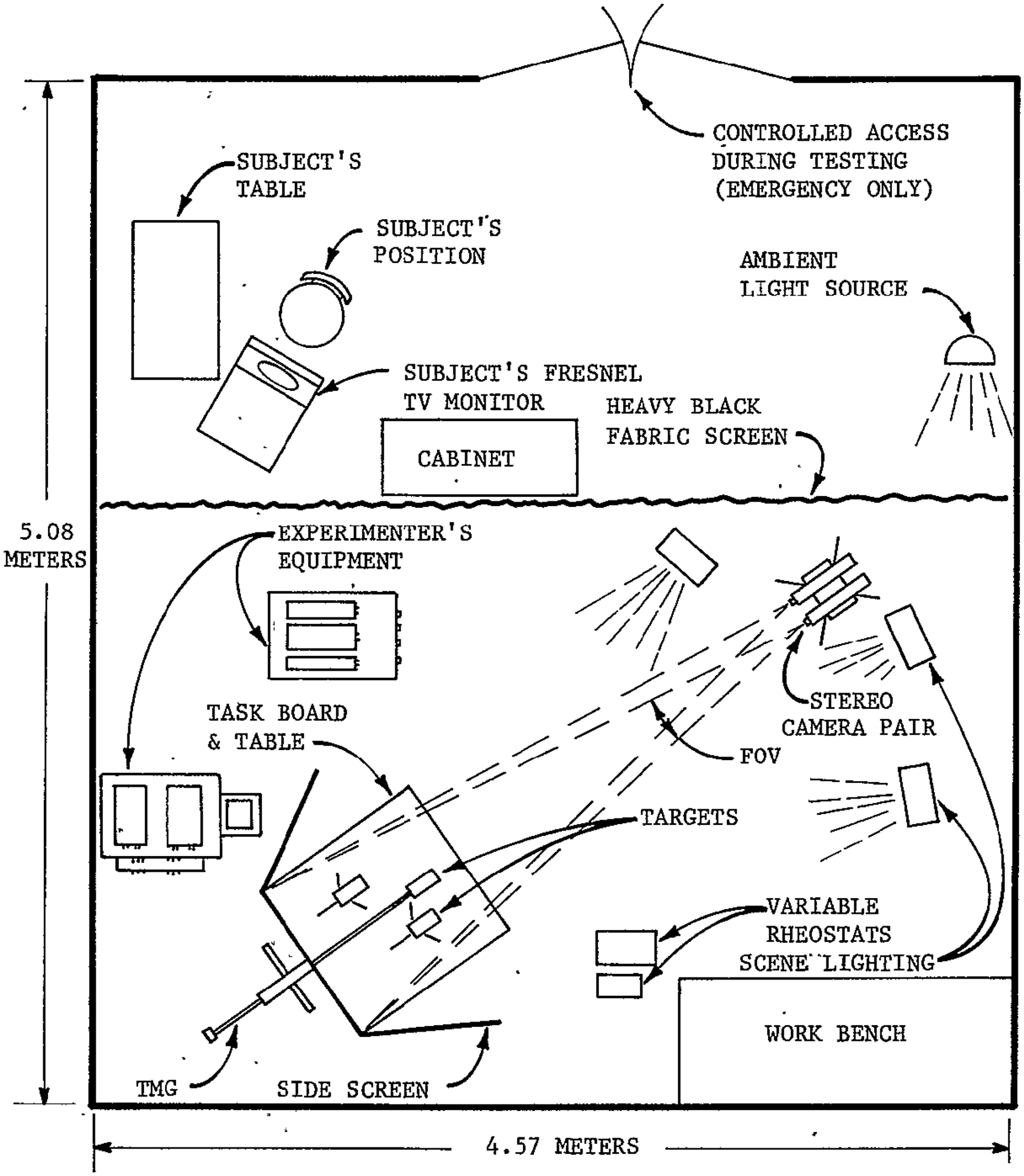

Figure 5-2. VISUAL SYSTEM LABORATORY LAYOUT FOR RANGE RESOLUTION EXPERIMENT 1

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Four subjects were used in the resolution test. These persons were screened for normal acuity and stereopsis using the Standard Orthorater Eye Examination. Each subject performed the range resolution task under each of the 72 possible combinations of levels of the independent variables. The display modes were run in blocks counterbalanced to control learning effects. The remaining variable levels were randomized within blocks.

5.4 Procedure

Prior to the data collection trials, the operator was read a set of standard instructions. These explained the nature of the stereoptic video system. The operator was instructed to move his head until stereopsis was obtained. These movements were lateral and verticle. The viewing distance was maintained at 71.1 cm. (28 in.). The TMG was adjusted to provide a range difference between the fixed and variable targets and the operator reported when he could perceive depth based on detecting this difference. The operator was then instructed to hold his head within the exit pupil tolerance during a series of trials. The TMG controls were also explained to the operator and he was instructed to attempt to null out any perceived range difference and to press a response key when he had completed the adjustment (i.e. when he judged the fixed and variable targets to be aligned).

A single trial commenced with the operator's display disabled. The experimenter placed the fixed target at one of the six pre-established positions shown in Figure 5-3. He then operated the TMG to place the variable target at one of the three initial positions shown in Figure 5-3. The operator was then warned that a trial was about to begin. The experimenter pressed a switch to initiate a trial. This action activated

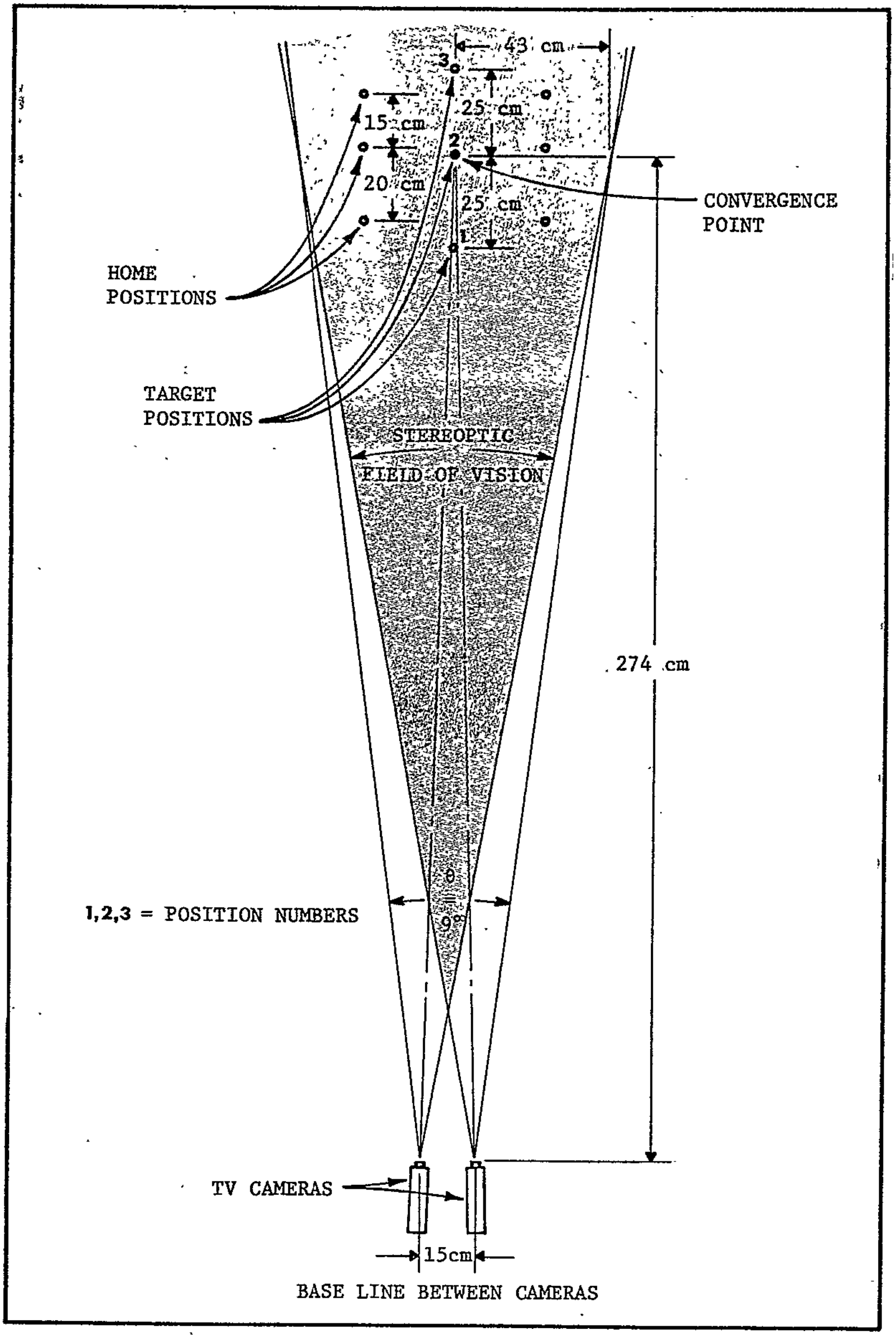

Figure 5-3. FRESNEL STEREOPTIC CAMERA ARRANGEMENT UTILIZED IN TARGET ALIGNMENT TASKS

both the operator's display and the digital timer. The operator then maneuvered the variable target via the TMG control box. When he judged the variable and fixed targets to be aligned, he pressed the response key which stopped the timer and terminated the display. The experimenter then recorded the response time and the adjustment error or remaining range difference between the fixed and variable targets. This completed the wingle trial sequence and a new trial was begun.

5.5 Results

The variable target adjustment error was measured by the distance between the fixed and variable targets when the subject had completed the adjustment and judged the targets to be at the same range. The adjustment error data were subjected to two analyses of variance - one with the sign of the error retained yielding average error and the second without the sign yielding average absolute error. The mean error statistic measures constant error or bias. Mean error should equal zero if there is no consistent under-or-over-shoot. Mean absolute error is a dispersion measure since it quantifies average distance from the fixed target regardless of sign. Absolute error is sensitive to both constant and variable error. The analysis of variance model employed was appropriate for a treatments by subjects design with six independent variables. All factors were assumed to be fixed except subjects.

Mean Error

The analysis of variance of mean error is shown in Table 5-1. The grand mean for both stereoptic and monoptic systems was found to be 1.742 cm. (.686 in.). This value is significantly different from zero ($\alpha < .05$) so that a constant tendency to place the variable target closer than the fixed target or to undershoot the correct range was present.

Difference in the bias due to variation in the independent variables were restricted to the main effect of fixed target range ($\alpha < .05$) and the interaction of video system type with the side of the fixed target on which the variable target was located ($\alpha < .01$). The effect of fixed target range is shown in Figure 5-4. The mean error bias appears to be negative for the

TABLE 5-1. ANALYSIS OF VARIANCE OF SIGNAL ERROR

SOURCE	DF	SS	MS	F
MEAN	1	135.5162	135.5162	14.9073
SYSTEM	1	.6441064	.6441064	.2884
S/N RATIO	1	73.48468	73.484668	5.2676
DISTANCE	2	367.5637	183.7819	6.7985
CONTRAST	1	5.216328	5.216328	.2020
INITIAL POS.	2	134.3366	67.16828	2.6832
SUBJECTS	3	27.27254	9.090859	
MS	1	95.19562	95.19562	67.7141
MD	2	242.6569	121.3284	4.0896
SD	2	25.44246	12.72123	.4803
MC	1	1.516667	1.516667	.0724
SC	1	24.01180	24.01180	.9389
DC	2	123.6409	61.82047	3.5869
MH	2	80.04328	40.02164	1.3749
SH	2	114.3167	57.15836	2.2967
DH	4	203.2741	50.81851	1.5318
CH	2	48.88492	24.44246	1.5781
MP	3	6.700703	2.233530	
SP	3	41.85172	13.95072	
DP	6	162.1959	27.03328	
CP	3	77.48468	25.82820	
HP	6	150.1959	25.03230	
MSD	2	39.06656	19.53328	.6254
MSC	1	19.29207	19.29207	.5957
MDC	2	101.0472	50.52359	2.3779
SDC	2	116.3402	58.17008	2.3944
MSH	2	125.5589	62.77945	2.5216
MDH	4	214.2897	53.57242	1.8244
SOH	4	128.6647	32.16617	1.3924
MCH	2	50.59781	25.29891	1.8995
SCH	2	35.03140	17.51570	.6077
DCH	4	157.8053	39.45133	1.4656
MSP	3	4.217549	1.405828	
MDP	6	178.0084	29.66805	
SDP	6	158.9069	26.48445	
MCP	3	62.85953	20.95320	
SCP	3	76.72297	25.57527	
DCP	6	103.4105	17.23445	
MHP	6	174.6569	29.10945	
SHP	6	149.3209	24.88680	
DHP	12	398.0950	33.17398	
CHP	6	92.93000	15.48881	
MSDC	2	114.1761	57.08805	2.7949
MSDH	4	126.5511	31.63777	1.1850
MSCH	2	58.20719	29.10359	1.1513

TABLE 5-1, Continued:

SOURCE	DF	SS	MS	F
MDCH	4	138.6100	34.65250	1.1528
SDCH	4	166.6959	41.67398	1.3892
MSDP	6	187.3912	31.2350	
MSCP	3	97.16437	32.38687	
MDCP	6	127.4847	21.24715	
SDCP	6	145.7662	24.29500	
MSHP	6	149.3756	24.89656	
MDHP	12	352.3606	29.36434	
SDHP	12	277.2044	23.10066	
MCHP	6	79.90656	13.31791	
SCHP	6	172.9381	28.82234	
DCHP	12	323.0325	26.91902	
MSDCH	4	164.7975	41.19937	1.2074
MSDCP	6	122.5550	20.42586	
MSDHP	12	320.3762	26.69832	
MSCHP	6	151.6725	25.27840	
MDCHP	12	360.7044	30.05867	
SDCHP	12	359.9700	29.99812	
MSDCHP	12	409.4544	34.12125	

** $p < .01$

* $p < .05$

249 cm. (98 in.) range and positive for the other two ranges. This relationship is consistent with a tendency to overshoot the shorter ranges and undershoot the longer ones. This tendency is frequently found in manual control tasks and consists of a bias where the operator errors toward the mean of the correct positions of the controlled element. It sould also be pointed out, however, that the 249 cm. (98 in.) range was short of the stereo camera convergence point, the 267 cm.(108 in.) range coincided with the convergence point, and the 300 cm. (118 in.) range was beyond the convergence point. The departure of the short range bias from the nearly constant bias of the two longer ranges may be related to the fact that subjects report images of objects short of the convergence point to be visually disturbing. Performance in this case may differ qualitatively from that for objects beyond convergence. In fact, the purpose of using a long covergence distance in the fresnel system studied here was to permit evaluation of this problem.

The interaction of camera system type and the side of the fixed target on which the variable target was located is illustrated in Figure 5-5. The stereoptic system appears to produce a small positive bias which is independent of fixed target side. The monoptic system, however, shows a bias reversal depending on fixed target side. The data show that the right-hand target tended to be at lesser range than the left-hand target at the judged point of equality. It seems likely that this effect is due to apparent size and brightness. It appears that subjects may have utilized brightness as a cue and responded to small right-left brightness differences which could not be completely eliminated in the laboratory due to the necessity to vary range. This may suggest a problem of false depth cues if artificial lighting and monoptic television are used for servicing operations.

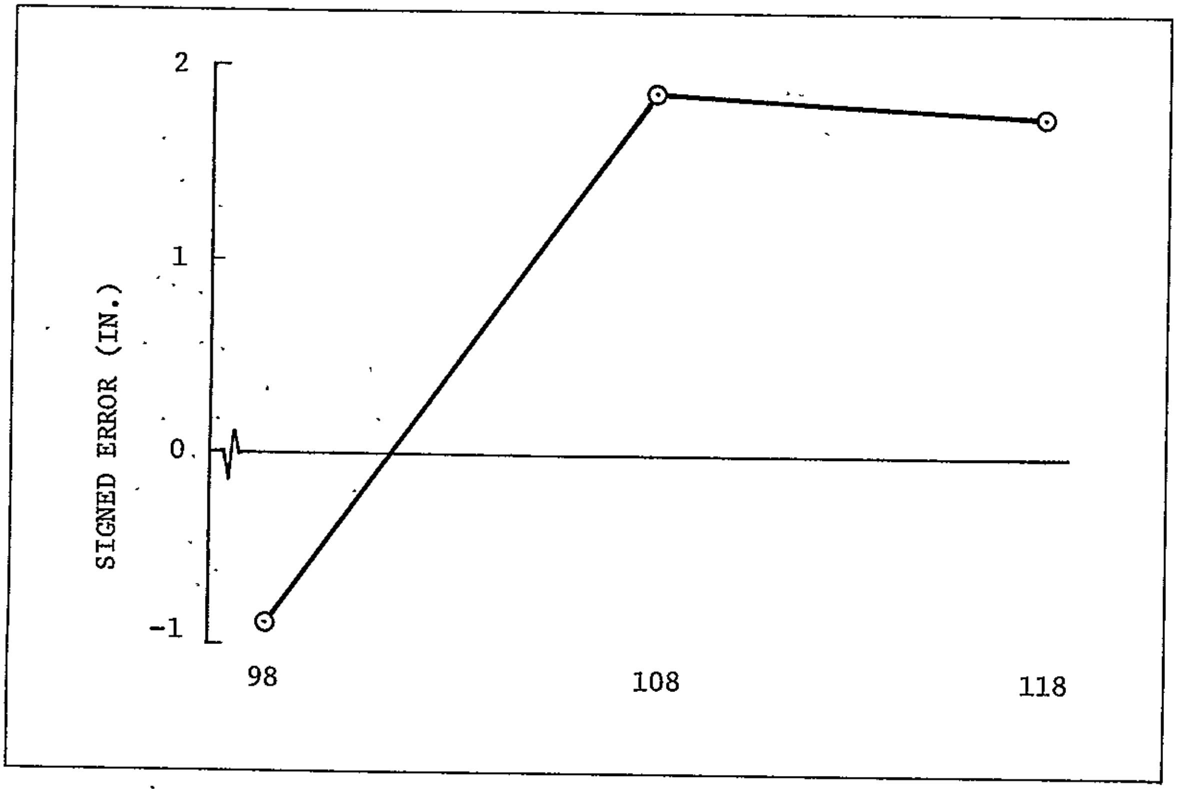

FIGURE 5-4. MEAN SIGNED ERROR AS A FUNCTION OF TARGET RANGE

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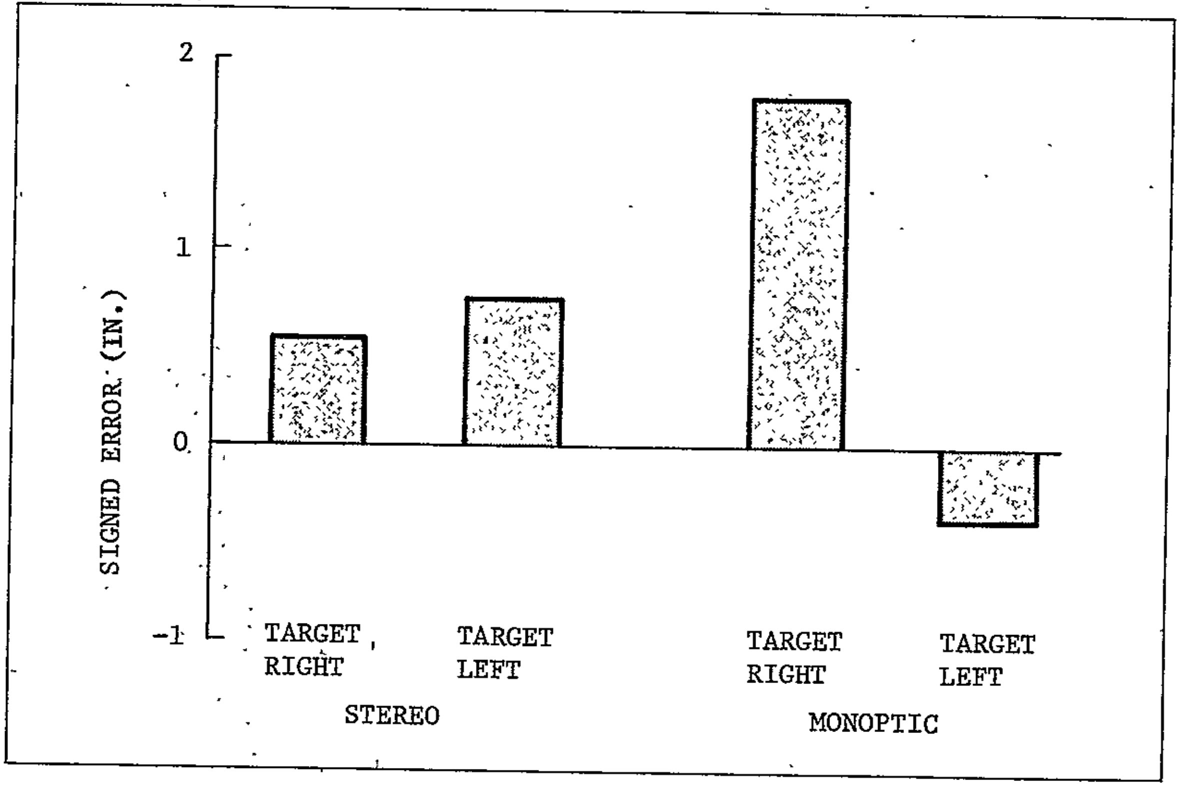

FIGURE 5-5. MEAN SIGNED ERROR AS A FUNCTION TARGET POSITION AND VISUAL

Mean Absolute Error

The analysis of variance of mean absolute error did not reveal any significant differences. The sensitivity of this analysis appears to be insufficient. The loss of one subject during the test reduced the number of subjects to four. The lack of significant effects may be partially attributed to the small values of degrees of freedom upon which the critical F-ratios are determined. The main effect of camera type was found to be such that the mean absolute error value for the monoptic system was more than three times that for the stereoptic system. The data were considered to justify separate parameter estimation for the three fixed target ranges and two video systems. (Table 5-2.)

To generalize the results of the stereoptic portion of the data, the relationship between range resolution and the retinal disparity threshold $\Theta t'$ was employed. Eq. 5-1 may be arranged to yield:

$$\Theta t = \frac{\Delta R \; BK}{R^2 L} \qquad (2\text{-}23)$$

To solve eq. 2-23, empirical range resolution values were required. To provide these data, the cumulative distribution of adjustment error were obtained. These functions are shown in Figure 5-6 for the three range levels. The required threshold was considered to be the 90th percentile points on these functions. The corresponding range increment values are thus detectable in 90 percent of cases. Substituting these increments estimated from Figure 5-6 in eq. 2-23 together with the appropriate system parameters yielded retinal disparity values as shown in Table 5-3.

TABLE 5-2 ANALYSIS OF VARIANCE OF PERCENT ABSOLUTE IMAGE SIZE ESTIMATION ERROR

SOURCE		DF	SS	MS	F
MEAN		1	3.491709	3.491709	109.8552
RETICLE	(R)	1	.8574548	.8574548	24.3104
TRANS. MODE	(X)	2	.1981745-02	.9908723-03	.3311
S/N RATIO	(N)	2	.1022227	.5111137-01	5.2941
CONTRAST	(C)	1	.1651771-01	.1651771-01	5.6821
TARGET SIZE	(T)	8	3.223887	.4029858	31.5217
SUBJECTS	(S)	4	.1261368	.3178421-01	
RX		2	.9028473-02	.4514236-02	2.0962
RN		2	.7586319-01	.3793159-01	6.4440
XN		4	.1615150-01	.4037876-02	1.3683
RC		1	.4067245-01	.4067245-01	59.4199
XC		2	.2120266-02	.1060133-02	.3707
NC		2	.1684006-01	.8420028-02	2.1186
RT		8	1.339360	.1674200	23.2276
XT		16	.5141846-01	.3213653-02	.8637
NT		16	.7107956-01	.4442472-02	1.1875
CT		8	.7475311-01	.9344139-02	4.5264
RS		4	.1410834	.3527084-01	
XS		8	.2393825-01	.2992282-02	
NS		8	.7723648-01	.9654560-02	
CS		4	.1162819-01	.2907047-02	
TS		32	.4091046	.1278452-01	
RXN		4	.3534326-02	.8835816-03	.3914
RXC		2	.3550810-03	.1775405-03	.1292
RNC		2	.9350815-02	.4675407-02	2.0793
XNC		4	.1836689-01	.4591722-02	2.1171
RXT		16	.8070022-01	.5043764-02	1.6579
RNT		16	.8367187-01	.5229492-02	1.5270
XNT		32	.1419989	.4437366-02	1.1047
RCT		8	.1807944	.2259930-01	11.0661
XCT		16	.4521004-01	.2825627-02	1.0778
NCT		16	.1009105	.6306906-02	4.3969
RXS		8	.1722820-01	.2153525-02	
RNS		8	.4709259-01	.5886574-02	
XNS		16	.4721847-01	.2951155-02	
RCS		4	.2737889-02	.6844723-03	
XCS		8	.2288063-01	.2860079-02	
NCS		8	.3179375-01	.3974218-02	
RTS		32	.2306525	.7207889-02	
XTS		64	.2381369	.3720889-02	
NTS		64	.2394186	.3740916-02	
CTS		32	.6605942-01	.2064357-02	
RXNC		4	.1225857-01	.3064642-02	.8390
RXNT		32	.9941131-01	.3106604-02	.9825
RXCT		16	.1130489	.7065554-02	2.3260
RNCT		16	.1349036	.8431472-02	3.9083
XNCT		32	.1038821	.3246317-02	.9930
RXNS		16	.3611389-01	.2257118-02	

TABLE 5-2 (Con't)

SOURCE	DF	SS	MS	F
RXCS	8	.1099113-01	.1373892-02	
RNCS	8	.1798828-01	.2248535-02	
XNCS	16	.3470055-01	.2168784-02	
RXTS	64	.1946951	.3042111-02	
RNTS	64	.2191855	.3424773-02	
XNTS	128	.5141626	.4016895-02	
RCTS	32	.6534988-01	.2042184-02	
XCTS	64	.1677786	.2621541-02	
NCTS	64	.9180099-01	.1434391-02	
RXNCT	32	.2267462	.7085819-02	2.2968
RXNCS	16	.5844704-01	.3652940-02	
RXNTS	128	.4047406	.3162036-02	
RXCTS	64	.1944052	.3037581-02	
RNCTS	64	.1380698	.2157340-02	
XNCTS	128	.4184582	.3269205-02	
RXNCTS	128	.3948834	.3085027-02	

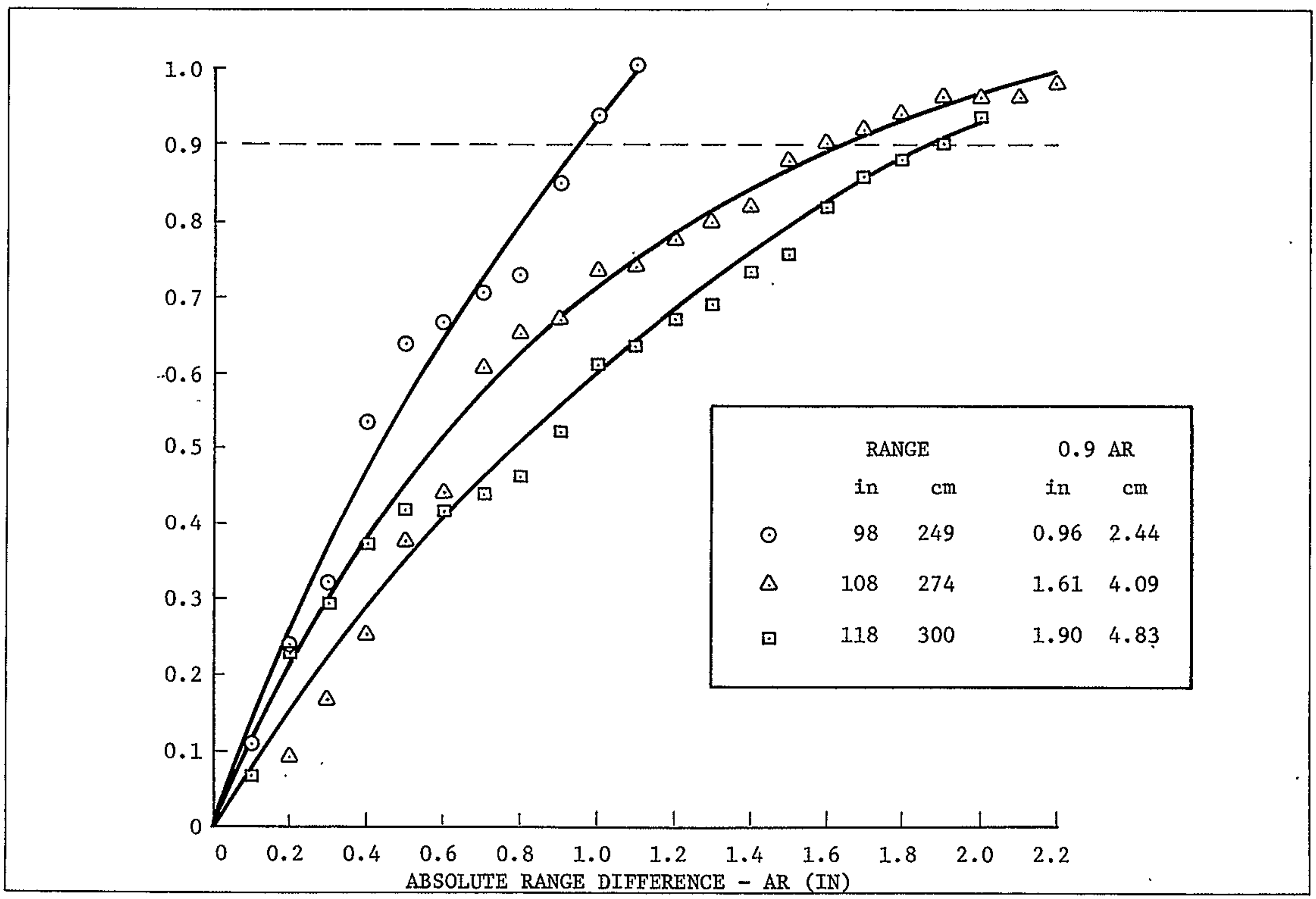

FIGURE 5-6. CUMULATIVE DISTRIBUTION OF ADJUSTMENT ERROR AS A FUNCTION OF AR

Table 5-3 Estimated Retinal Disparity Angles for .90 Probability of Range Increment Detection

Range		Retinal Disparity		
cm.	in.	rad.	min.	sec.
249	98	.00061	2.10	126.0
274	108	.00084	2.89	173.4
300	118	.00082	2.82	169.2

The estimated disparity angle obtained for the two longer ranges are in agreement. The angle for the smaller range, however, is reduced. This result does not suggest any decrement in range resolution for objects short of the convergence point. In fact, the 249 cm. (98 in.) range yields somewhat greater acuity than do the longer ranges. In view of the small deviations in estimated retinal disparity angle, it was considered valid to use the average of the three estimates as the empirical disparity threshold under the video system conditions utilized. This yielded a disparity value of approximately 156 arc seconds for detection at the 90 percent level. This result may be substituted in eq. 2-23 yielding a general range resolution function:

$$\frac{\Delta R}{R} = \frac{\Theta T}{a} \frac{R}{E_\theta}$$

or substituting .00076 radians for Θt and 6.35 cm. (2.5 in.) for a:

$$\frac{\Delta R}{R} = \frac{.000041\ R}{E_\theta}$$

where:

ΔR = range increment for .90 detection probability (cm.)
R = range (cm.)
E_θ = disparity exaggeration ratio

This result may be compared with the theoretical range resolution curves proposed by Tewell, et.al. (1973). Using Tewell's equations (12) and (14) may be used to obtain:

$$\frac{\Delta R}{R} = \frac{2 \cdot R \cdot \varphi}{B} \qquad (5\text{-}1)$$

where $\varphi = \frac{\text{angular field of view (radians)}}{\text{horizontal resolution}}$

Substituting the present paramater values in eq. 5-1:

$$\frac{\Delta R}{R} = .000036\ R$$

The obtained expression based on the empirical data is obtained from eq. 2-23 with the current exaggeration ratio of 2.424:

$$\frac{\Delta R}{R} \doteq .000036\ R \qquad (5\text{-}2)$$

The obtained minimum range resolution is about one half that for the theoretical expression. This discrepancy may be due to the fact that the theoretical expressions of eqs. 2-23 and 5-2 are based on geometric relationships between dimensionless points whereas the targets employed are extended objects and have lateral separation. A theoretical treatment of the actual case appears warranted since range resolution capability exceeds the theoretical maximum as currently formulated.

<u>Response Time</u>

The analysis of variance of response time did not yield significant effects of camera system. The only significant effects noted were due to the TMG travel distance relationships which depended on fixed target position and TMG initial position.

6.0 RANGE RESOLUTION - EFFECTS OF VIDEO PARAMETER

6.1 Introduction

Based upon the findings in the previously reported study dealing with target alignment, it was decided to compound the basic task with system variables in order to determine the effects of camera/target geometry and varied video system parameters on the operator's ability to align a moveable target with a fixed target.

6.2 Apparatus

The task board, targets, and the target motion generator utilized in Section 5 were also employed in this experiment. The 1.22 m.by 1.22 m. task board shown in Figure 6-1 was covered with black, non reflective, felt and was inscribed with position markings for target placement, as in Section 5. The stationary targets were 8 cm. cylinders painted to an albedo of .5 and .7, the target mounted on the TMG was .5. The TMG target and stationary target remained in the same positions with respect to one another, but the camera/target geometry was changed. Where, in Section 5 the camera was in plane and normal to the translation axis of the time target, the camera position for this test was in plane, but 45 degrees to the left of the TMG translation plane (Fig. 6-2). Figure 6-3 shows additional information with regard to the placement of the targets with respect to the camera line-of-sight.

The video system utilized in this experiment consisted of the same sensors, transmitters, and displays as in Section 5, but in addition to those pieces of equipment, a GRC random noise generator was introduced to provide RF noise with the video signal. A Computer Labs Analog/Digital and a Digital/Analog converter were used to provide a 4 bit digital transmission format,

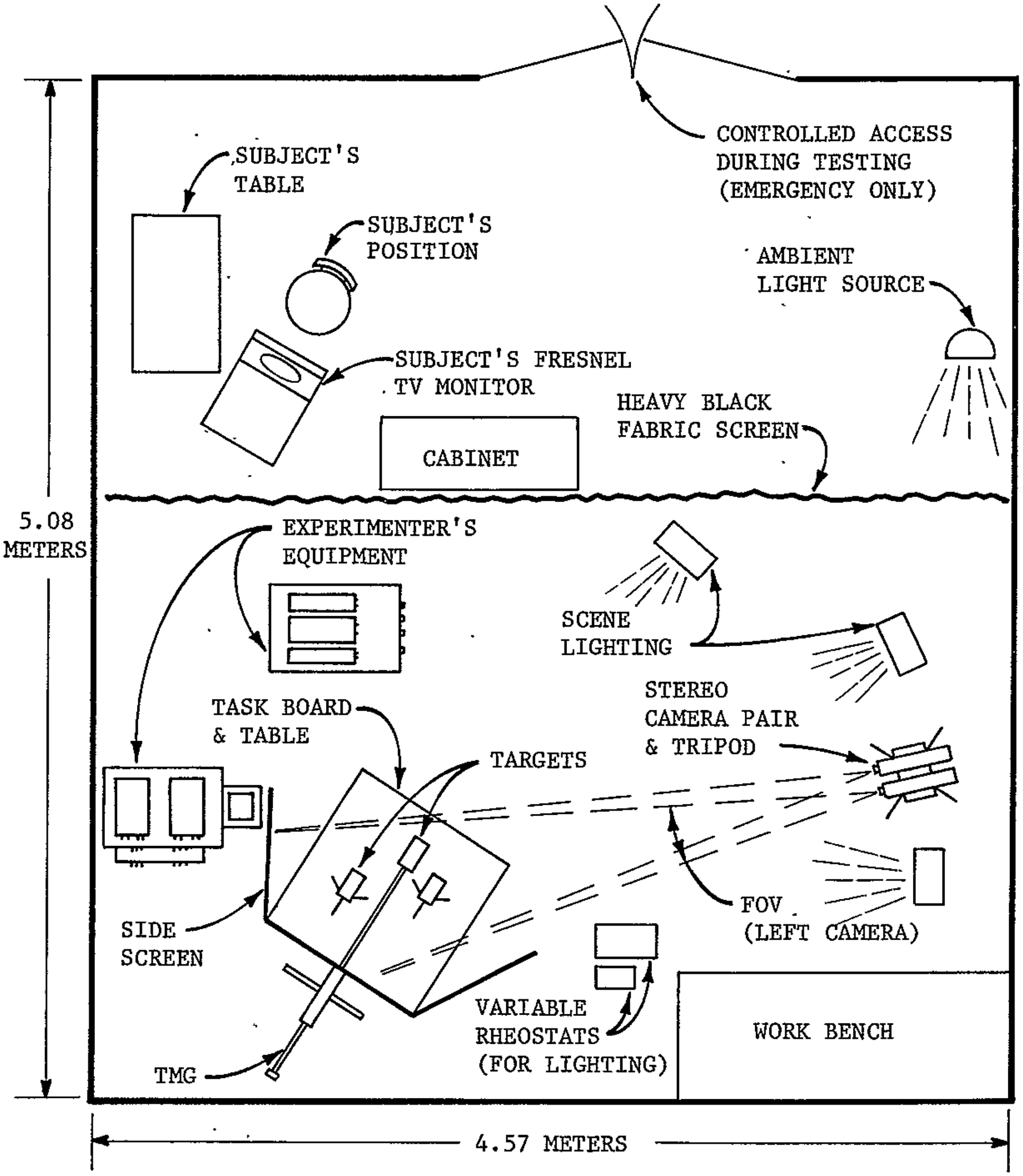

Figure 6-1. VISUAL SYSTEM LABORATORY LAYOUT FOR RANGE RESOLUTION EXPERIMENT 2

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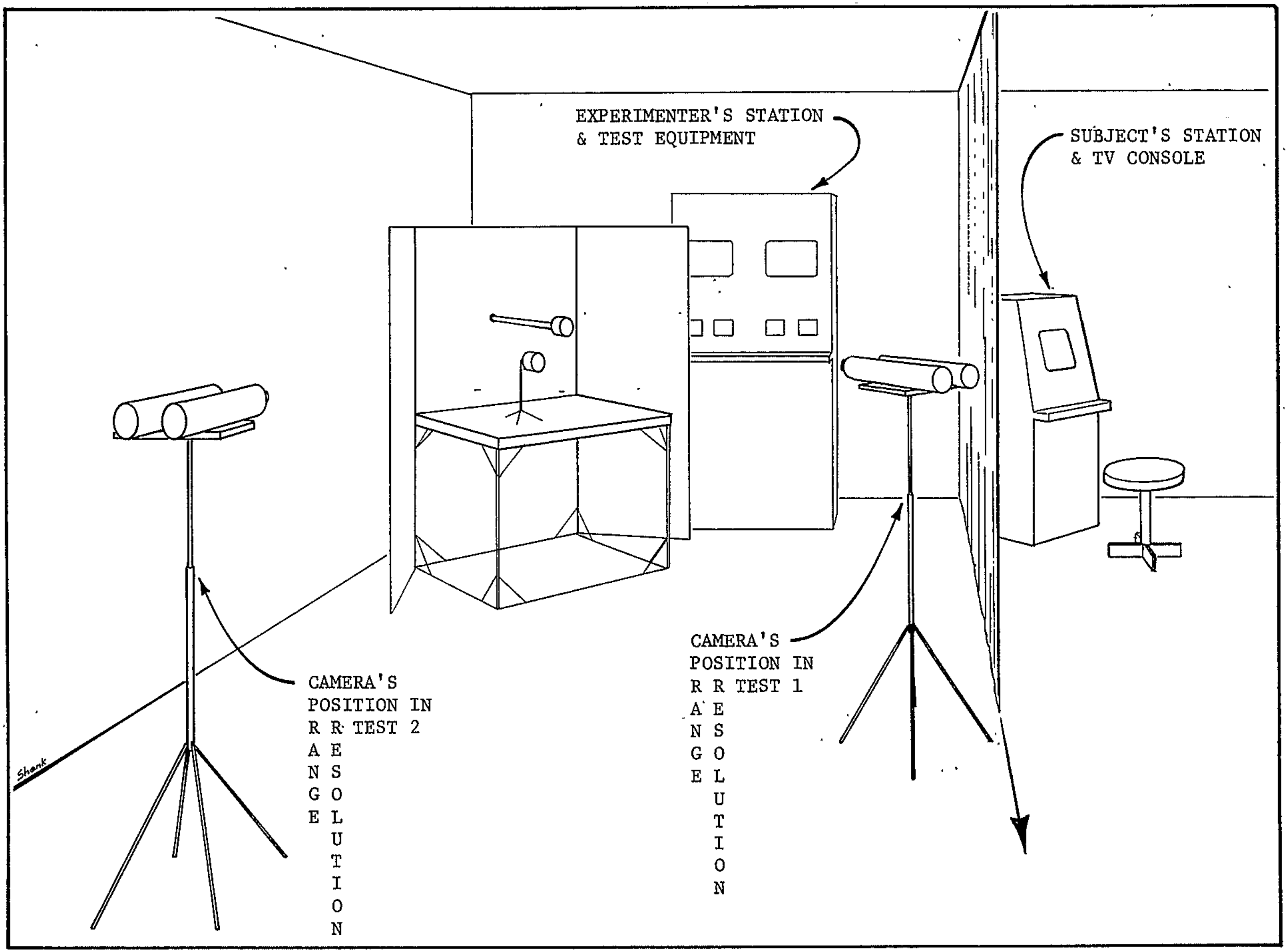

Figure 6-2. LATERAL VIEW OF CAMERA POSITIONS

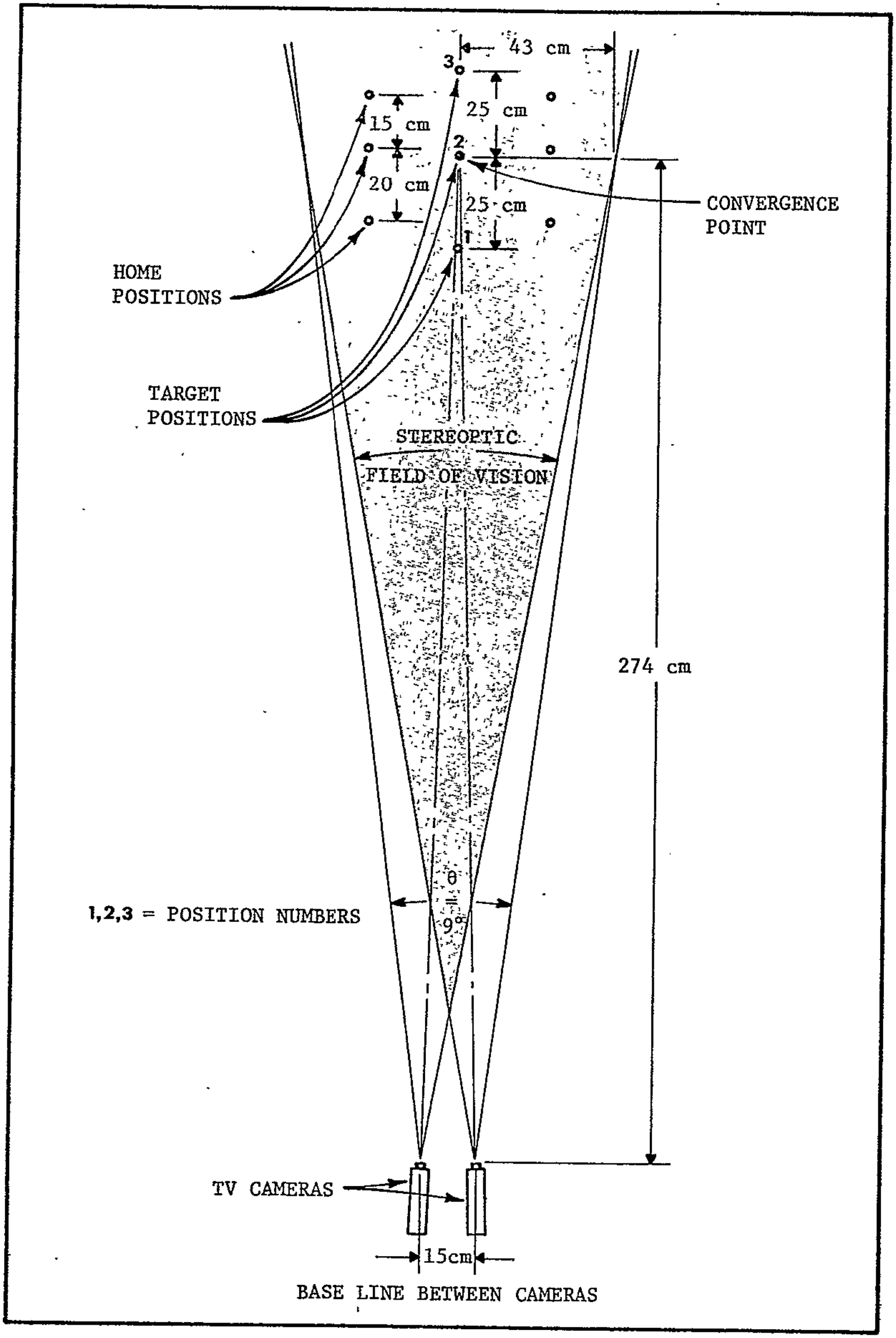

FIGURE 6-3. TARGET ARRANGEMENT UTILIZED IN TARGET ALIGNMENT TASKS

and a narrow band pass filter was installed to allow the transmission to be limited to 1 MHz. The RF noise was introduced into both the left and right channels of the fresnel TV system. While the 4 bit digital and 1 MHz narrow band transmission were each introduced only into the left channel of the system. The 4.5 MHz Analog 32 db signal was a baseline format, and was the same format used in Section 5.0.

6.3 Experimental Design

The independent variables which were manipulated for this experiment were:

1. Two (2) target/background and target/target contrast conditions
    a) .5 target compared to a .7 target, both against a black field
    b) .5 target compared to a .5 target, both against a black field
2. Three (3) initial positions of the movable (TMG) target
    a) 20.3 cm (8 in) behind the converence point
    b) 5 cm (2 in) behind the convergence point
    c) 15.2 cm (6 in) ahead of the convergence point
3. Three initial positions of the fixed target
    a) 25 cm (10 in) in front of the camera convergence point
    b) at the point of convergence
    c) 25 cm (10 in) behind the convergence point
4. Three signal-to-noise levels
    a) 15 db
    b) 21 db
    c) 32 db
5. Two levels of video transmission
    a) 4.5 MHz Analog
    b) 1.0 MHz Analog

It will be noted that, as viewed from the camera, the case where the fixed target was positioned to the right of the TMG movable target has been eliminated from this experiment because of interposition problems. Also, retaining the same target separations in this experiment as in Section 5 means that the camera base to target distance will have to be different as a function of the changes in camera target geometry.

The dependent measure recorded in this experiment was the relative error in positioning the TMG target with respect to the fixed target. This accuracy was measured with respect to the target faces. The variables held constant during this experiment were:

a. Scene lighting conditions

b. Subject's visual acquity

c. Ambient light and noise at the subject's station.

6.4 Procedure

The test and video system equipment were turned on and allowed to stabilize. When all equipment had warmed up, it was then calibrated prior to each test run.

Each of four male subjects was individually scheduled for testing in the laboratory. Each subject was seated at a display console containing the Fresnel Screen and was read the Standard Instructions (see Appendix 6-0). The subjects sat approximately 25 inches from the display face, and viewed it 15 degrees below the horizontal plane. When the subject understood the task instructions, the experimenter left and went to the test area.

The experimenter set the TMG at one of three start positions to the right of the fixed target, with respect to the off set camera axis. The lateral separation of the TMG and the fixed target was five inches.

When the scene was set, E initiated the video signal to S, who then translated the TMG targetfore or aft to a position he perceived to be target alignment. When alignment was perceived, S depressed a response key and terminated his video image. E recorded any error in target alignment and then set up the next trial according to a prepared test sequence.

6.5. Results

The dependent measures employed in the second range resolution test were mean error, mean absolute error, and response time. Each measure was subjected to six-way analysis of variance using the model for repeated measures and all factors other than subjects fixed.

Mean Error

The results of the analysis of variance of mean signed error are shown in Table 6-1. The significant effects isolated included the two-way interaction of contrast and signal-to-noise ratio ($\alpha<.05$) and the three way interaction of fixed target position, contrast, and transmission mode ($\alpha\approx.05$). These three variables also produced four-way interactions with signal-to-noise ratio ($\alpha<.05$) and initial variable target position ($\alpha<.05$).

The grand mean for all trials in the test was -.677 cm. (-.267 in.) The negative constant bias indicates a tendency to place the variable target farther than the fixed target was present. The operators thus tended to overshoot the correct range.

The interaction of contrast and signal-to-noise ratio is illustrated in Figure 6-4. Constant error appears to increase slightly as signal-to-noise ratio is increased under .5 contrast conditions. For higher contrast, little effect of signal-to-noise ratio was evident. The interaction of fixed target position, bandwidth, and contrast is illustrated in Figure 6-5. The tendency to overshoot the correct range may be seen to generally increase with increasing distance of the fixed target from the camera. The combination of reduced bandwidth on the left camera channel and contrast of .5 appears to produce a maximum constant error at the intermediate camera position with reduced error at the extremes.

TABLE 6-1. ANALYSIS OF VARIANCE OF SIGNED ERROR

SOURCE	DF	SS	MF	F
MEAN	1	38.39859	38.39859	2.6578
DISTANCE	2	2.672373	1.336186	1.3337
CONTRAST	1	.9733612-01	.9733612-01	.0874
S/N	2	.4567578	.2283789	.6161
TRANSL. MODE	1	.1499945	.1499945	2.0120
INIT. POSITION	2	.1348959	.6744797-01	1.0621
SUBJECTS	4	57.79312	14.44828	
DC	2	.2101218	.1050609	.4403
DN	4	1.554143	.3885358	1.3074
CN	2	.9920679	.4960339	5.1070*
DB	2	.3286450	.1643225	2.2908
CB	1	.1157413-03	.1157413-03	.0021
NB	2	.7656128-01	.3828064-01	.9523
DH	4	1.336431	.3341077	2.9371
CH	2	.2783497-01	.1391748-01	.1688
NH	4	.6010156	.1502539	1.8465
BH	2	.4126599	.2063300	1.9579
DP	8	8.014687	1.001836	
CP	4	4.453877	1.113469	
NP	8	2.965586	.3706982	
BP	4	.2982037	.7455093-01	
HP	8	.5080285	.6350357	
DCN	4	1.859807	.4649518	2.3072
DCB	2	1.021184	.5105920	5.2646*
DNB	4	.3520825	.8802063-01	1.0768
CNB	2	.3222668	.1611334	1.7429
DCH	4	2.043833	.5109582	1.1711
DNH	8	.6145654	.7682068-01	.2963
CNH	4	.4806683	.1201671	1.3174
DBH	4	.8701196	.2175299	1.3981
CBH	2	.1757513	.8787567	.9452
NBH	4	.2357642	.5894104-01	.4152
DCP	8	1.908757	.2385947	
DNP	16	4.755146	.2971966	
CNP	8	.7770105	.9712631-01	
DBP	8	.5738244	.7172806-01	
CBP	4	.2252890	.5632225-01	
NBP	8	.3215802	.4019752-01	
DHP	16	1.820073	.1137546	
CHP	8	.6596399	.8245498-01	
NHP	16	1.302007	.8137542-01	
BHP	8	.8431116	.1053889	
DCNB	4	2.377207	.5943017	4.4436*
DCNH	8	.8960596	.1120074	.6954
DCBH	4	2.468516	.6171289	4.3318*
DNBH	8	.9475427	.1184428	.8172

TABLE 6-1, Continued:

SOURCE	DF	SS	MF	F
CNBH	4	1.036199	.2590497	1.2332
DCNP	16	3.224253	.2015158	
DCBP	8	.7759118	.9698898-01	
DNBP	16	1.307927	.8174545-01	
CNBP	8	.7396264	.9245331-01	
	16	6.981221	.4363263	
	32	8.297402	.2592938	
	16	1.459416	.9121353-01	
	16	2.489512	.1555945	
	8	.7437768	.9297210-01	
	16	2.271372	.1419607	
	8	1.409551	.1761938	1.6355
	16	2.139780	.1337363	
	32	5.154072	.1610648	
	16	2.279429	.1424643	
	32	4.637959	.1449362	
	16	3.360972	.2100607	
	32	3.447397	.1077312	

** p <.01

* p <.05

The four-way interactions shown in Table 6-1 were found to involve small effect parameters generally on the order of .25 cm. (.1 in.). The absolute levels of these effects appear to be of little practical significance. The lack of significant main effects of the independent variables show the stereoptic system tested to be quite insensitive to bandwidth reduction on one channel or to reduction in signal-to-noise ratio in terms of constant error.

Absolute Error

The results of the analysis of variance of absolute error are shown in Table 6-2. The significant effects isolated by this analysis included the main effects of fixed target position ($\alpha < .05$), transmission mode ($\alpha < .05$), and the interaction of contrast and transmission mode.

Mean absolute error as a function of fixed target position is shown in Figure 6-6. The increase in absolute error with increasing fixed target position is statistically significant but the total range of the effect amounts to only about .6 cm. (.24 in.). At the ranges involved, the mean absolute values obtained represent a percent of true range of only about .5 percent. The changes in mean absolute error due to variation of fixed target position represent about .2 percent of true range. The effects produced by bandwidth and contrast reduction represent even smaller percentages of true range, the contrast by bandwidth interaction parameters estimates being on the order of .1 cm. (.04 in.).

In view of these extremely small performance variations due to the independent variables studied, the statistic of most importance would appear to be the general average error for all trials. This was found to be 1.24 cm. (.49 in.). The stereoptic system employed under conditions of off-axis viewing at 45 degrees to the axis of the TMG appears to produce quite accurate range adjustment and to be fairly insensitive to image degradation due to signal-to-noise ratio and bandwidth reduction. In summary, the constant error or bias in the range adjustments was found to be -.677 cm. (-.267 in.) and the mean absolute or variable error was 1.24 cm (.48 in.). Neither error measure showed marked variation when signal-to-noise ratio, bandwidth, or contrast were reduced.

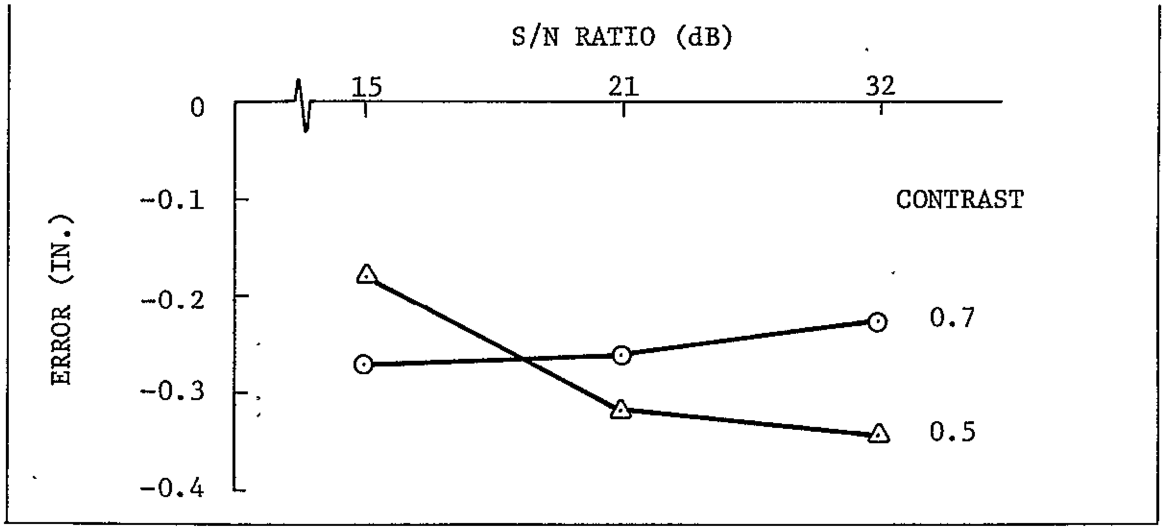

FIGURE 6-4. MEAN SIGNED ERROR AS A FUNCTION OF SIGNAL-TO-NOISE RATIO AND CONTRAST

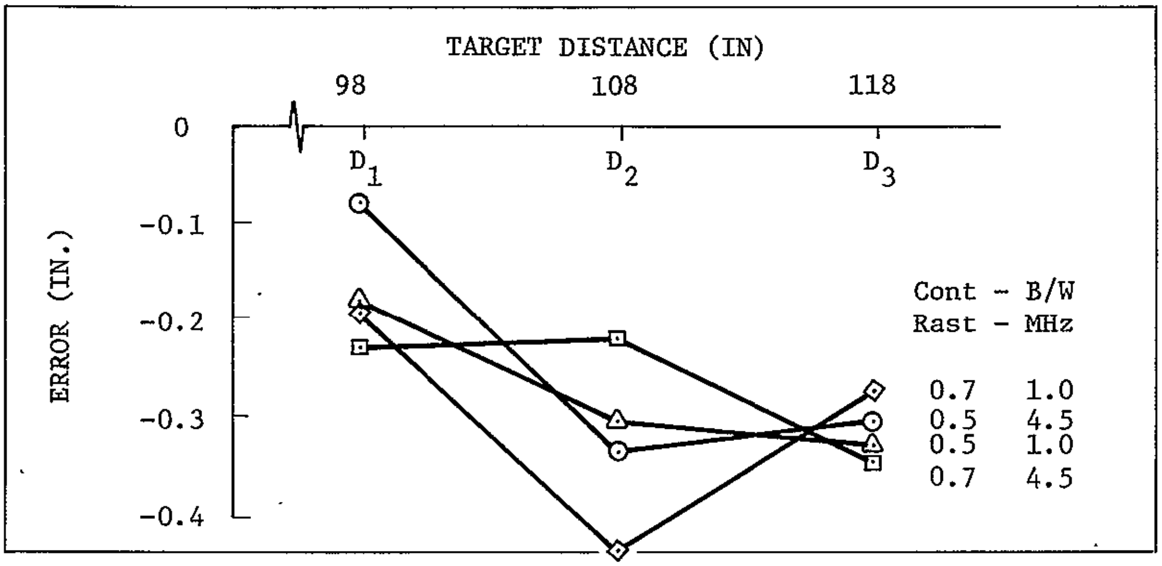

FIGURE 6-5. MEAN SIGNED ERROR AS A FUNCTION OF FIXED TARGET POSITION, BANDWIDTH, AND CONTRAST

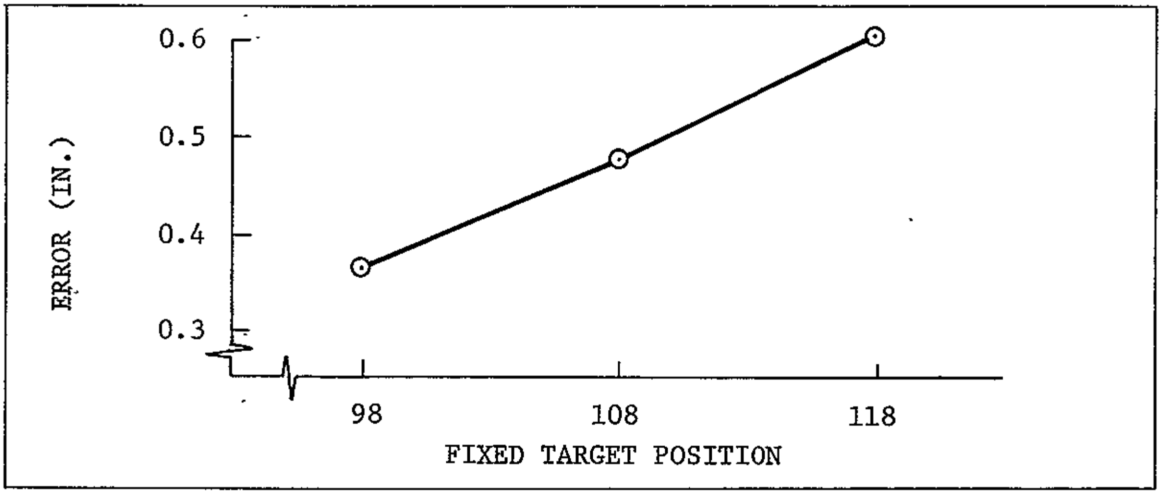

FIGURE 6-6. MEAN ABSOLUTE ERROR AS A FUNCTION OF FIXED TARGET POSITION

TABLE 6-2. ANALYSIS OF VARIANCE OF SIGNED ERROR

SOURCE	DF	SS	MF	F
MEAN	1	127.8441	127.8441	49.4718
DISTANCE	2	5.170185	2.585093	6.3606*
CONTRAST	1	.2893384	.2893384	1.0249
S/N RATION	2	.4380623-01	.2190311-01	.1199
TRANS MODE	1	.2778943	.2778943	11.3456*
INITIAL POS.	2	.1146396	.5731979-01	.4731
SUBJECTS	4	10.33695	2.584238	
DC	2	.2625439	.1312720	1.9290
DN	4	.6313501	.1578375	.6085
CN	2	.5960483-02	.2980242-02	.0364
DB	2	.5180993	.2590497	2.3176
CB	1	.8166528	.8166528	14.2798*
NB	2	.5156579	.2578290	3.0704
DH	4	.1469885	.3674713-01	.4123
CH	2	.3234878-01	.1617439-01	.1092
NH	4	.3525403	.8813507-01	1.9663
BH	2	.3477875-01	.1738937-01	.9110
DP	8	3.251352	.4064191	
CP	4	1.129338	.2823346	
NP	8	1.461980	.1827475	
BP	4	.9797317-01	.2449329-01	
HP	8	.9692712	.1211589	
DCN	4	.5087915	.1271979	1.0714
DCB	2	.7413131-01	.3706566-01	.3934
DNB	4	.8622390-01	.2155598-01	.3174
CNB	2	.2621468-01	.1310734-01	.2227
DCH	4	.2386557	.5966392-01	.2348
DNH	8	.3759167	.4698959-01	.7840
CNH	4	.2712872	.6782181-01	.5788
DBH	4	.4348309	.1087077	.6177
CBH	2	.1453101	.7265503-01	.5688
NBH	4	.2039343	.5098358-01	.3723
DCP	8	.5444360	.6805450-01	
DNP	16	4.150166	.2593854	
CNP	8	.6543298	.8179123-01	
DBP	8	.8941980	.1117747	
CBP	4	.2287604	.5719009-01	
NBP	8	.6718164	.8397705-01	
DHP	16	1.426213	.8913833-01	
CHP	8	1.185247	.1481558	
NHP	16	.7171655	.4482284-01	
BHP	8	.1527182	.1908977-01	
DCNB	4	.2715161	.6787903-01	.5484
DCNH	8	.5113244	.6391556-01	1.1463
DCBH	4	.2951343-01	.7378359-02	.1501
DNBH	8	.3707135	.4633919-01	.4631

TABLE 6-2, Continued:

SOURCE	DF	SS	MF	F
CNBH	4	.4888776	.1222194	.9007
DCNP	16	1.899480	.1187175	
DCBP	8	.7536950	.9421188-01	
DNBP	16	1.086492	.6790573-01	
CNBP	8	.4708874	.5886093-01	
DCHP	16	4.065449	.2540906	
DNHP	32	1.918035	.5993858-01	
CNHP	16	1.874822	.1171764	
DBHP	16	2.815928	.1759955	
CBHP	8	1.021916	.1277396	
NBHP	16	2.190928	.1369330	
DCNBH	8	.9774194	.1221774	1.2516
DCNBP	16	1.980474	.1237796	
DCNHP	32	1.784368	.5576149-01	
DCBHP	16	.7867456	.4917160-01	
DNBHP	32	3.202158	.1000674	
CNBHP	16	2.171030	.1356894	
DCNBHP	32	3.123789	.9761841-01	

** $p < .01$

* $p < .05$

For purposes of comparison with the results of the first range resolution test, the range increment distributions for the second test were obtained. The cumulative distributions of range adjustment errors for the three fixed target positions are shown in Figure 6-7. The range increments necessary for .90 probability of detection are also given.

Response Time

The response time data for the second range resolution test were analyzed but it was noted that the same situation occurred in these data as was found in the first test results. The significant effects of the independent variables on response time were found to be those associated with the obvious correlation between initial variable target position, fixed target position, and TMG travel time.

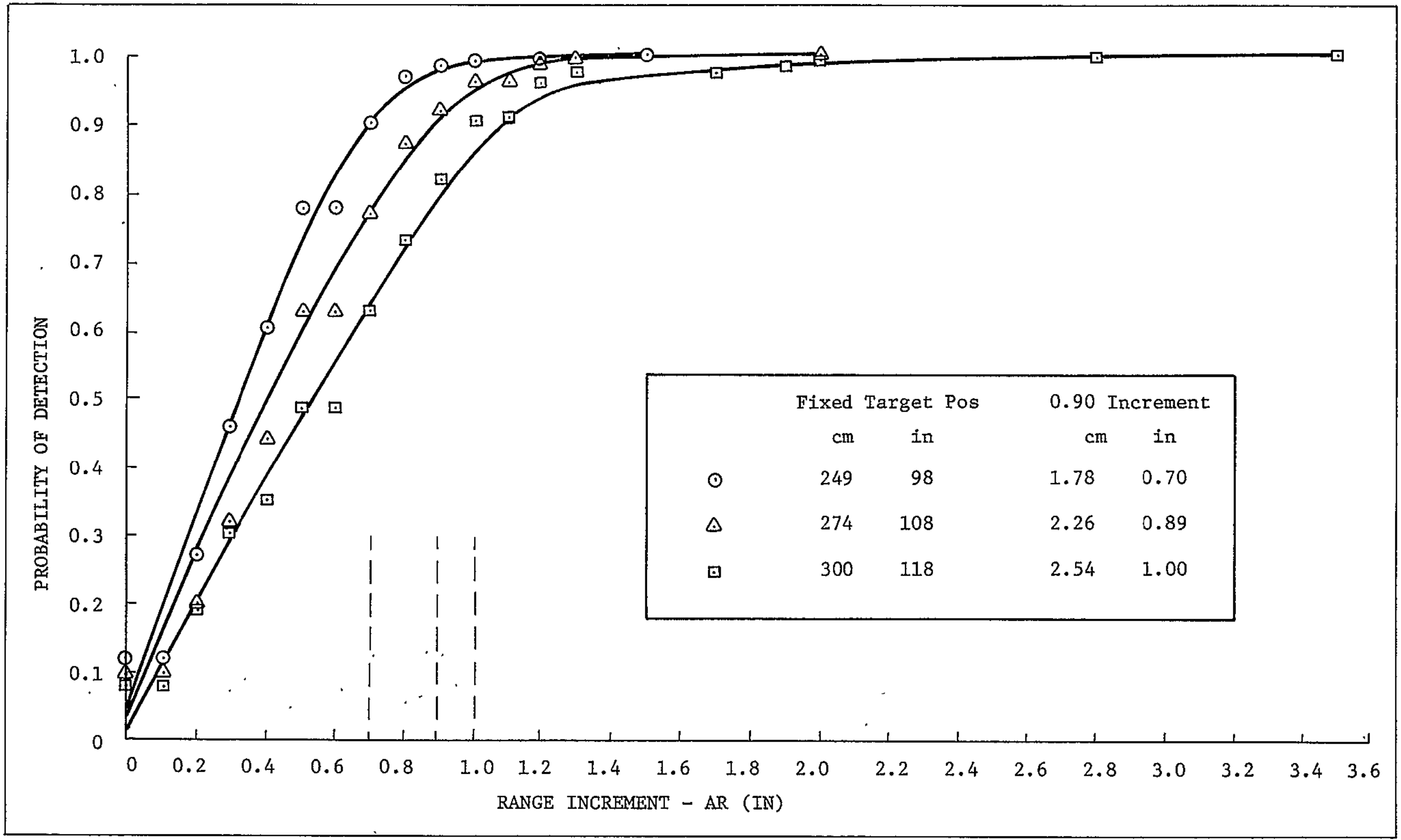

FIGURE 6-7. CUMULATIVE DISTRIBUTIONS OF ADJUSTMENT ERROR

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Range Estimation

The image size estimation test reported in section 4 was motivated by an analysis of potential range and range rate measuring approaches using monoptic television presented by Kirkpatrick et.al.(1974). That analysis suggested that range and range rate estimation could be carried out using parameters of the TV system and suitable operator commands to a movable cursor system superimposed on the monitor. The present investigation provides empirical support for this notion as regards estimation of a fixed range. For example, during the approach of a teleoperator system to an orbiting satellite, the operator would be closing the range at a rate which would depend on range (i.e. would be following a range-range rate profile). The present data suggest that a computer using satellite dimension, zoom feedback voltage, and cursor separation voltage could calculate range. Furthermore, given the level of accuracy of cursor setting in the present study, such estimation would be expected to contain a measurement error on the order of one to two percent for appropriate choice of target dimension and zoom setting. That is, the displayed image size should not drop below the one to two centimeter range to prevent increase in error.

These results compare favorably with the accuracy available from dedicated ranging systems such as radar. The optical approach also has the advantage that accuracy would be expected to increase as range decreases. The delta cost for an optical ranging approach should be mimimal since the video system is necessary for general viewing in any case. The optical method thus appears to have potential. It should be noted, however, that the present data were obtained with a stationary target. A non-zero range rate would be expected to increase errors. Rate cursor control is presently being investigated since this should permit instantaneous measurement of range-although probably with greater error than was obtained in the present study. Such a system would also permit range rate estimation and studies of the accuracy of the latter are presently being planned.

7.2. Range Resolution

The two range resolution studies provide empirical data for estimation of the retinal disparity thresholds discussed in section 5. The range from camera to target employed centered around 274 cm. (108 in.) which was considered to be an approximate upper limit on the reach of small servicing manipulators. Thus, the range utilized approximates the worst case for range resolution during servicing of a satellite. As would be expected, the maximum range increments necessary for detection were found in the first study which dealt with motion in the axis of the camera pair (pure range). The second study which involved placing the camera pair at an angle of 45 degrees to the motion axis yielded reduced range increments presumably because the target separation was partially represented by lateral image separation on the display.

For the stereoptic system employed, range increments of from 2.44 cm. (96 in.) to 4.83 cm. (1.9 in.) were obtained for a probability of detection of .90 using viewing along the motion axis. The necessary modifications to the system to provide detection of smaller increments were discussed in section 5. It would appear that either zoom capability or variable baseline capability would suffice to obtain exaggerated or enhanced stereoptic cues. The present system utilized a modest exaggeration ratio of 2.24.

Increased range resolution could easily be obtained in a baseline visual system by increases in exaggeration ratio. The problem in recommending an exaggeration ratio at present is that the resolution requirements for servicing tasks are not presently well defined. The data obtained, however, would suffice to specify stereo parameter requirements at any time that worst case resolution requirements become available.

In comparing the results of the two range resolution studies completed, it is apparent that camera position with respect to motion axis is a continuous variable which is characterized by the angle between the camera viewing axis and the motion axis. This angle was zero degrees in the first range resolution study and was 45 degrees in the second study. In addition, it is also possible to consider an angle of 90 degrees. This represents a special case where target separation becomes a lateral dimension on the display. The requirements placed on the video system for detection in this situation obviously do not include stereoptic capability. That is, stereoptic television and monoptic television should perform equally well. This permits prediction of performance of the current system had this case been investigated based on the gap resolution data presented by Kirkpatrick et.al. (1973). This result and the data from the current studies are plotted in Fig. 7-1 which shows .90 probability detectable target separation increments for the three cases. This serves to approximately define the envelope of target separation sensitivity for the present system at a constant range of 274 cm. (108 in.). The reliance of the operator on stereoptic cues clearly increases as the viewing angle decreases. The stereo system should provide no additional cues at 90 degrees and would be the primary source of cues at zero degrees. For the data in Figure 7-1, the accuracy of range resolution decreases with increasing viewing angle, but the decrease would be greater for monoptic television. The present data would suggest a slope about four times as great for a monoptic system as for stereo in Figure 7-1. For a stereoptic system, the slope could be reduced by increasing the exaggeration ratio.

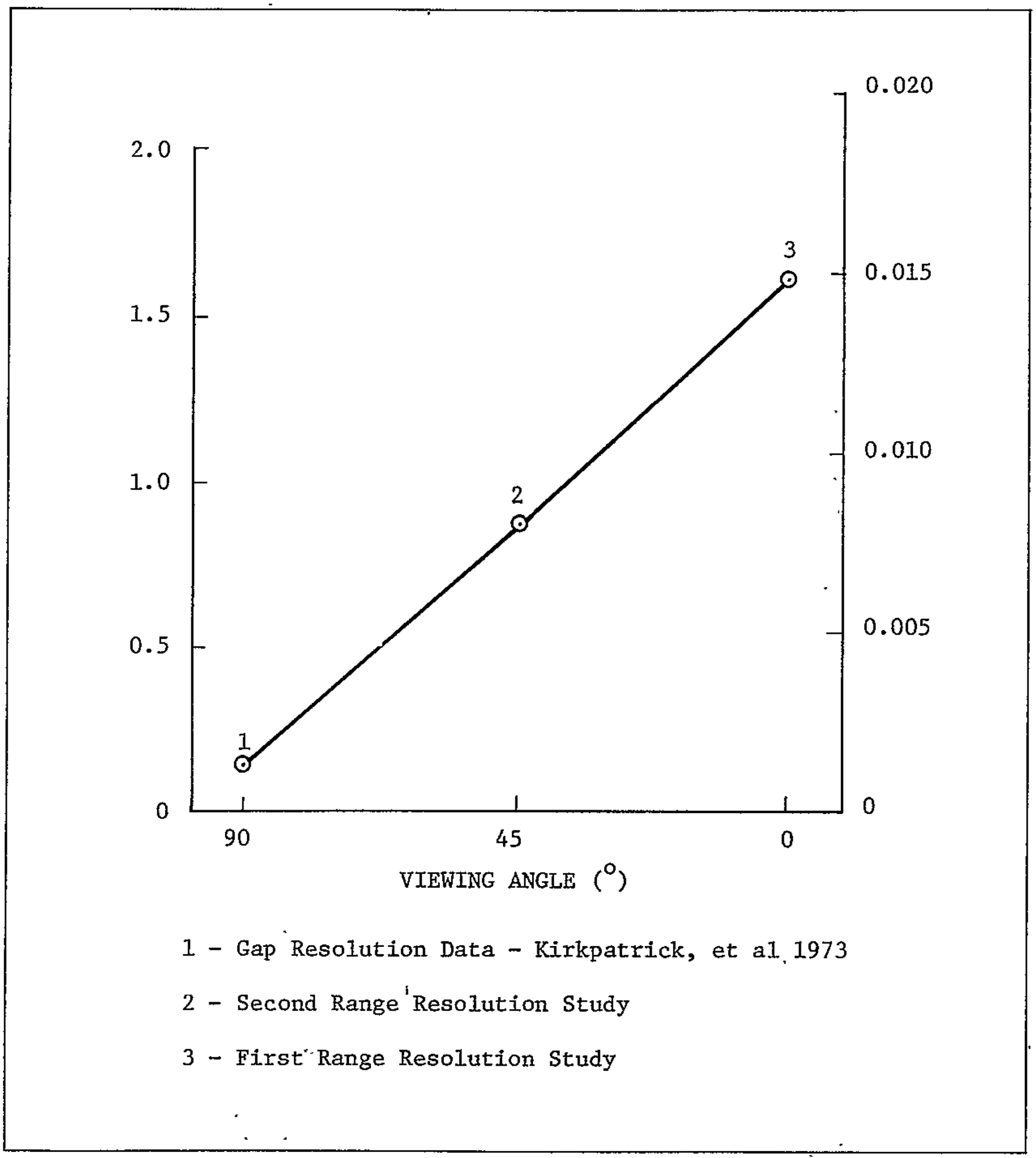

FIGURE 7-1. .90 PROBABILITY OF DETECTABLE TARGET SEPARATION FOR THREE VIEWING ANGLES

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