

Phase II
Final
Report

April 1973

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**Conceptual
Design Study
for a
Teleoperator
Visual System**

MARTIN MARIETTA

MCR-73-96
Contract NAS8-29024

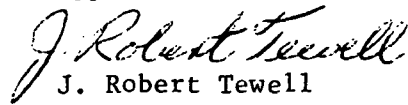
Phase II
Final Report April 1973

CONCEPTUAL
DESIGN STUDY
FOR A
TELEOPERATOR
VISUAL SYSTEM

Prepared by

C. Grant
R. Meirick
C. Polhemus
R. Spencer
D. Swain
R. Tewell

Approved


J. Robert Tewell
Program Manager

MARTIN MARIETTA CORPORATION
DENVER DIVISION
Denver, Colorado 80201

FOREWORD

This document presents the results of work performed by Martin Marietta Corporation's Denver Division under contract to the National Aeronautics and Space Administration's Marshall Space Flight Center. This Phase II Final Report was prepared in partial fulfillment of Contract NAS8-29024, Conceptual Design Study for a Teleoperator Visual System. The work was administered under the technical direction of the Astrionics Laboratory Instrumentation and Communication Division with Mr. Carl T. Huggins as the Contracting Officer's Representative.

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I. INTRODUCTION

Plans for extending man's exploration and understanding of space may possibly include the use of remotely controlled teleoperators which, when controlled from a safe, habitable location, have the advantage of using man's ability to make decisions as unforeseen conditions arise while contributing significantly to his safety by permitting him to "stand-off" from any hazardous conditions.

Teleoperators, for space application, are generally classified into three distinct systems: (1) Attached Teleoperators; (2) Unmanned Roving Vehicles; and (3) Teleoperator Spacecraft. These systems are extremely complementary in that the first operates solely within the range of a manned spacecraft such as the 15.3 meter (50.0 feet) shuttle attached manipulator presently under study for use in shuttle cargo handling while the second operates on lunar or planetary surfaces similar to the Russian Lunokhod. The third system, the teleoperator spacecraft, takes up the gap between the other two systems by enabling the inspection, retrieval, and maintenance of satellites within those earth orbits unattainable by the Shuttle, as well as long range missions such as comet and asteroid exploration.

The functional requirements and lead technology items for these teleoperator spacecraft systems are presently being studied and developed by the NASA. One such teleoperator spacecraft system is the free-flying teleoperator (FFTO, Ref. 10) referred to throughout this report. It is a typical, experimental prototype to be used for orbital demonstration and evaluation purposes and was selected by this study as a baseline system. This FFTO concept, when developed, will comprise one of two Life Sciences Shuttle payloads, the other being a bio-research module. The FFTO is considered a Life Sciences payload by virtue of the fact it is inherently a man-machine system, depends on man for control inputs, and exists for the purpose of extending

man's unique capabilities beyond his physical presence. The FFTO consists of four basic elements: (1) a vehicle, remotely controlled, to provide maneuvering to and from the work site and mobility about the satellite as required; (2) one or more manipulative devices, representative of man's arms and hands, to enable the performance of tasks at the work site; (3) a visual system, analogous to man's eyes, to allow viewing of the work site and task activity; and (4) a control and display station, remotely located in a manned spacecraft or on the surface of the earth, from which the total FFTO mission operations are manually supervised and controlled. One of the most important of these four elements is the visual system, as this system is the primary sensor used by the FFTO operator in accomplishing the FFTO tasks. Therefore, a study was undertaken to establish the requirements of the visual system, evaluate candidate concepts, and provide a preliminary design of the preferred visual technique.

This study was divided into two phases, Conceptual Design and Preliminary Design. The Conceptual Design phase was completed in November, 1972 at which time a final report documenting the results of the work performed was published (Ref. 1). Briefly, the objective of Phase I was to investigate visual system concepts for application to teleoperator operations, and based on technical judgement, purpose a candidate for consideration by NASA for preliminary design. The initial activity consisted of reviewing documents provided by NASA to establish the general requirements and guidelines for the visual system. Based upon these requirements, four general categories of visual system concepts were considered: direct vision; television; optical radar/computer generated displays; and holography. The direct vision concept was eliminated from consideration as a result of the FFTO operations conducted outside of the direct visual range. The optical radar/computer generated concept did not provide an adequate visual scene relative to the simplicity of the television

concept, and the holographic concept was considered too advanced for a 1975 state-of-the-art time frame. Thus, the only remaining candidate was television. However, with television as a recommended visual technique, the number of cameras required and the relative operator performance with monoscopic or stereoscopic views were unanswered questions.

Therefore, a detailed investigation of TV concepts resulted in eight potential systems: a monoscopic technique and six stereoscopic techniques. The stereoscopic techniques included polarized, color-separated, helmet-mounted, fresnel, lenticular, and foveal-peripheral systems. Based upon operator comfort, system complexity, state-of-the-art considerations, and bench test evaluations, the fresnel stereoscopic was the preferred stereoscopic system. Hence, two visual techniques remained: the monoscopic and the fresnel stereoscopic.

These two systems were assembled and evaluated using man-in-the-loop simulations. The simulations consisted of three phases: static, master slave manipulator, and a six degree-of-freedom moving base. The static phase investigated camera locations and depth alignment. In the second phase, the two systems were compared on the basis of typical FFTO maintenance operations using a task panel and a Control Research Laboratories Model L manipulator arm. In the third phase, Martin Marietta's six degree of freedom moving base, programmed with the FFTO maneuvering characteristics, was used with a scaled spinning/nutating satellite to provide data on system performance relative to a satellite inspection or retrieval mission. Based on the results of these simulations, a hybrid stereo-monoscopic visual system concept was recommended. This concept, consisting of one monoscopic and one stereoscopic-fresnel display television system, was selected as the single concept to be investigated in detail during the

Phase II portion of this contract.

The primary objective of Phase II is to generate a preliminary design of the selected concept. This report describes the results of the work performed during Phase II.

II. SUMMARY

This report describes the results of the work performed by Martin Marietta during the second phase of the conceptual design study for a teleoperator visual system. Based upon the results of Phase I, a hybrid stereo-monoscopic television visual system was recommended and selected by the NASA for further study during Phase II. Phase II consisted of a detailed analysis of this visual system concept.

A. GENERAL OVERVIEW

A description of the visual concept is presented in Section III. Briefly, the monoscopic portion is identical to the commercial type television systems while the stereoscopic portion employs two TV cameras, two monitors, imaging lenses, and a fresnel screen to present a stereoscopic view to the FETO operator. The subsystems required by this concept are identified and analyzed in the following sections of this report. The subsystems include sensors, illumination, deployment/articulation, telecommunications, visual displays, and the controls and displays station.

B. SENSOR SUBSYSTEM

Space qualified and developmental cameras were analyzed in-depth. Based upon past usage, present availability, and conformance to the visual system requirements, an Apollo type TV camera was recommended as the FETO visual sensor. However, if camera developmental activity continues and results in a better space qualified unit, the sensor choice must be re-evaluated. The stereoscopic sensor parameters including baseline, convergence angle and field of view were theoretically analyzed and their interrelationships established. Man-in-the-loop simulations were conducted, using an FETO type manipulative device, and resulted in the recommendation of a fixed baseline, fixed convergence angle, and variable field of view stereoscopic sensor subsystem. (Section IV).

C. ILLUMINATION SUBSYSTEM

Passive illumination techniques were analyzed and bench type evaluations conducted. A diffuse hemispherical reflector was included as part of the illumination subsystem based upon the relative merits established.

An in-depth study of available artificial lighting was emphasized. Several lamp manufacturers were contacted in order to determine the present state-of-the-art. The extent of existing developmental lighting programs and space qualified lamps from the Apollo and Skylab programs were identified. Additional effort was directed toward the spectral matching of lamps and TV cameras for improved illumination efficiency. A computer program was generated to evaluate various lamp characteristics with respect to the camera spectral sensitivities and frequency response in order to establish an illumination "figure of merit". This "figure of merit" was used in conjunction with passive lighting theory and simulation results to determine optimum lighting components and configurations. (Section V)

D. DEPLOYMENT/ARTICULATION SUBSYSTEM

The minimum visual sensor deployment/articulation requirements were established in Section VI. An in-depth analysis was conducted which proceeded from a simple un-articulated sensor to one, or more sensors, provided with complex articulation. The concepts were analyzed and the results indicated that while a two degree of freedom articulated boom was adequate, the flexibility provided by implementing a three-degree-of-freedom device well overshadowed the minor additional control requirement.

A full scale FFTO model, including the sensor articulator and a manipulator, was used to verify adequate FFTO operational area visual coverage was provided with this concept.

A preliminary design of the articulation device was made and the power, mass, and control characteristics were established.

E. DISPLAY SUBSYSTEM

A detailed analysis of the fresnel stereoscopic TV display subsystem, described in Section VII, was made to establish the parametric relationship between monitor size and the total display volumetric requirements. Two engineering designs, one using 7.6 cm (3 in) monitors; the other 22.9 cm (9 in) monitors, for ground-base mono-stereo visual system type simulations, were completed.

Additional investigations were made to determine the potential of polarized stereoscopic TV displays in hopes of avoiding the head restriction for stereo viewing encountered in the fresnel-stereo system. The prohibitively low illumination efficiency eliminated polarization as a possible candidate for use with conventional CRT displays. Consequently, emphasis was directed toward modification of the fresnel display to allow additional viewer freedom and stereo-to-mono conversion for redundancy. The result was a modified fresnel stereoscopic display with unlimited vertical head movement using a lenticular pupil spreader. It was further demonstrated that the lenticular pupil spreader provided an improved method of stereo-to-mono conversion when rotated 90 degrees.

Augmented visual displays, alpha numerics and stereo reticles, were investigated. A stereo reticle generator was designed, built, and used in ranging simulations.

F. TELECOMMUNICATION SUBSYSTEM

Methods to reduce the total visual system bandwidth requirements were investigated. Both multiplexed and non-multiplexed systems were analyzed with the primary emphasis placed upon reducing the stereo-sensor bandwidth to that equivalent to typical monoscopic

systems. A method, based upon a phase modulated subcarrier similar to color TV, was technically evaluated and man-in-the-loop simulations of this concept established the feasibility of this recommended approach.

Additionally, the visual system command and control requirements were integrated with other FFTO systems such that a telecommunication subsystem could be recommended. Based upon the total FFTO system data bit rate required, a unique concept of inserting the command and control data into the TV vertical blanking interval, hence providing essentially a "free" ride, was recommended. Redundancy, based upon the minimum requirements to return a FFTO to "home", was established. (Section VIII)

G. CONTROLS AND DISPLAYS SUBSYSTEM

The controls and display subsystem requirements, as related to the FFTO visual system, were initially emphasized and followed by an investigation of other control and display elements required of the FFTO system. Integrated man-machine requirements were identified and a recommended preliminary design concept of a typical FFTO control station was established. A Fome-Cor mockup was made for use in future evaluations. (Section IX)

III. GENERAL OVERVIEW

The FFTO visual concept selected for Phase II detail analysis was a hybrid stereo-monoscopic system. This concept required several subsystems, as identified in Fig. III-1 and discussed in the following sections, which received varying levels of analysis during Phase I. As expected with any type visual system, the emphasis was initially placed upon the sensor used and the display technique provided to the viewer. Once a visual technique is established, all subsystems must receive detailed attention. Since a television concept was selected, the sensor (TV cameras) and the display (TV monitors) received less emphasis during Phase II as both were identified during the Phase I activity as state-of-the-art components and, except for minor modifications, were space qualified. However, where a specific TV component selection impacted the other visual subsystems, in-depth analyses were performed.

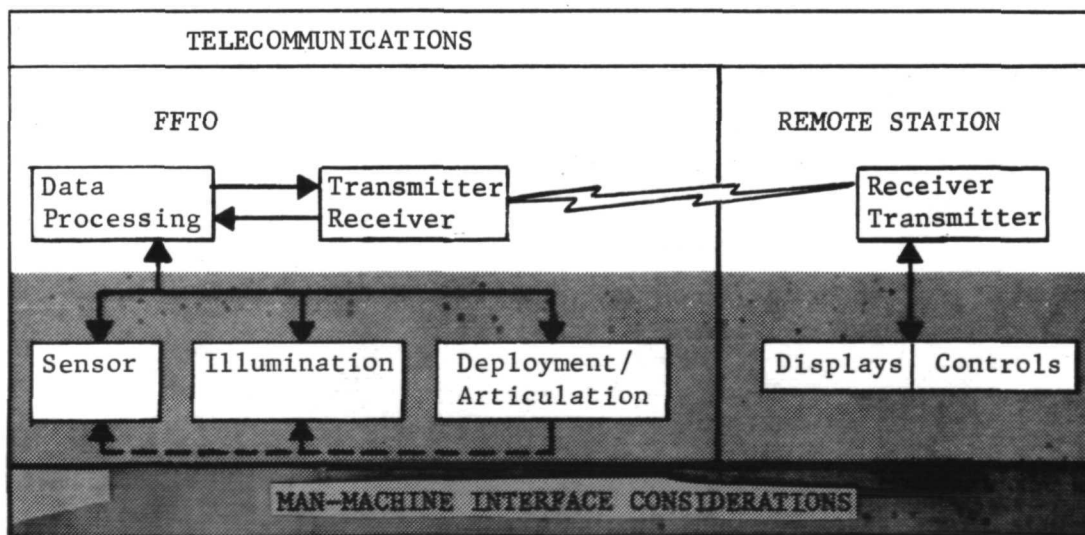


Fig. III-1 Subsystems in the TV Visual System

A brief description of the FFTO visual concept recommended as a result of the Phase I contractual effort is presented here in an attempt to provide continuity to this report.

The proposed baseline FFTO visual system concept incorporates both monoscopic and stereoscopic television. The monoscopic view is identical to the familiar commercial TV systems. The stereoscopic view is provided by a Fresnel-stereo system. This system, illustrated in Fig. III-2, is a simple, but extremely realistic stereo display concept. Signals, from two adjacent TV cameras, are fed to two TV monitor faces, one for each stereo image. These images are projected through imaging lenses onto a fresnel screen. The screen acts as a field lens and forms a separate exit pupil for each image. The size and shape of the exit pupil is predetermined by the imaging lens selected and the display-to-viewer distance is set by the focal length of the fresnel screen.

This concept had numerous advantages over the other stereo display techniques analyzed in Phase I. Since the fresnel screen collects light over a large field and concentrates it at the exit pupils, image illumination (i.e. power efficiency) is optimized. The apparent field of view can be designed to accommodate nearly full peripheral vision and no "glasses" or other viewing aids are required. Hence, the random viewing of the peripheral FFTO controls and displays is natural and effortless. As the two optical axes cross in the image plane, maximum ease of stereo registration is provided. This system is simple, compact, and occupies less volume than any other stereo concept evaluated. The only limitation inherent in this system is the viewer head movement is restricted to the viewers interpupillary dimensions.

A prototype of this system concept is shown in Fig. III-3. The complete system, about the size of a suitcase, consists of two 7.6 cm (3 in) diagonal monitors and mirrors which provide the required optical path while reducing the overall volume.

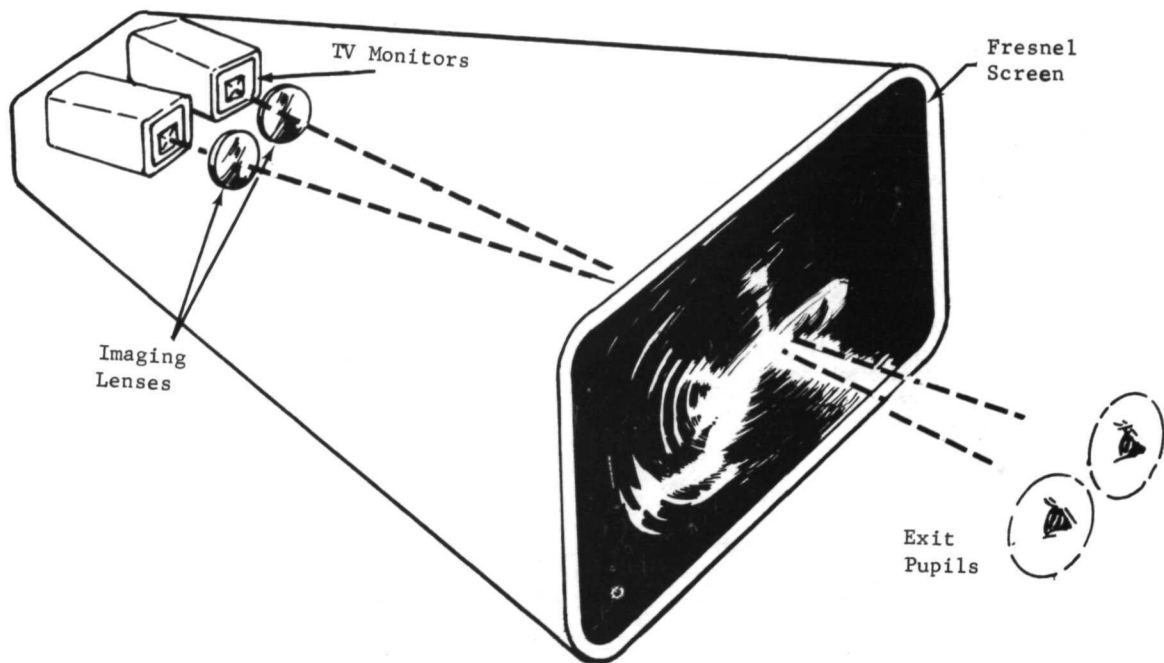


Fig. III-2 Fresnel Stereo Display Concept

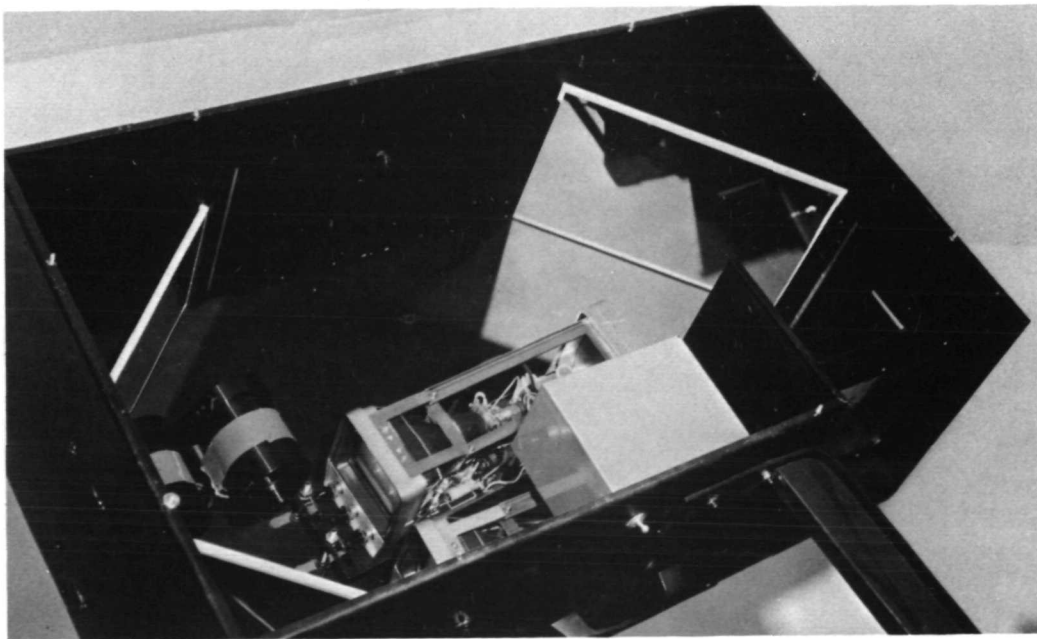


Fig. III-3 Stereoscopic Fresnel Display

IV. SENSOR SUBSYSTEM

Phase I Summary: State-of-the-art surveys established that the primary FFTO visual system must be a TV system, that several space qualified TV cameras are presently available from the Apollo and Skylab Programs, and at least one camera, for space application is under development. Three television cameras were baselined for the FFTO visual system in order to provide one monoscopic view for broad coverage and one dual-camera stereoscopic view for performance of dexterous tasks. Monochrome television was recommended for present investigations since existing color television systems are more complex and require excessive illumination.

Phase II Emphasis: The primary sensor subsystem effort was directed towards identifying, in more detail, the characteristics of the candidate space qualified and developmental TV cameras to establish a recommended sensor. Additionally, the stereoscopic sensor package required an in-depth study of stereoscopic vision parameters including baseline, convergence and field-of-view, and their integrated effect on depth perception, acuity and operator performance.

A. SENSOR SPECIFICATION

1. TV Cameras

In this section the characteristics are given for the television camera recommended for service in the FFTO Visual System (VS). Some suggested modifications and alternatives are also given.

The Apollo GCTA Television Camera (Ref. 1), shown in Fig. IV-1, is the recommended unit because it (1) most nearly meets the VS requirements in an "off-the-shelf" space-qualified camera, (2) it has performed exceptionally in the hostile space environment during the later Apollo missions, (3) it can be easily modified for monochrome operation and is quite sensitive in that mode, and (4) several flight and qual units are currently NASA property. Table IV-1 lists the salient characteristics of the GCTA camera as modified to monochrome operation. This modification consists of removing the color filter wheel and motor. The lens drive mechanism is also modified so that the focus and zoom can be separately controlled.

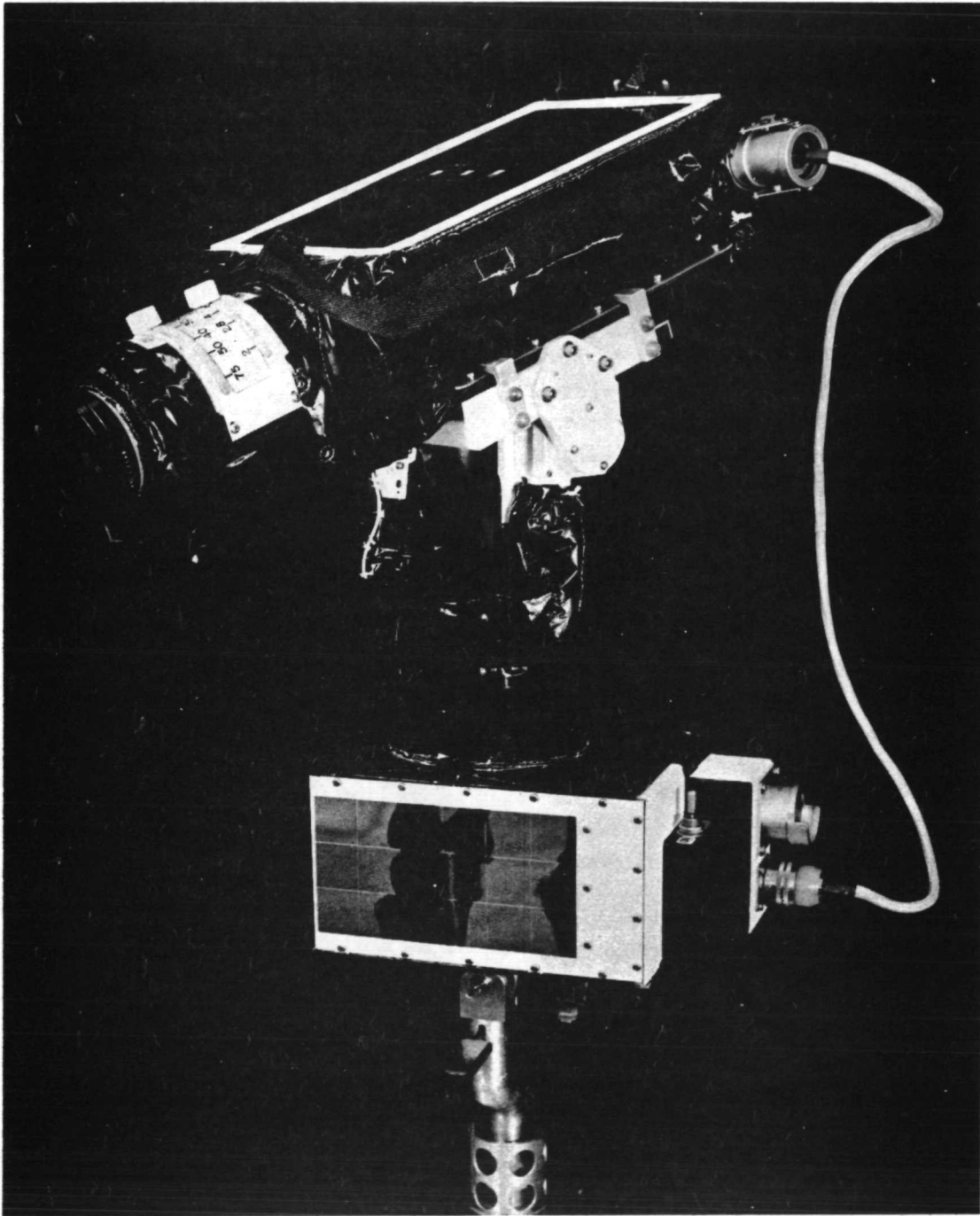


Fig. IV-1 RCA GCTA Camera

A more involved modification can be made which improves the camera's sensitivity when combined with incandescent lighting. The power drain for the auxiliary illumination would thus be reduced. In Section V, it is shown that incandescent lighting, which radiates a large portion of its energy in the infrared, gives a much better match to the silicon-target (S-T) camera tube than to the SIT vidicon used in the Apollo GCTA Camera. In addition, some increase in resolution can be obtained by eliminating the intensifier. Modification of the camera to use a silicon-target vidicon would require electronics changes in the camera and necessitate requalification.

Table IV-1 RCA Apollo GCTA TV Camera

Apollo GCTA Camera	
Sensor	1-inch SIT
Sensitivity	0.03 ft-lamberts at 32 db S/N
Resolution	80% at 200 lines ¹
ALC dynamic range	1000:1 minimum
Nonlinearity	3% maximum
Gray scale	10 $\sqrt{2}$ steps
Video output level	1.0 volts p-p into 75 ohms, full EIA sync
ALC modes	Peak or average detection
Zoom ratio	6:1
Iris control	f/2.2 to f/22
Pan angle	± 170 degrees
Tilt angle	± 85 , -45 degrees from horizontal
Power	12 watts at 28 VDC input
Size	18 in. long x 6.5 in. wide x 4 in high
Weight	5.9 Kg (13 lbs)
Input voltage	24-32 volts DC

¹ Camera resolution is expressed as the normalized video signal amplitude at the number of lines specified when the camera is trained on a resolution chart. The reference amplitude (100%) is normally measured at 50 lines.

for space. Another potential drawback is that sensing of direct or reflected infrared radiation may be undesirable, overriding the advantages of the S-T tube.

The NASA/Lockheed developmental camera (Ref. 3 & 4), illustrated in Fig. IV-2, represents a minimal-qualification alternative to the Apollo GCTA. It is smaller in size and weight and has better resolution capability. It incorporates an automatic iris circuit in conjunction with a tri-level ALC which can be

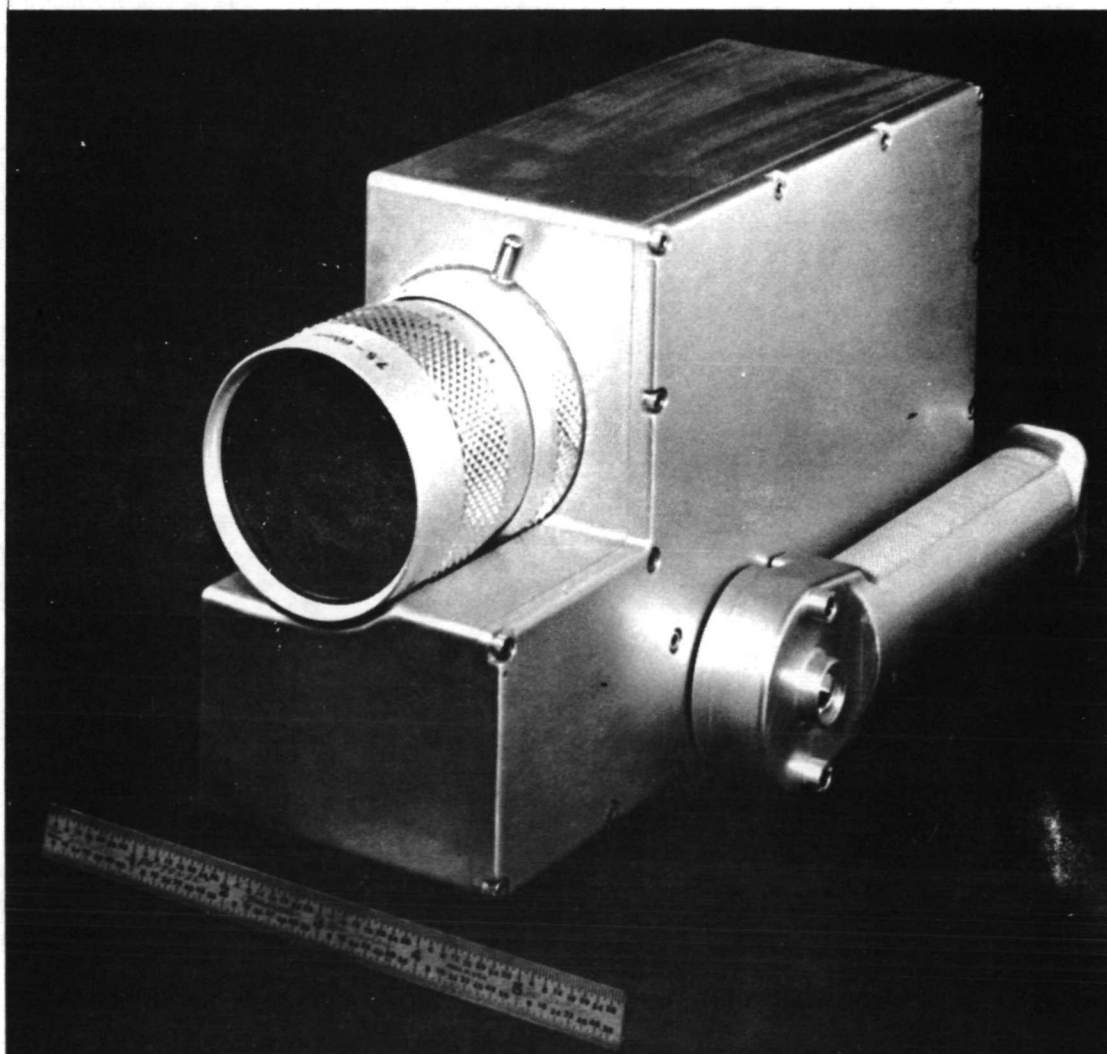


Fig. IV-2 NASA/Lockheed Advanced Spaceflight TV Camera

remotely switched. The NASA/Lockheed camera is equipped with a remotely controlled zoom lens but the focus is, at present, only under manual control. The remote control for focus would have to be added for use on the FFTO where both near and distant vision are required. The sensor is a standard $\frac{1}{2}$ inch vidicon, and as such has a target subject to burn under direct imaging of the sun. Silicon target tubes are not presently available in this small a size. The characteristics of the NASA/Lockheed camera, modified to remove the color wheel and motor are given by Table IV-2.

Table IV-2 NASA/Lockheed TV Camera

Sensor	$\frac{1}{2}$ -inch vidicon
Sensitivity	1 ft lambert at 34 db S/N
Resolution	80% at 300 lines
ALC dynamic range	300:1 plus automatic iris
Nonlinearity	—
Gray scale	—
Video output level	3.5 volts p.p into 50 ohms, full EIA sync
ALC modes	Peak, average, intermediate
Zoom ratio	8:1
Iris control	Automatically controlled with ALC
Pan angle }	Remote functions not included
Tilt angle }	
Power	11 watts
Size	$9\frac{1}{2}$ in. long x $3\frac{1}{4}$ in. wide x $5\frac{3}{16}$ in. high
Weight	2.8 Kg (6.1 lb)
Input voltage	24-32 volts DC

Another camera, shown in Fig. IV-3, which could possibly be space qualified in time for early FFTO missions is the Westinghouse WTC-22. This unit is attractive primarily for its small physical size and weight. The characteristics of the WTC-22 are given by Table IV-3. It is basically a monochrome camera and would not have to be modified to produce a black-and-white picture. It operates on the standard 525-line, 30-frame-per-second format. Moreover, its basic resolution capability is considerably higher.

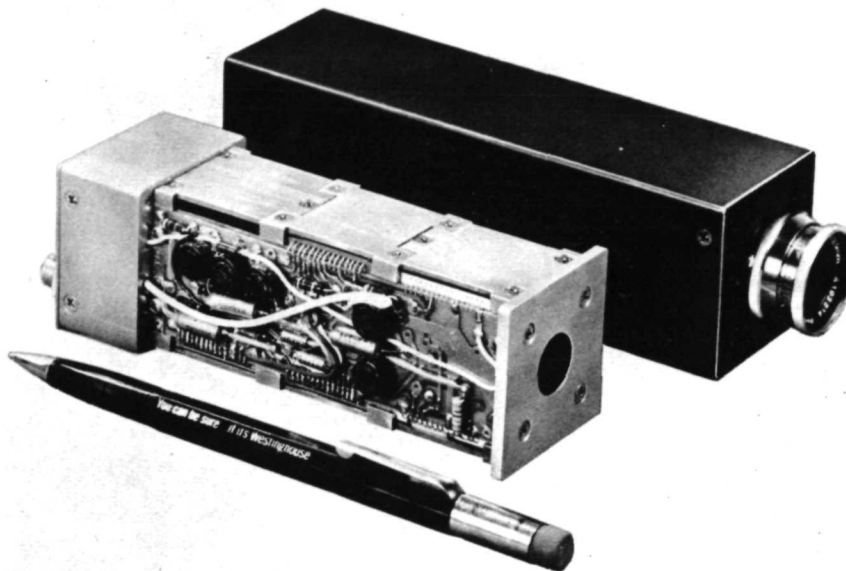


Fig. IV-3 Westinghouse Subminiature TV camera

Table IV-3 Westinghouse WTC-22 TV Camera

Sensor	$\frac{1}{2}$ -inch vidicon
Sensitivity	10 ft lamberts at 40 db S/N
Resolution	80% at 275 lines
ALC dynamic range	300:1
Nonlinearity	5% maximum
Gray scale	$10\sqrt{2}$ steps
Video output level	1.4 volts p-p into 75 ohms, full EIA sync average
ALC modes	Remote control not included
Zoom ratio	
Iris control	
Pan angle	
Tilt angle	
Power	6 watts
Size	5 in. long x 1.5 in. square
Weight	0.27 Kg (0.6 lb)
Input voltage	12 VDC $\pm$ 1 volt

Because of its light weight it is well suited to mounting on the end of a manipulator. It should be noted, however, that the housing and thermal protection required for a vacuum environment could add considerable weight. According to the manufacturer the WTC-22 is being space-qualified for use on ATS-F Applications Technology Satellite. Because it uses a standard vidicon, this camera is capable of better resolution than the S-T or SIT vidicons. For the same reason, protection must be provided to prevent damage from imaging the sun. At present, no such protection is provided.

Three cameras have been described which are suitable for use with the FFO Visual System. The Apollo GCTA Camera can be used essentially "as is" with only minor modification. Replacement of the vidicon with another type has been suggested to increase sensitivity and resolution. The NASA/Lockheed camera offers some advantages but must be qualified. The Westinghouse WTC-22, has been presented as a possible alternative. Its attractive features must be balanced against a higher-risk qualification.

2. Zoom Lenses

Fully remotely adjustable, space qualified lenses have thus far been flown only on the Apollo program as part of the GCTA assembly--and possibly on secret reconnaissance satellites about which there is no available information. The Skylab color camera will have the capability for remote control of zoom, focus, and iris. The NASA/Lockheed camera has remote zoom, fixed focus and an automatically controlled iris. Table IV-4 compares the lens parameters. The Apollo GCTA, the Skylab, and the NASA/Lockheed lenses are driven open loop by stepper motors. No feedback of the controlled parameter's position is obtained. The Apollo and NASA/Lockheed lenses are gear driven while the Skylab camera has

Table IV-4 Space-Qualified, Remotely-Controlled Zoom Lens Parameters

	Apollo GCTA	Skylab	NASA/Lockheed
Zoom control	Yes	Yes	Yes
Iris control	Yes	Yes	Yes (automatic)
Focus control	(coupled to zoom)	Yes	No
Control mode	Open loop	Open loop	Open loop
Motor type	Stepper	Stepper	Stepper
Drive	Gearhead	Belt	Gearhead
Position feedback	None	None	None
Field of View (diagonal)	9° to 54°	9° to 54°	7° to 55°
Iris range	f/2.2 to f/22	f/4.4 to f/44	f/1.4 max

a belt drive as shown in Fig. IV-4. For the FFTO Visual System it is desirable to have separate control of zoom and focus for operation at close range with high magnification. From this standpoint the Skylab lens has the advantage. However, it is

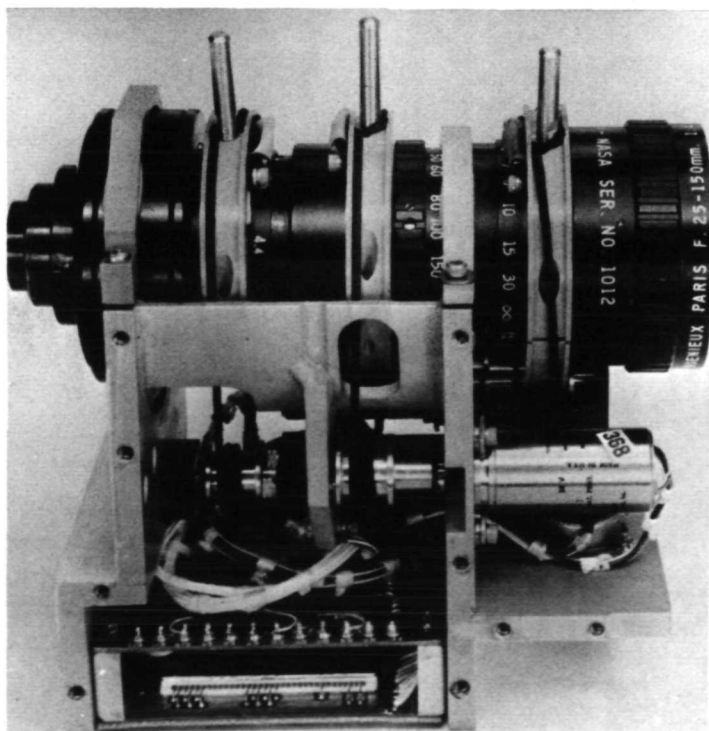


Fig. IV-4 Skylab Camera Zoom Lens

somewhat questionable whether the belt drive allows sufficiently fine control.

B. STEREOSCOPIC SENSOR SUBSYSTEM ANALYSIS

Selection of the proper optics for any given stereo television application first requires consideration of the parameters involved and their influence on the application at hand. Numerous factors come under consideration in the analysis of an optimized stereoscopic television system. Some of the display parameters are necessarily linked to sensor parameters and vice versa. Also, certain visual system parameters are dictated or at least limited by power, weight, volume, or human factors considerations. In light of these considerations we will choose representative values for display-to-viewer distance, approximate display screen size, and TV camera resolution in order to simplify the analysis of an optimized stereoscopic visual display. However, the same parametric analysis can similarly be performed for subsystem components with different characteristics.

1. General Discussion

The objects in the stereoscopic field of view will appear at or behind the display screen provided the two TV cameras comprising the stereo sensor converge at the near end of the desired depth of field. This is important since a scene appearing closer to the viewer than its restricting border is unnatural and consequently disturbing. The objects appear to be floating in space in front of the display console. Stereoscopic perception of such images is not impossible but frequently causes discomfort and image registration difficulties. If the camera fields of view are at least as great as the convergence angle of the camera pair, objects ranging in distance from the camera convergence point to infinity will be properly displayed. As the field of view (FOV) of the cameras is increased, the effective field of view of the system

increases, as illustrated in Fig. IV-5. The broken lines represent the optical axes of the two cameras intersecting at the convergence point, the solid lines represent the individual camera FOV's, and the shaded area represents the usable stereo FOV. It can be seen from this figure that if the FOV of each camera is less than the convergence angle, the usable stereo field becomes finite in range. This situation could easily result from the use of zoom

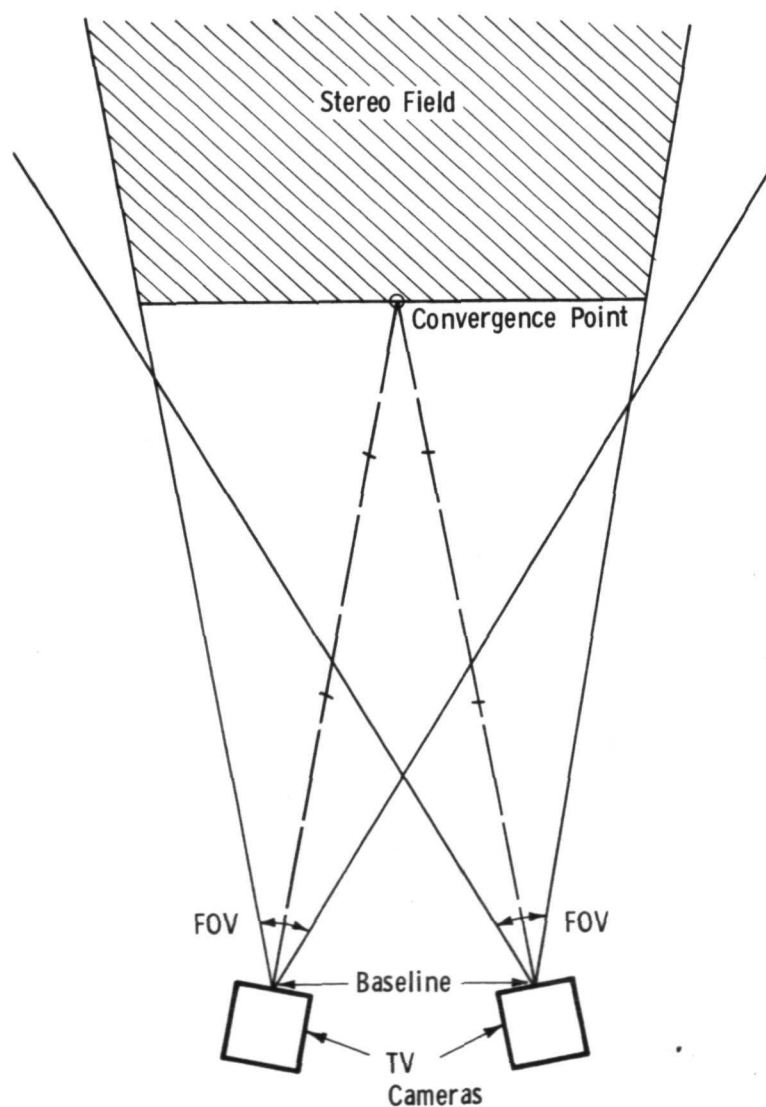


Fig. IV- 5 Visible Stereo Field

lenses. If distances and dimensions are to appear realistic, the convergence point should be the same distance from the cameras as the screen is from the eye and the camera field of view should be equivalent to the visual field of view of the display. Satisfaction of these criteria will result in a display as realistic as the system resolution allows.

A reduction in the field of view, as with zoom lenses or an increase in the stereo baseline, will provide an enhanced view of a smaller volume, but some degree of visual distortion will result due to a conflict between stereoscopic image disparity, eye convergence cues, and apparent field of view. Depth dimensions will be exaggerated and perspective will be distorted. Enhanced depth perception can be of great benefit in tasks where the depth range is small and realism and actual dimensions are not the prime consideration.

As in monoscopic imaging systems, size scaling can also be achieved with a stereoscopic visual system. In monoscopic systems accurate scaling is achieved by changing the object distance while holding the camera field of view and display size constant. A stereoscopic system also requires a fixed field of view and display size for accurate scaling, but now the stereo baseline, in addition to the object distance must be changed by a factor equal to the desired scale factor. For example, if a small 1/10th scale image of a large object is desired, the stereo baseline and the object distance must be increased by a factor of ten while the camera field of view, convergence angle, and display size are held constant. A combination of scaling, depth exaggeration (or suppression) and image distortion will occur if these criteria are not followed.

2. Theoretical Analysis

The following analysis of sensor and display parameters provides a more detailed discussion of the relationships described above and establishes a theoretical basis for this discussion.

a. Stereoscopic Equation Derivation

An approximate solution showing the interrelationships between the stereoscopic sensor and display system is readily obtained if small angle approximations are valid for the convergence angle, β . This primarily specifies that the convergence angle remains less than 15 degrees.

From Fig. IV-6, the object positional difference as viewed from each camera relative to its FOV centerline is given by

$$X_L - X_R \approx R_1 \beta \quad (1)$$

The relationship between the camera baseline, B, and convergence angle, β , again for small β , is given by

$$B \approx R_o \beta \quad (2)$$

The object range, R, is

$$R = R_o + R_1 \quad (3)$$

Substituting Eqs. (2) and (3) into Eq. (1) yields

$$X_L - X_R = (R\beta - B) \quad (4)$$

An additional factor which we will refer to as system gain relates dimensions at the sensor to dimensions at the display. The total

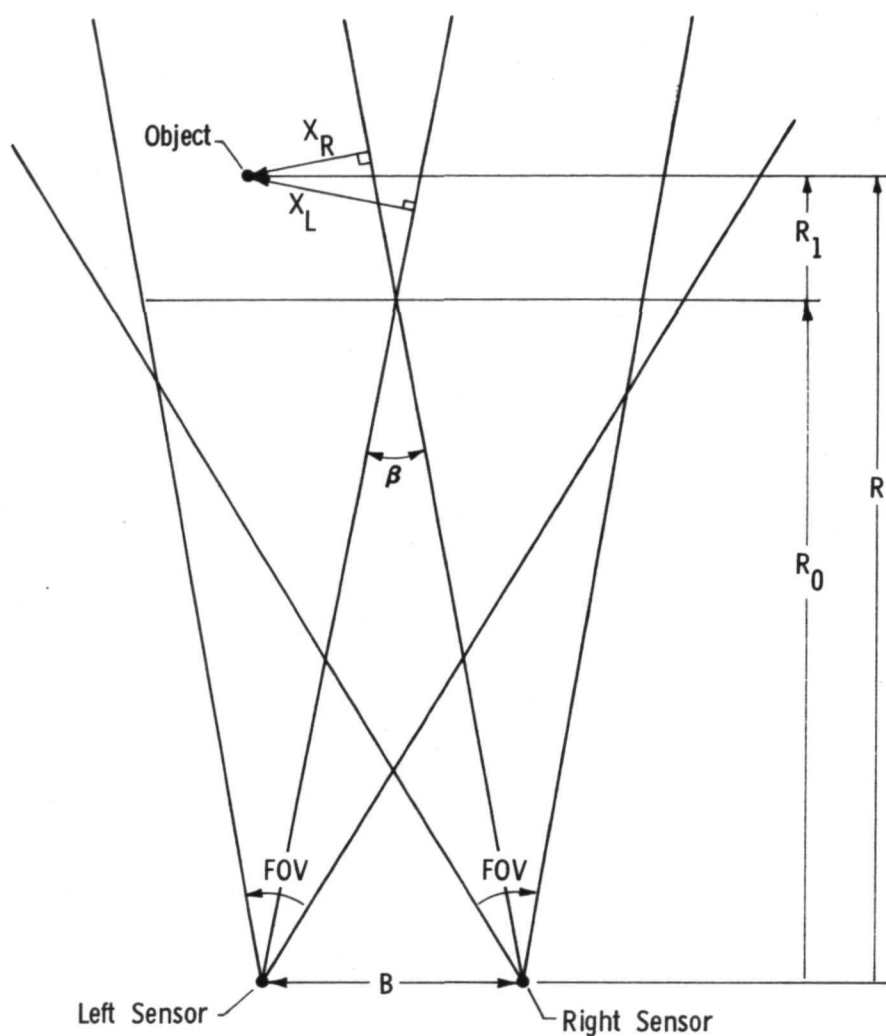


Fig. IV-6 Stereoscopic Sensor Geometry

half view of the camera is given by $R \cdot \tan \frac{FOV}{2}$. This will appear on half the display screen. Hence, the system gain becomes

$$G = \frac{D}{2R \tan(\frac{FOV}{2})} \quad (5)$$

where D is the display screen size. The display displacement, d , of the object position difference is the product of the camera displacement and the system gain. Multiplying Eqs. (4) and (5)

yields

$$d = (R\beta - B) \times \frac{D}{2R \tan(\frac{FOV}{2})} \quad (6)$$

This equation will be used as the basis of establishing the interrelationships between the stereoscopic system parameters. The first term, $(R\beta - B)$ will be selected based upon stereo range and acuity considerations while the second term will be based primarily upon monoscopic resolution and viewing area coverage considerations.

b. Fixed Stereo Sensor Subsystem

First consider a fixed sensor subsystem designed to approximate normal vision as closely as possible. Distant objects must appear distant and near objects must appear the same distance from the viewer as they are from the sensor. Assume, based on Phase I dimension, D , is 25 cm. (10 in) and the viewer-to-display distance, Q , is 53 cm (21 in). The lateral image disparity on the screen, d , must be approximately equivalent to the viewer's interpupillary distance, 6.5 cm (2.5 in), for an object to appear at infinity, and that d must be zero for an object to appear at the display screen. With reference to Eq. (6), as $R \rightarrow \infty$, $(R\beta - B) \rightarrow R\beta$ such that:

$$d_{R \rightarrow \infty} = \frac{\beta D}{2 \tan(\frac{FOV}{2})} \quad (7)$$

Substituting the display and interpupillary dimensions from above yields

$$4\beta = 2 \tan(\frac{FOV}{2}) \quad (8)$$

Combining Eq. (8) and Eq. (6) results in

$$d = (R\beta - B) \frac{D}{4\beta R} \quad (9)$$

This relationship must hold for distant objects to appear distant. This expression, when d is set equal to zero, provides the relationship of the stereoscopic parameters for the object to appear at the display screen. Neglecting an infinite convergence angle and consequently an infinite sensor FOV, then

$$(R\beta - B) = 0 \quad \text{or } B = R\beta \quad (10)$$

For minimum range distortion and maximum realism the display field of view must be equal to the camera field of view. The display field of view is given by

$$\text{FOV} = 2 \tan^{-1} \left(\frac{D}{2Q} \right) \quad (11)$$

Based upon the dimensional data previously assumed, this FOV is 27° and the sensor convergence angle, from Eq. (8), must be 6.8° . Substituting a sensor object range equal to the viewer-to-display distance, 54 cm (21 in), and a convergence angle of 6.8° into Eq. (10) results in a sensor baseline requirement of 6.5 cm (2.5 in). As one would expect, maximum realism is obtained when the baseline of the cameras is equivalent to the viewers inter-pupillary distance.

The above analysis established the recommended set of stereoscopic sensor parameters assuming no parametric variations are permitted. These parameters are summarized below:

Horizontal Display Dimension:	25 cm (10 in)
Viewer - Display Range:	53 cm (21 in)
Sensor Baseline:	6.5 cm (2.5 in)
Sensor Convergence Angle:	6.8°
Sensor Field of View:	27°

The system defined above will result in a display as realistic

as the system resolution allows. Consequently it has many advantages over variable parameter sensor subsystems. One important factor unique to a fixed system is size constancy. It is known from monoscopic television systems experience that size constancy can be an important cue as to range and range-rate information. Another advantage of a fixed system is accurate and constant perspective of the object or scene without distortion. This cue can also aid in the estimation of range and range-rate information.

c. Variable Stereo Sensor Subsystems

The most significant advantage of a variable stereo sensor subsystem is to provide additional stereo depth acuity, often referred to as "enhanced" or "exaggerated" stereo. This results when the sensor baseline exceeds that of normal vision. The major disadvantage is obviously additional system complexity.

In order to determine the stereo depth acuity of a stereoscopic visual system, consider Fig. IV-7. Based upon an angular resolution of the sensors, φ , a monoscopic resolution element, p , can be expressed as

$$p = \varphi R \text{ where } \varphi = \frac{\text{field of view}}{\text{camera resolution}} \quad (12)$$

indicating that the spatial resolution, $1/p$, is inversely proportional to range. The stereoscopic depth resolution element, r , given by

$$r = \frac{2Rp}{B} = \frac{2R^2\varphi}{B} \quad \text{for } \theta \gg \varphi \quad (13)$$

indicates that the stereo depth acuity (or depth resolution), $\frac{1}{r}$, is inversely proportional to the square of the range. The minimum resolvable depth increment, r , as a function of range for the

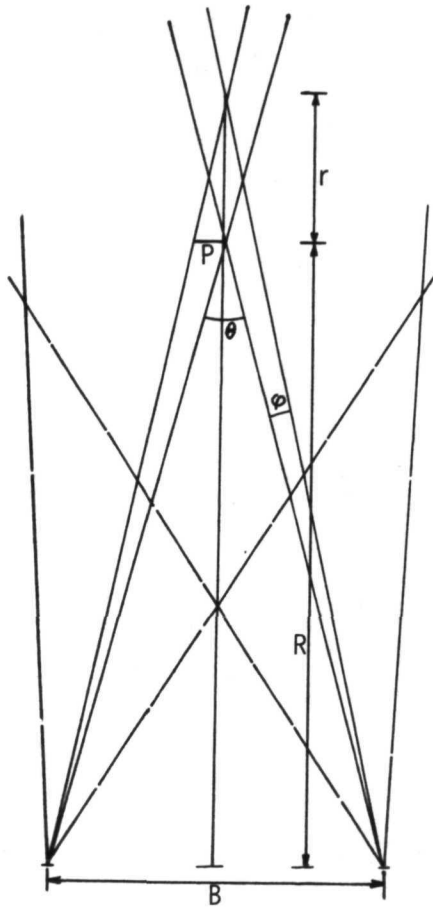


Fig. IV-7 Stereo Depth Acuity Determination

recommended fixed system is shown in Fig. IV-8. In addition, according to Eq. (13), the monoscopic resolution is related to the depth resolution by

$$\frac{B}{2p} = \frac{R}{r} = K \frac{1}{p} \quad (\text{for a fixed baseline}) \quad (14)$$

where $K = B/2$. Fig. IV-9 illustrates how R/r , and consequently $K (1/p)$, varies with the sensor-to-object range. Hence, based upon these curves, the primary disadvantage of a fixed sensor subsystem is that stereo acuity drops off rapidly with range.

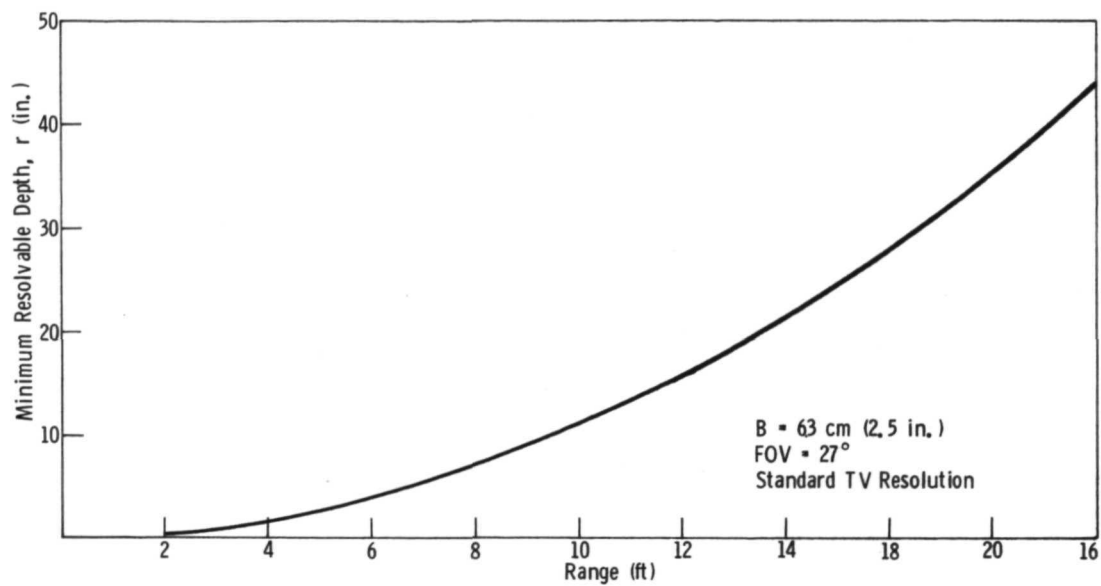


Fig. IV-8 Resolvable Depth Increment

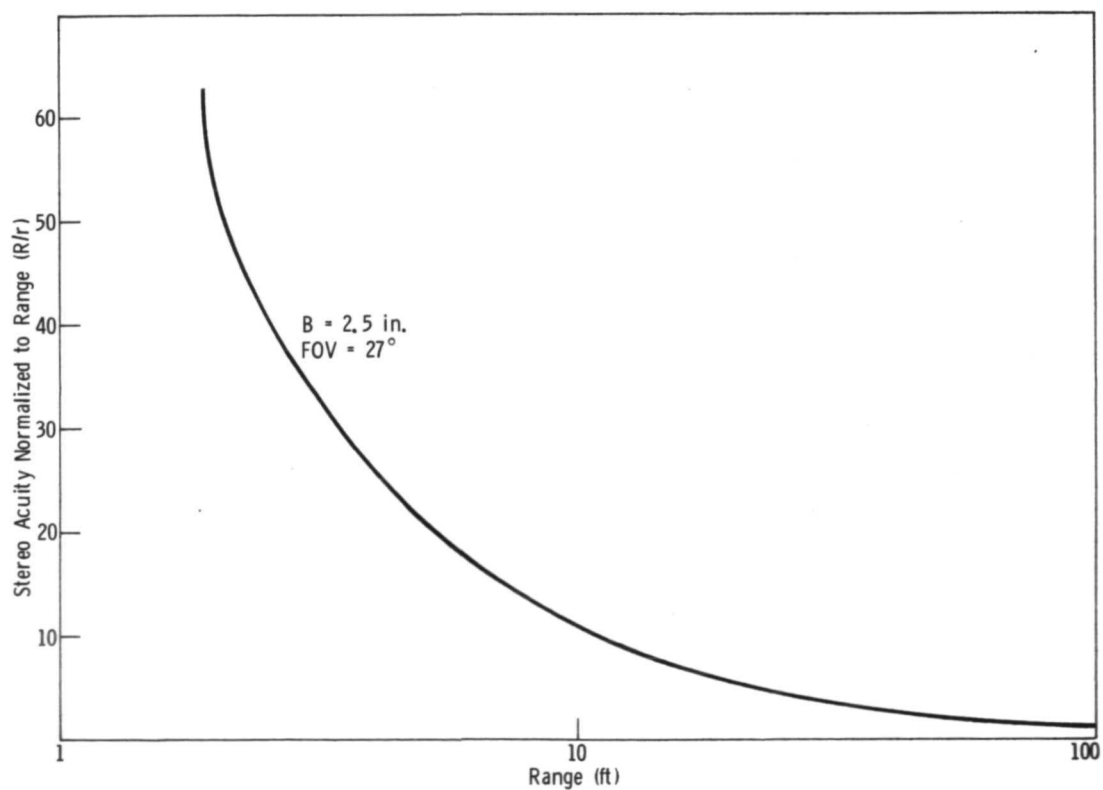


Fig. IV-9 Stereo Acuity of Fixed System

Fig. IV-9 indicates that stereo acuity is minimal beyond ranges of 3 meters (10 ft).

In order to obtain more information about the object under observation, the field of view could be reduced to provide greater resolution or the stereo baseline could be increased to provide greater parallax. The field of view can be easily changed through the use of a zoom lens on each camera, but unless the sensor convergence angle, β , is also changed, the stereo visual range becomes finite. Fig. IV-10, shows the ratio between $R_{\max}$ and R_o as a function of the ratio between β and sensor FOV. It is apparent from this figure that unless the ratio between β and FOV is very nearly that established by Eq. (8), the stereoscopic visual range, $R_{\max}/R_o$, is very small. In order to avoid a finite stereoscopic range one must

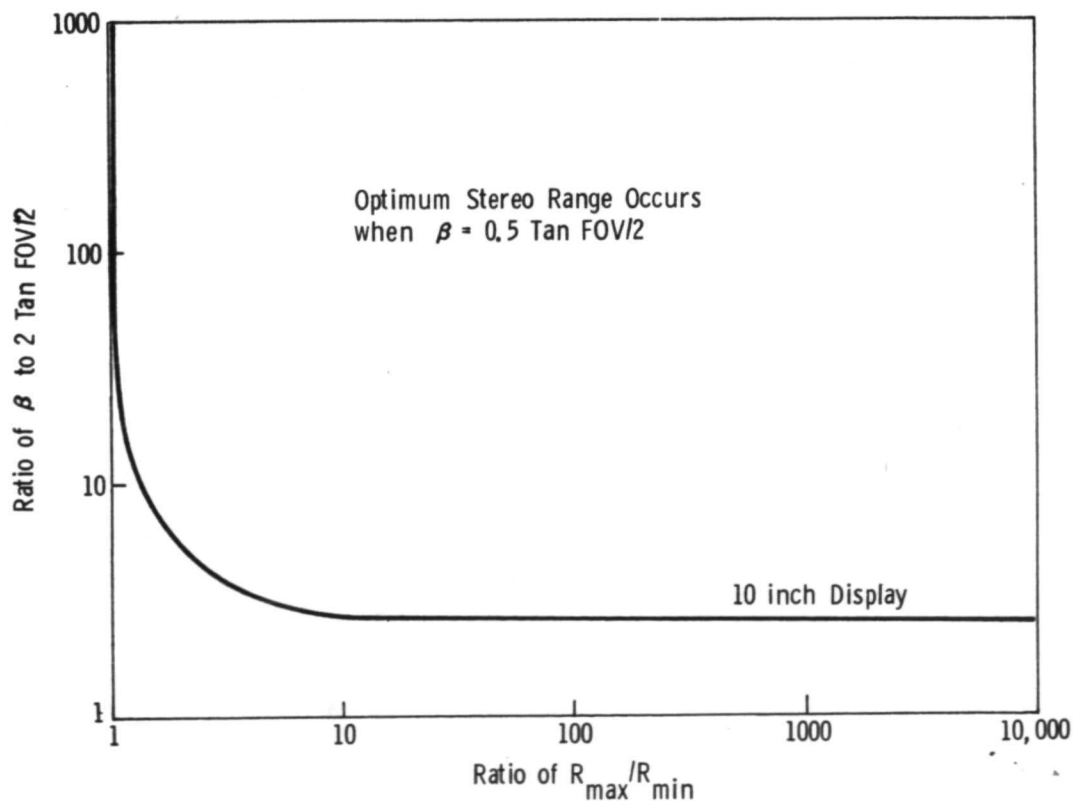


Fig. IV-10 Stereoscopic Range Coverage

hold β in direct proportion to the field of view. This is important not because of the limited stereoscopic visual range itself, but because of the associated undesirable implications.

Failure to maintain an infinite $R_{\max}$ implies lateral image disparities greater than normal interpupillary distances, and dissimilar backgrounds for the right and left eyes. It is known from MMA simulations that both situations can be very disturbing and uncomfortable. Situations do exist, however, where both of these implications are completely eliminated. For example, assume that a wide field of view is acceptable for long range viewing and for teleoperator navigation and approach situations. The zoom capability is then necessary only for close inspection of objects of finite depth. Care should be taken to assure that all potentially disturbing objects subtending the field of view of the camera lie within the range limits defined in Fig. IV-11. Then the camera

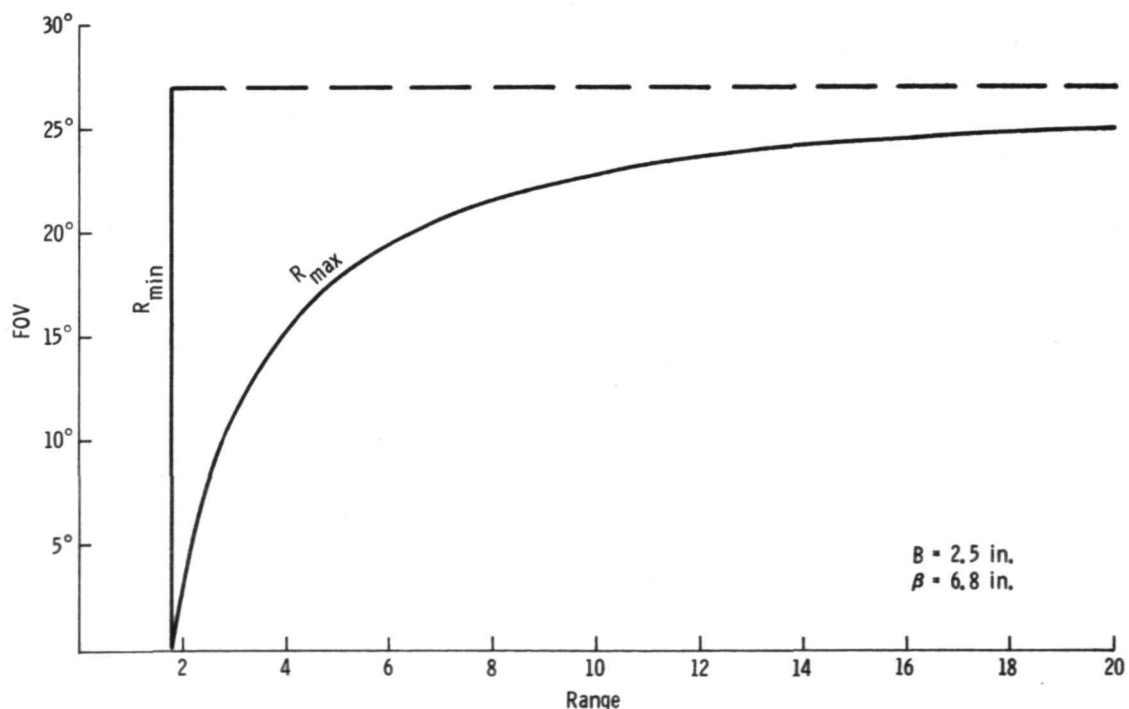


Fig. IV-11 Stereoscopic Range Limits (Fixed System)

lenses can be zoomed to that field of view in order to enhance depth acuity without visual strain or confusion. If these criteria cannot be assured for most near object observations, it is recommended that β be slaved to the field of view. Note that some image distortion will result from unequal sensor and display fields of view, but field of view limits can be set so that the distortion is easily tolerable. These limits must be determined through man-in-the-loop simulations.

The stereo acuity of the variable field of view system described above is again given by Eq. (13). Substituting Eq. (2), (8), and (12) into Eq. (13), the stereo acuity becomes

$$\frac{1}{r} = \left(\frac{\text{camera resolution}}{4 \frac{B}{R_0}} \right) \frac{B}{R} = \left(\frac{244 R_0}{4 B} \right) \frac{B}{R^2} = 61 \frac{R_0}{R^2} \quad \text{or}$$

$$\frac{R}{r} = 61 \frac{R_0}{R} \leq 61 \quad \text{since } R \geq R_0. \quad (15)$$

Eq. (15) states that $\frac{R}{r}$ is maximized when $R = R_0$. In other words, for a given range, the stereo acuity can be optimized by setting R_0 equal to the range of the object under observation. Substituting Eq. (8) into Eq. (2) it can be seen that a 6° to 48° zoom lens will optimize stereo acuity out to a range of

$$R_{0 \text{ max}} = \frac{B}{\beta_{\text{min}}} \approx \frac{2 B}{\tan \frac{\text{FOV}}{2}} \approx 2.4 \text{ meters (8 ft)} \quad (16)$$

It is interesting to note that this system will maintain a constant proportionality between $\frac{R}{r}$ and $\frac{1}{p}$ out to this distance, whereas an increased baseline will increase depth acuity only without increasing monoscopic resolution.

Fig. IV-12 shows $\frac{R}{r}$ as a function of range for a variable field of

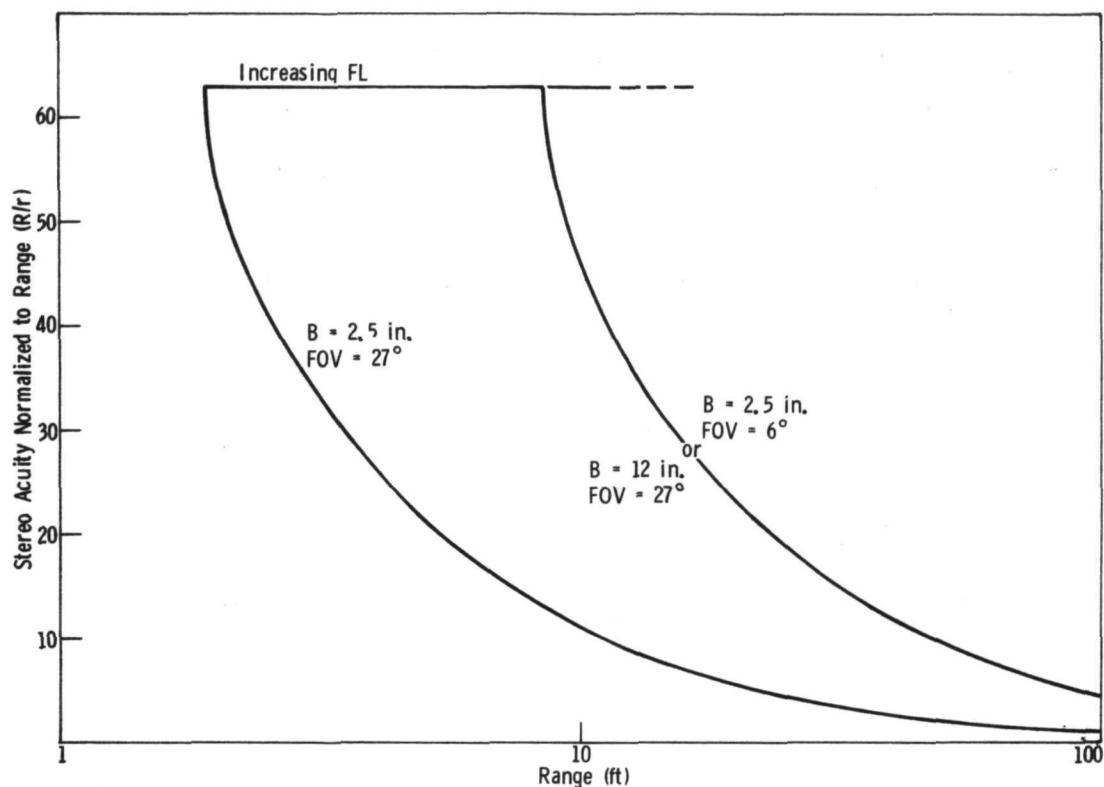


Fig. IV-12 Effect of Variable FOV on Stereo Acuity

view ranging from 6° to 48° and a baseline again fixed at 6.3 cm (2.5 in). Note that once R_o reaches its limit, stereo acuity drops off rapidly.

If β and FOV are fixed, then R_o and consequently stereo acuity, can be increased by increasing the sensor baseline. If the FOV and β are held constant at 27° and 6.8° , as in the fixed system R_o will be related to B from Eq. (8) by

$$R_o = \frac{B}{.12} \quad (17)$$

In order to obtain the same range for R_o as was achieved with a variable 6° to 48° field of view, the baseline must be variable up to $B = (.12) R_o = 0.3\text{m}$ (12 in) as is indicated in Fig. IV-12.

Variation of the baseline alone will increase parallax without magnification resulting in constant monoscopic resolution and an apparent scale reduction between object space and image space without distortion. The scale factor is given by the relationship

$$\text{Image size} = \frac{6.3 \text{ cm (2.5 in)}}{B} \times \text{object size} \quad (18)$$

Hence, as the baseline is increased, the scene is scaled down.

If both the field of view and baseline are variable within the above limits, maximum stereo acuity, again expressed as an increment of range, could be maintained to a range of almost 12 m (40 ft) as shown graphically by Fig. IV-13. For optimum stereo acuity

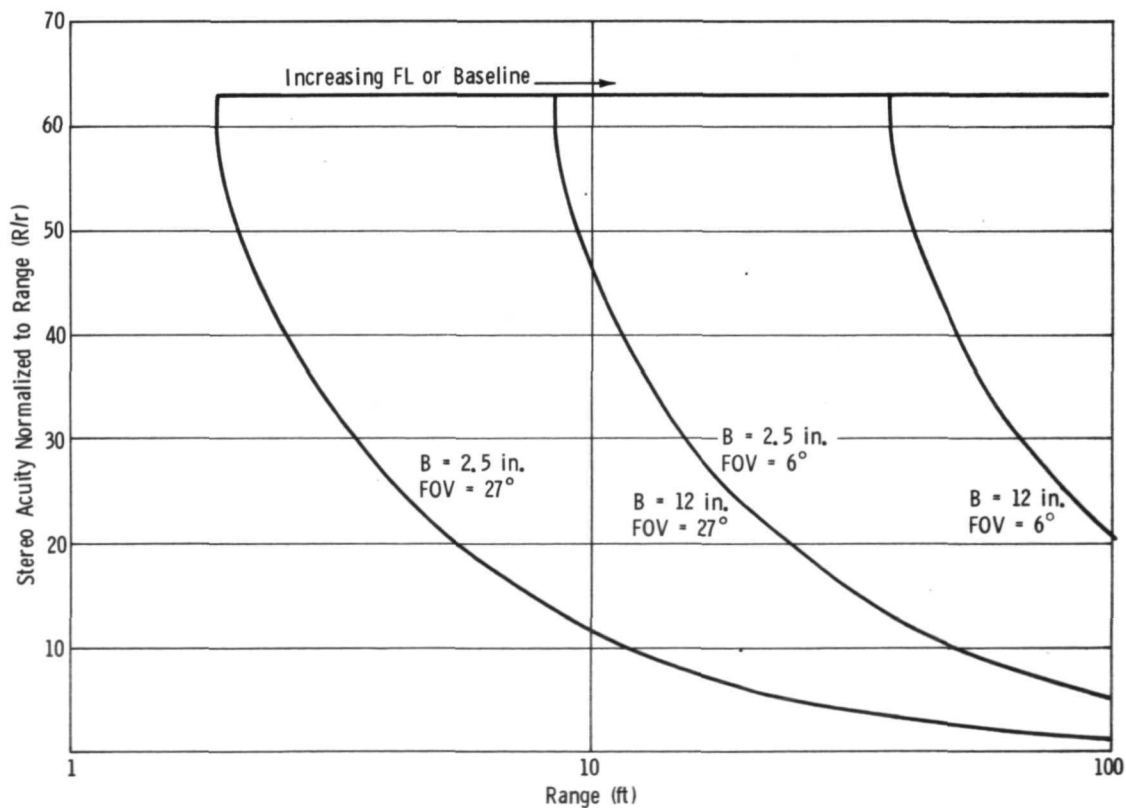


Fig. IV-13 Effect of Variable FOV and Baseline on Stereo Acuity

beyond this distance, the baseline can be increased further, but only at the cost of weight and volume. The need for greater stereo acuity at ranges beyond 3 m (10 ft), as provided by a variable field-of-view sensor must be established through simulations and an analysis of the FFTO tasks as the tasks become more definitive.

d. Sensor Alignment Considerations

The alignment tolerance between the two cameras in the sensor's vertical plane can be determined by using the general stereo parametric equation derived in Paragraph IV.2.a in a vertical rather than horizontal sense. The disparity d becomes vertical disparity δ , the convergence angle β , becomes an elevation angle α , the baseline becomes the vertical displacement h , and D and FOV refer to the vertical display size and sensor field of view respectively. The equation for analysis of vertical alignment, based upon Eq. (6), is expressed as

$$\delta = (Ra - h) \frac{D}{2R \tan \frac{FOV}{2}} \quad (19)$$

For a fixed allowable δ , and assuming a fixed display size and range, it can be seen that the tolerances required of α and h become more critical as the field of view is decreased and, for zero vertical disparity, α and h should be zero. Zero disparity can also be achieved as long as $h = Ra$ (provided h is small compared to R). However, as h approaches R , differences in vertical perspective will cause confusion and discomfort. For this reason, a tight tolerance on α could be used to compensate for a loose tolerance on h . For any given h the required elevation angle tolerance, $\Delta\alpha$, can be expressed as

$$\Delta\alpha = \left(\frac{\delta_{\max}}{D} \right) 2 \tan \frac{FOV}{2} \quad (20)$$

It is also recommended that the sensor baseline and convergence

angle meet the same horizontal tolerances as h and α in the vertical direction such that these relationships, discussed previously, are satisfied within these tolerances.

Consideration must also be given to differences in the fields of view of the two cameras if zoom lenses are used. The relationship between δ and the display size will be the same as that between the field of view gradient and the field of view. Thus,

$$\frac{\delta}{D} = \frac{\Delta \text{FOV}}{\text{FOV}} \quad (21)$$

The allowable field of view tolerance must be held to assure a total disparity $\delta \leq \delta_{\max}$. The field of view tolerance can then be written as

$$\Delta \text{FOV} = \frac{\delta_{\max} \text{FOV}}{D} \quad (22)$$

If identical tolerances are specified for both cameras in the sensor subsystem, then each camera must be restricted to one half of the specified values for Δh , $\Delta \alpha$, ΔB , $\Delta \beta$ and ΔFOV .

e. Theoretical Analysis Summary

Several parameters must be optimized in order to obtain accurate stereoscopic vision using a television system. The stereo baseline, the camera field of view, the convergence angle, the display size, and the viewer-to-display distance can all be balanced to provide a stereoscopic image as realistic as the system resolution allows. This balance occurs when the sensor subsystem parameters are matched to the corresponding parameters in the display. It should be emphasized, however, that realism and accurate perspective are not always the prime consideration. Variation of a given parameter may significantly enhance the performance of a remote task while

introducing an insignificant distortion of the image. The actual influence of sensor alignment and variation of stereoscopic visual system parameters must be determined through man-in-the-loop simulations.

3. Stereoscopic Sensor Simulations

In order to more accurately determine the actual influence of the various stereoscopic parameters on viewer comfort and performance, a series of man-in-the-loop simulation studies were conducted. These simulations concentrated primarily on the effects of changing the camera convergence angle, the stereo baseline, and the camera field of view. As pointed out earlier in this section, variations of any one of these parameters, without proper balance of the others, may result in greater than normal aspect angles for near objects and/or negative aspect angles for distant objects. Table IV-5 identifies, based upon the theoretical analysis, the effect of the stereo sensor parameters on the maximum stereoscopic visual range, the ratio between minimum and maximum stereo visual range, the stereoscopic acuity, and the monoscopic acuity or resolution. The objective of the simulation studies was to determine, with respect to the above parameters, the limits and ranges of stereo vision and their effect on operator performance.

Table IV-5 Effects of Stereo Sensor Variables

Maximum Stereo Range	Increase Convergence	Increase Baseline	Decrease FOV
	Decrease	Increase	Decrease
Stereo Min. to Max. Ratio	Decrease	--	Decrease
Stereo Acuity	--	Increase	Increase
Monoscopic Resolution	--	--	Increase

The simulation study was divided into four phases to establish the following: (1) the lateral disparity limits; (2) the maximum "comfortable" object view as related to sensor baseline and angle; (3) the relative merits of a variable FOV stereoscopic sensor subsystem, and (4) the magnitude of allowable vertical disparity (i.e. sensor alignment requirements).

a. Lateral Disparity

The maximum and minimum lateral disparity acceptable to the viewer was investigated using a special purpose video synthesizer (described in detail in Section VII, Display Subsystem) and a typical three dimensional object (rectangular block).

The special purpose video synthesizer has the capability, when used with the stereo display, to generate a 2 dimensional spot on the display which may be moved in 3 dimensional space. The third dimension (depth) is controlled by varying the lateral disparity "d" on the display. This in turn controls the viewer's eye convergence angle. By fixing the viewer to display distance, knowing the viewer's interpupillary distance, and measuring the lateral disparity on the display, the viewer's eye convergence angle may be determined.

Basically, the spot separation was increased such that the subject's eye convergence angle decreased until the subject said that he could either no longer retain a stereo image or the stereo image was disturbing. Then the spot separation was decreased to zero and then increased such that spot appeared in front of the fresnel until the subject again reported loss of the stereo image or the image was disturbing. These tests were performed several times on each test subject until the subjects' two limits were stable.

The results of the simulation indicated that most of the test

subjects could not resolve or retain the stereo image when the disparity exceeded their interpupillary dimension. Those subjects retaining the image in stereo, all commented that a noticeable ocular disturbance existed once the interpupillary distance was exceeded.

At the other end of the display disparity region, where $d = 0$, there were large variations among test subjects. This was attributed to the varying ability of the test subjects to separately control eye convergence angles and focus accommodation. This is a result of the stereo display characteristics which focuses the image on the display and thereby requires the eye accommodation to remain constant independent of image disparity. Further tests using the three-dimensional object indicated that objects which appear to pass through the fresnel lens are disturbing.

Based upon the simulations, the acceptable lateral disparity agrees with that analytically assumed in that the maximum disparity should be restricted to the viewer interpupillary distance and the lower disparity limit should produce a stereo image on, or behind, the display screen.

b. Sensor Baseline/Convergence Angle

Due to the interrelationships between object distance, camera baseline, and camera convergence angle, and the general scene characteristics, the first portion of this study was separated into two basic categories; 1) a single rectangular block in the entire scene and 2) a complex scene with many three-dimensional objects of varying size, complexity and contrast ratios, as shown in Fig. IV-14, which were positioned randomly in the three-dimensional view of cameras. Within these two categories two separate tests were run. The first retained a constant baseline while the convergence angle was varied over the working range dictated by the maximum and minimum lateral disparity limits previously established.

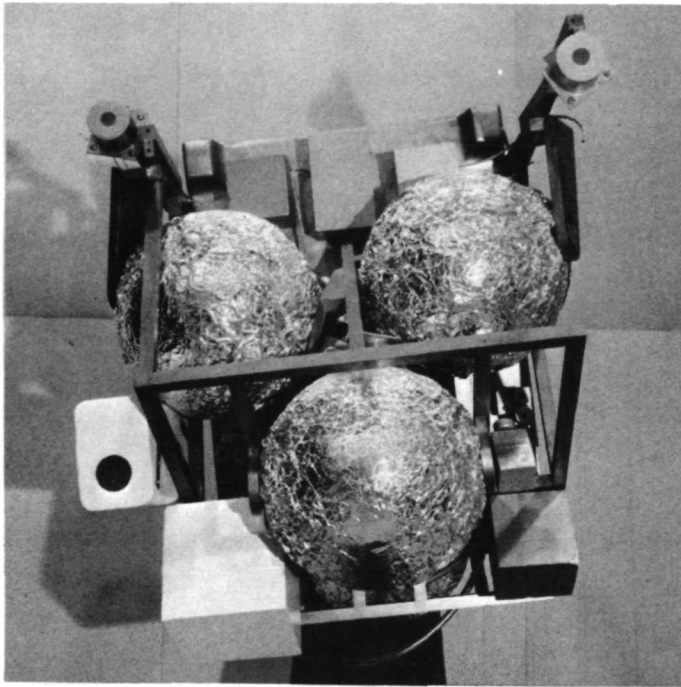


Fig. IV-14 Complex Three-Dimensional Object

Then the baseline was changed and again the convergence angle was varied until the test subject found the scene disturbing to view. The second test was essentially the converse of the first in that the convergence angle was fixed and the baseline was varied within the prescribed lateral disparity limits. The camera configuration used for the tests is shown in Fig. IV-15.

Due to the completely subjective nature of the data, there was a noticeable variance both within and between subjects. This was readily apparent when one subject did not find the view disturbing with the convergence angle much larger than that acceptable to the other test subjects. However, further testing of this subject indicated that his stereo acuity was very poor at the larger convergence angles.

The generalized results from these tests are:

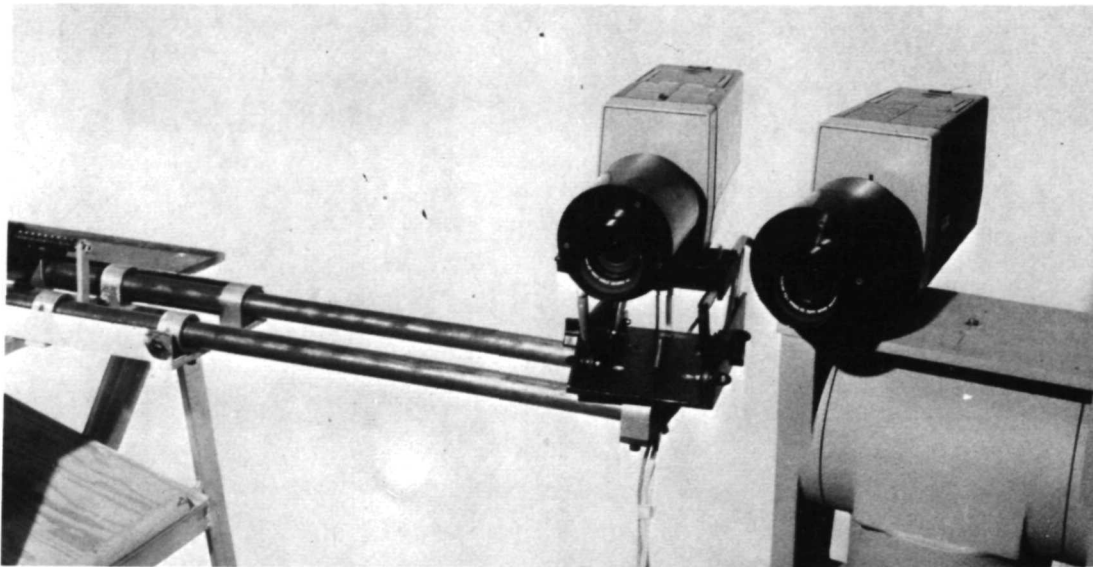


Fig. IV-15 Simulation Camera Configuration

1. A short training period shows a significant improvement in the test results.
2. Although baseline to object distance is the primary consideration when concerned with the aspect angle, limiting the convergence angle may be used to retain an acceptable aspect angle because fixing the convergence angle fixes the stereo working range for any given baseline.
3. Convergence angles up to and including 15° cause no noticeable eye strain or ocular disturbances for the test subjects, regardless of the scene characteristics.
4. As the convergence angles are increased above 15° , complex three-dimensional scenes are less disturbing than scenes with a single three dimensional object floating in the camera view. This is probably due to the complex scenes being the more normal scene that is viewed in the real day to day environment.
5. Convergence angles greater than 20° were found to be either disturbing or the subject lacked stereo acuity. This remained true for all subjects tested with three-dimensional objects in

the scene and over the entire stereo field-of-view. This result was apparently independent of the baseline to object distance ratio within the stereo working range.

The significant conclusions established are (1) a short training session using the stereo system is recommended and (2) by restricting the convergence angle to less than 15° , no disturbing aspect angle should be encountered.

The second portion of this phase involved the use of a CRL model L manipulator and a task panel as shown in Figs. IV-16 and IV-17. The test subjects used for these tests were experienced manipulator operators who use the CRL Model L manipulator on a daily basis in MMA's Environmental Effects Lab.

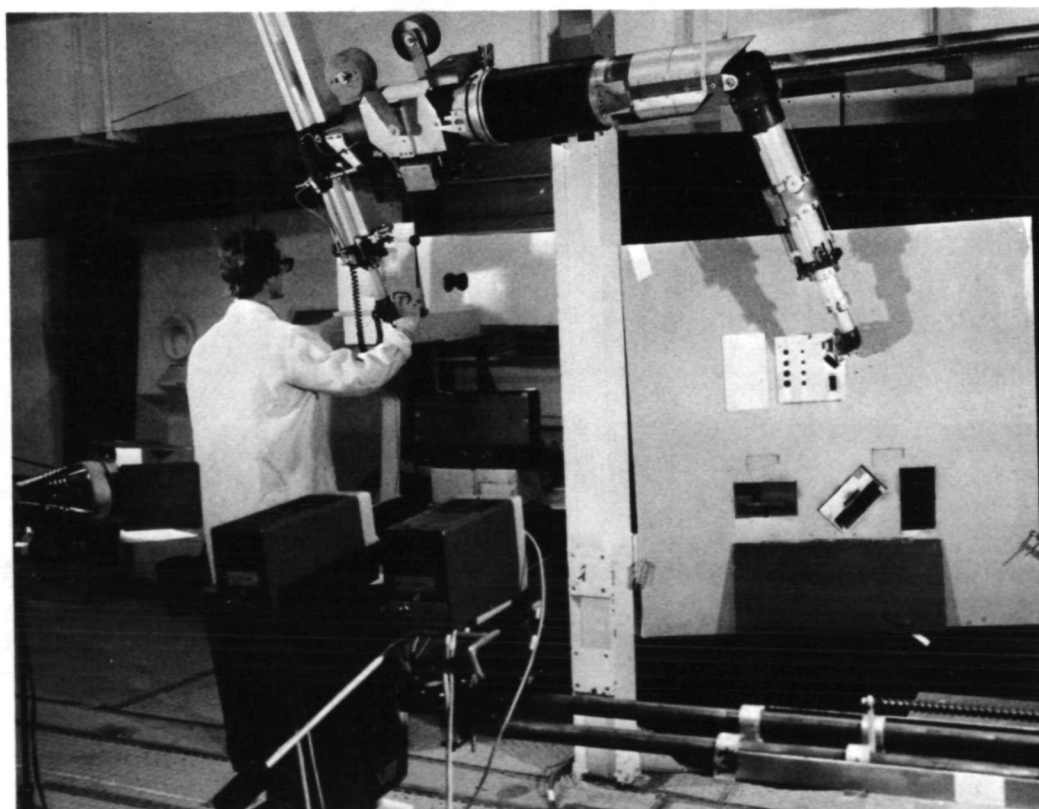
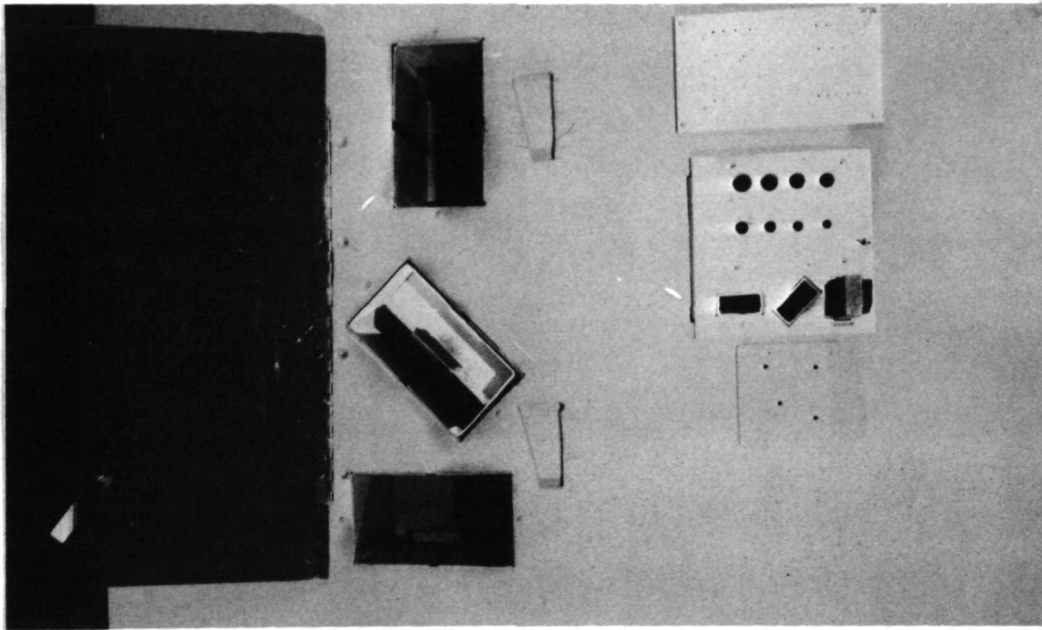


Fig. IV-16 Manipulator Task Test Set-Up



Fig, IV-17 Task Panel For Manipulator Study

A task panel was made from aluminum and oak and mounted on a plywood panel as shown in Figure IV-17. The task consisted of inserting an oak block 1.9 cm (0.75 in) by 4.4 cm (1.75 in) by 23 cm (9 in) into each of three holes that were 0.16 cm (1/16 in) larger than the blocks and oriented 0 deg. (0 rad), 45 deg (0.785 rad) and 90 deg (1.571 rad) off the horizontal.

The task panel was located 2.5 meters (8 ft) from the sensor package, and the baseline was varied from 15 to 60 cm (6 to 24 in). Each time the baseline was changed, the convergence angle was adjusted so that the line of sight of the two cameras intersected at a distance of 1.81 meters (6 ft) from the cameras. The relationships between the baseline and the convergence angles used in this study are listed in Table IV-6. The camera horizontal FOV was fixed at 24° .

The results of these tests are shown in Fig. IV-18. It should be noted that as the baseline and convergence angle increase, the

Table IV-6 Simulation Baseline/Convergence Angles

Baseline	Convergence
15 cm (6 inches)	4.8°
30 cm (12 inches)	9.6°
45 cm (18 inches)	14.4°
60 cm (24 inches)	19.0°

task time decreases until the baseline equals about 45 cm (18 in) (convergence angle is about 15°). Any further increase in baseline and convergence angle causes a sharp rise in task time. The decrease in task time as the baseline increases is due to the increase in stereo acuity. However, when the baseline exceeds 45 cm (18 in) (convergence angle greater than 15°) the aspect angle is too large, as predicted in phase one, and the picture as seen by the operator becomes disturbing. This was further evidenced by the test subjects reporting that the scene was difficult to view and sometimes appeared as a double image.

c. Variable Field-of-View

In order to determine the relative merits of a variable FOV stereo

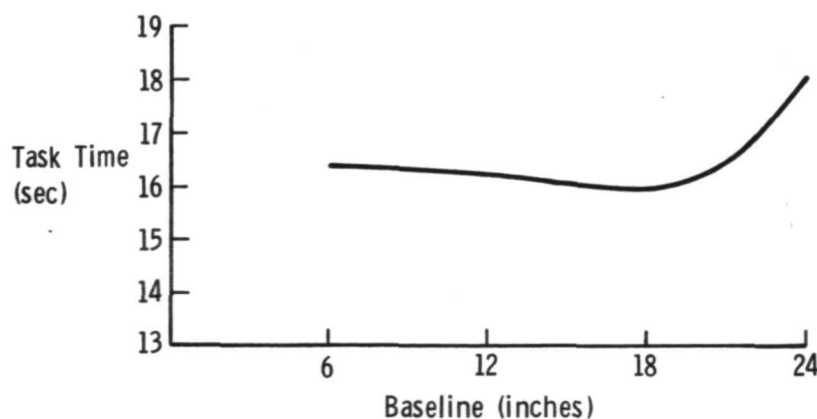


Fig. IV-18 Variable Baseline Simulation Results

system and correlate the results with previous data, the test set up and task was kept the same as in the baseline/convergence study. The baseline was fixed at the minimum of 15 cm (6 in) and the FOV was adjusted such that a 24° FOV was included as one of the test FOV's.

The results of this study are shown in Fig. IV-19 and indicate that for a dexterous manipulative task, the minimal image distortion encountered with a narrow sensor field of view is of little importance in light of the increased stereo acuity and monoscopic resolution.

d. Sensor Angular Alignment

Visual system simulation studies were conducted using both computer generated scenes and real scenes to determine the acceptable magnitude of vertical disparity, δ max. These studies indicated that the vertical disparity δ max should not exceed 0.076 cm (0.03 in) for the viewer to display distances involved here (18 to 24 in). A vertical disparity of 0.152 cm (0.06 in) was tolerable but required a short adjustment time of about 20 seconds. It is therefore recommended that δ max be confined to a tolerance of ± 0.076 cm (0.03 in). This represents approximately 2 TV scan lines.

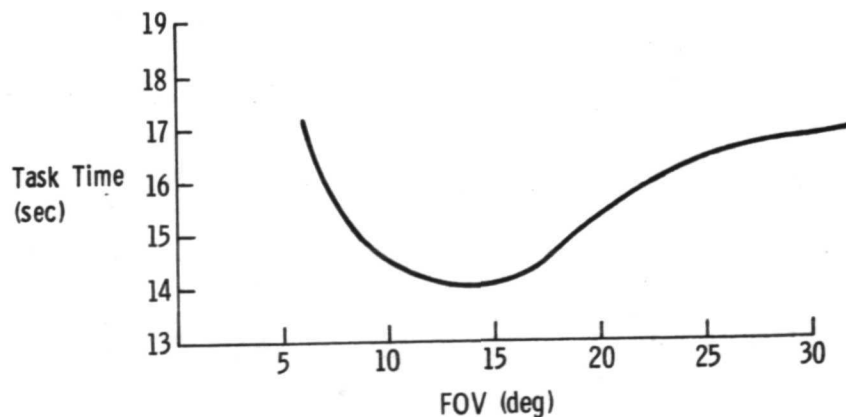


Fig. IV-19 Variable FOV Simulation Results

e. Simulation Summary

Variation of certain parameters in a stereoscopic sensor subsystem can significantly enhance the visual information relayed to the viewer and improve his performance of a remote task without introducing significant image distortion. A reduction in field of view (zoom) increases both monoscopic and stereoscopic acuity while an increased stereo baseline increases stereo acuity only. The camera convergence angle has little impact on task performance or visual acuity, but should be maintained within certain limits dictated by the baseline and camera field of view.

Since variation of camera baseline and convergence provide little improvement in the sensor subsystem capabilities, the sensors should be fixed with a variable FOV capability for minimum complexity. However, as the characteristics of the FFTO and its associated tasks become more clearly defined, further consideration should be given to the variation of parameters other than field of view.

C. RECOMMENDED SENSOR SUBSYSTEM

The visual system sensor presently recommended for both monoscopic and stereoscopic viewing is the Apollo GCTA camera, based upon its proven space-qualified applications. This camera can be used essentially "as is" with only minor modifications which include monochrome conversion and zoom and focus control separation.

The stereoscopic sensor system parameters recommended, based on the relatively low merit of varying either the sensor baseline or convergence angle, and the high merit of varying the field of view, are as follows:

Stereo Baseline: 6.4 cm (2.5 in)

Sensor Convergence Angle: 6.8°

Field of View: 9° to 54° variable

The stereo baseline may be increased slightly to accommodate the physical dimensions of the camera with very little impact on the performance of the visual system. These specifications are based on a 25.4 cm (10 in) horizontal display dimension and a viewer to display distance of 53 cm (21 in) and will provide a general purpose visual system as realistic as the system resolution allows with the versatility of providing increased resolution and stereo acuity when desired.

V. ILLUMINATION SUBSYSTEM

Phase I Summary: Phase I illumination studies indicated that the illumination requirements for the visual system were strongly influenced by the TV sensor sensitivity, the target reflectivity and range, the work site contrast ratio, and the 40 footlambert requirement specified in the statement of work. As a typical example it was shown that for the NASA/Lockheed color camera, about 775 watts of electrical power would be required to illuminate a 44 degree field at 6.1 m (20 ft) with a concentrated tungsten-halogen lamp. For the same camera modified for monochrome operation, only 62 watts would be required. Passive lighting techniques were also proposed in anticipation that one or more of these techniques could be used to conserve power under certain viewing conditions.

Phase II Emphasis: The primary illumination subsystem effort was directed towards analyzing in-depth methods to improve the overall illumination efficiency.

A. PASSIVE ILLUMINATION

The discussion of illumination in Phase I emphasized the possibility of using passive illumination techniques to reduce or eliminate the power consumption of artificial lamps whenever possible. Since the direction of incident sunlight with respect to a given FETO task area in space cannot be predicted, a very general approach to passive illumination is necessary. The following paragraphs discuss the merits of using a diffusely reflecting sphere or section of a sphere to reflect sunlight onto the task area or work site under observation. A sphere was chosen primarily because of its omnidirectional geometry and simplicity.

1. Theoretical Analysis

A diffusely reflecting sphere illuminated by a distant source will reflect light through a very wide field. The primary consideration for passive lighting applications is the amount of light which will be reflected by the sphere onto a portion of the task panel or work site under visual observation. The illumination incident

on any incremental area of the work site can be experimentally measured by substituting a light meter in place of that surface increment. The following analysis gives a theoretical prediction of the illumination reflected by the sphere into the solid angle subtended by the light meter or detector.

Assume a perfectly diffuse sphere with reflectivity R being illuminated with irradiance H from a distant source as shown in Fig. V-1. The surface brightness at any point with coordinates (α, β) is given by

$$L(\alpha, \beta) = RH \cos\alpha \cos\beta$$

Note that for a distant source, brightness is dependent only on α and β , and is independent of the radius r and the angle of observation ϑ . The effective area of an element dA viewed at an angle ϑ to the incident light is

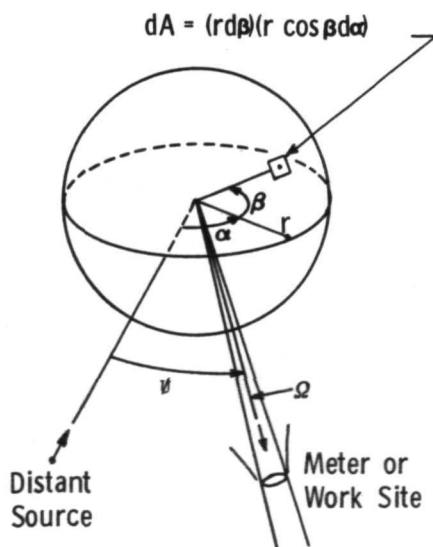


Fig. V-1 Diffusely Reflecting Sphere

$$dA' = dA \cdot \cos\beta \cos(\alpha - \psi)$$

Therefore, the power emanating from an infinitesimal surface element dA into a solid angle Ω at an angle ψ from the direction of incident light is given by

$$d^2P_{\Omega} = L \Omega dA' \text{ or}$$

$$d^2P_{\Omega} = RH \Omega \cos^2\beta \cdot \cos\alpha \cos(\alpha - \psi) dA = RH \Omega r^2 \cos^3\beta \cos\alpha \cos(\alpha - \psi) d\alpha d\beta$$

The total power emanating from the sphere is then

$$P_{\Omega} = RH \Omega r^2 \int \cos^3\beta d\beta \int \cos\alpha \cos(\alpha - \psi) d\alpha$$

The limits on α are set by the portion of illuminated sphere as seen from the meter, e.g. from $\psi - \pi/2$ to $\pi/2$. The limits on β set in the same manner are $-\pi/2$ to $\pi/2$. The expression for the total light emanating from the sphere into a solid angle Ω then becomes

$$P_{\Omega} = RH \Omega r^2 \int_{\psi - \pi/2}^{\pi/2} \cos^3\beta d\beta \int_{-\pi/2}^{\pi/2} \cos\alpha \cos(\alpha - \psi) d\alpha$$

Integrating and substituting the limits yields,

$$P_{\Omega} = \frac{4}{3} RH \Omega r^2 \left[(\pi/2 - \psi/2) \cos\psi + \frac{1}{2} \sin\psi \right]$$

This expression for P will hold true for a diffuse sphere as long as the source, the object, and the detector in Fig. V-1 lie in the plane of the paper and r and Ω are small compared to the source and detector ranges.

In order to determine the merits of a diffusely reflecting sphere as a passive lighting technique, let us assume a worksite at distance D from a 0.3 m (1 ft) diameter sphere, with a reflectivity of 0.8 illuminated by the sun. The equation for the incident light per square foot on the worksite due to the sphere is approximately:

$$P = \frac{4(13000)(.8)(.5)^2}{3 D^2} \left[\left(\frac{\pi}{2} - \frac{\psi}{2} \right) \cos \psi + \frac{1}{2} \sin \psi \right]$$

$$P = \frac{3470}{D^2} \left[\left(\frac{\pi}{2} - \frac{\psi}{2} \right) \cos \psi + \frac{1}{2} \sin \psi \right]$$

Figure V-2 shows the results of this equation in ft. candles as a function of the incident angle of light on the sphere with respect to the LOS of the camera (ψ) for D equal to 0.61 m (2 ft), 1.83 m (6 ft), 3.05 m (10 ft), and 6.1 m (20 ft). Also plotted on this graph is the intensity of the direct sunlight incident on a work task sight which is assumed to be normal to the LOS of the camera.

It can be seen that the 40 footlambert requirement specified in the statement of work is satisfied for work sight distances up to about 2 meters (6.5 ft) as long as the worksite is totally shadowed ($\psi \leq 90^\circ$). As ψ increases beyond 90 degrees the worksight is illuminated by direct sunlight in addition to light reflected by the sphere. In this case the contrast ratio between illuminated and shadowed areas increases sharply, and the working contrast ratio of the TV cameras becomes a critical factor. It was decided that further investigations should be made to determine the impact of the television sensor characteristics through laboratory simulations. The following paragraphs describe these illumination simulations and their results.

2. Illumination Simulations

a. Purpose - Simulations were conducted to determine if available

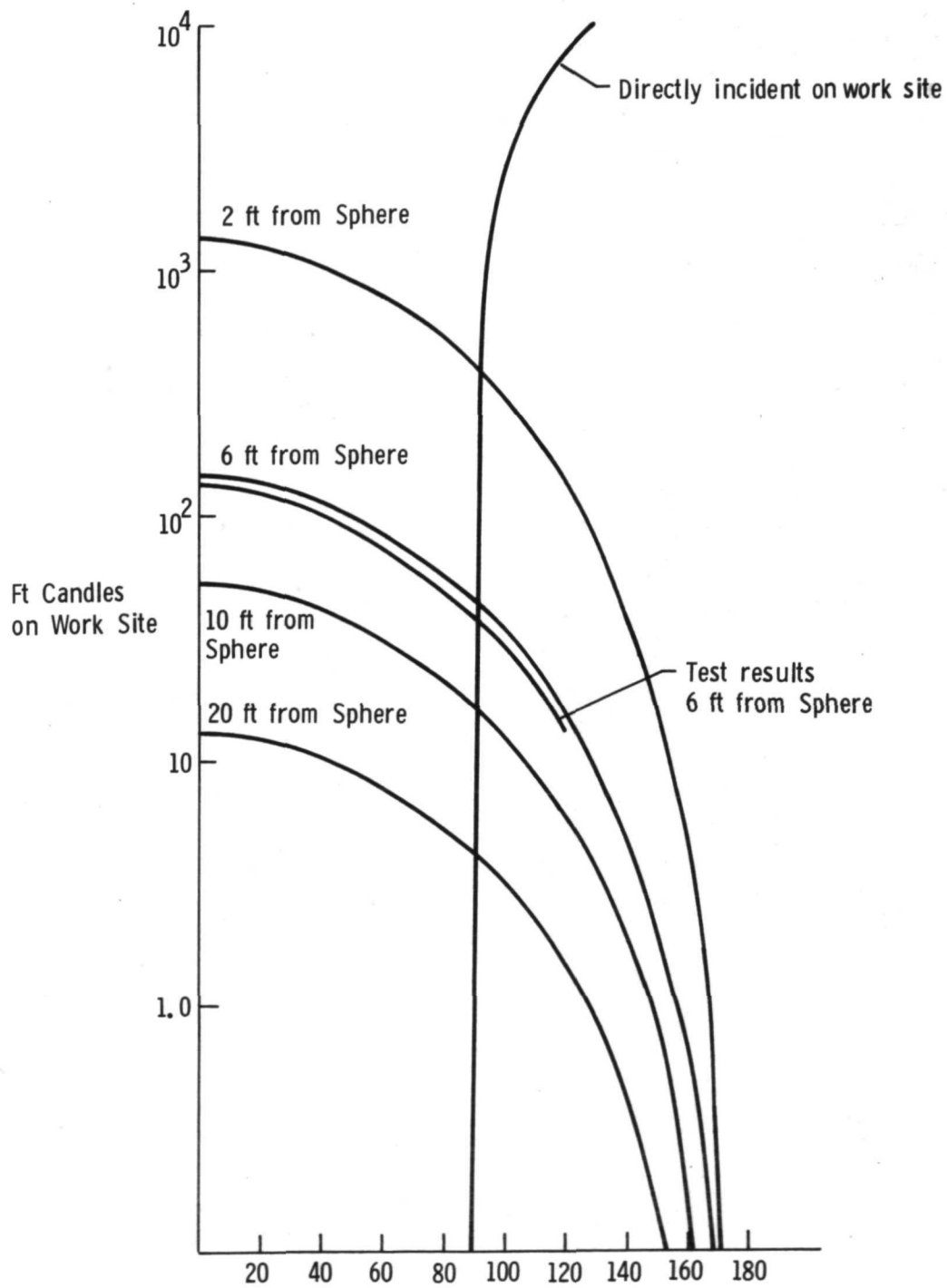


Fig. V-2 Passive Lighting Results

light may be used to illuminate the work site under two different conditions: 1) the work site is oriented such that the sun is incident on the back of the work site and the work site is therefore, totally shadowed and 2) the work site is oriented such that a portion of the work site is illuminated by the sun and the rest of the work site is shadowed.

b. Method - These simulations are separated into three phases:

1) determine the working contrast ratio of the TV system, 2) determine the merits of a diffuse reflector to light the worksite when the worksite is totally shadowed, and 3) determine the merits of a diffuse reflector to fill the shadows of a partially illuminated and partially shadowed worksite.

c. Apparatus -

- LDH-0050 TV camera
- 25-mm lens
- Audiotronics MMH-10 TV monitor
- task panel with three-dimensional characteristics and a 0.2 coefficient of reflectivity
- one fixed intensity spotlight and one variable intensity spotlight
- a one foot diameter ball painted flat white with a reflective coefficient of 0.84

d. Phase I - Determine the working contrast ratio of the TV system.

By illuminating the task panel at a 45° angle with a spotlight, a dark shadow is produced. Then by orienting the variable intensity spotlight so that it illuminates the shadowed area, the contrast ratio may be varied. The view of the task panel is then displayed on a TV monitor and by increasing the intensity of the variable spotlight the working contrast ratio of the TV system is determined.

Based upon subjective considerations, the following results were established:

1. First definition in the shadow.

Contrast ratio on the task panel equals 37.5 : 1

2. "Minimum working" definition in the shadow.

Contrast ratio on the task panel equals 22.6 : 1

3. "Best" definition over entire task panel.

Contrast ratio on the task panel equals 9 : 1

Figures V-3,4 and 5 illustrate these results.

e. Phase II - Determine the merits of a diffusely reflecting sphere to passively light the worksite.

This phase considered two cases: 1) when the site is totally shadowed from direct sunlight, and 2) when the site is partially shadowed and partially illuminated by direct sunlight.

Tests were run using a 30.48 cm (1 ft) diameter diffuse sphere with a reflectivity of 0.8. The sphere, shown in Fig. V-6, was illuminated by sunlight and measurements were taken to determine the amount of light reflected onto a task panel 2 meters (6.5 ft) from the sphere. The readings corresponded closely to those theoretically established.

When the sun was incident on both the sphere and the worksite, the contrast ratio on the worksite was calculated to be:

$$C_{\text{ratio}} = \frac{\text{Indirect from Sphere} + \text{Direct Sunlight}}{\text{Incident from Sphere}}$$

The contrast ratio must be less than 25 in order to satisfy the sensor requirements for good definition throughout the scene. The requirement cannot be satisfied with a 0.61 meters (2 ft) diameter sphere at distances greater than 2.0 meters (6.5 ft) when the angle of incident sunlight (θ) is in the 90 to 180 degree quadrant.

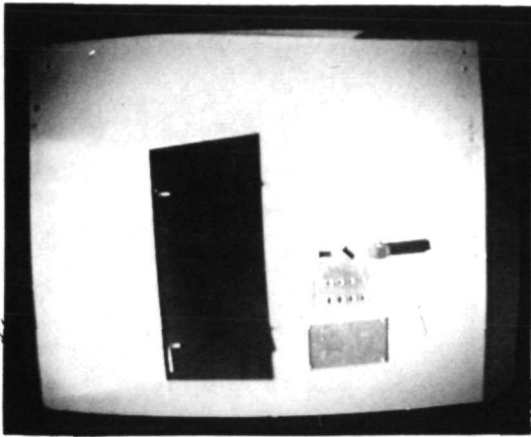


Fig. V-3 First Definition

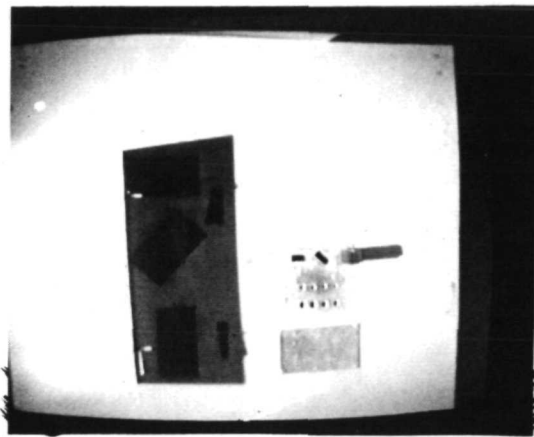


Fig. V-4 Minimum Working Definition

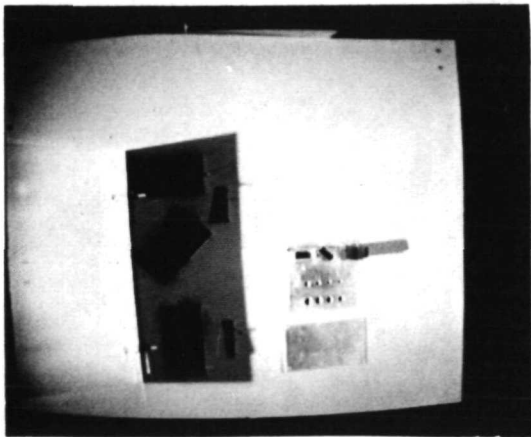


Fig. V-5 Optimum Definition

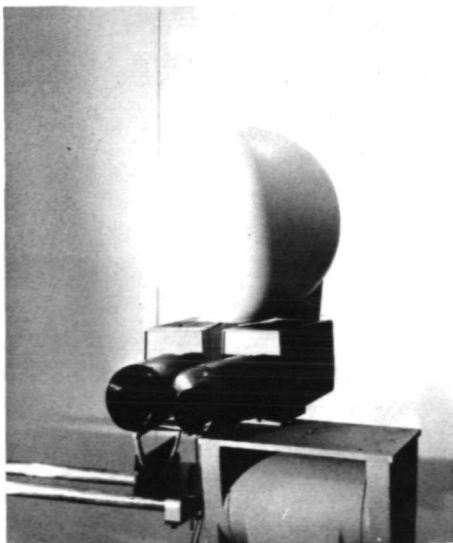


Fig. V-6 Passive Lighting Apparatus

3. Summary and Recommendations

A 30.48 cm (1 ft) diameter diffusely reflecting sphere may be used to illuminate a worksite at close ranges, on the order of 2 meters (6.5 ft), to a brightness of 40 footlamberts without the use of artificial lighting. Of course, this range limitation could be extended through the use of a more sensitive camera.

If sunlight is directly incident on the worksite, the light reflected by the sphere onto the worksite is not sufficient to fill the shadows to the brightness required for good definition throughout the scene, but it would reduce the amount of artificial illumination required. Based upon the relative merits of the diffuse reflector it is recommended that a diffuse reflector be included as part of the illumination subsystem.

B. ACTIVE ILLUMINATION

In order to determine the most effective methods of illuminating the teleoperator worksite, several types of lamps were considered. Primary emphasis was placed on incandescent lamps, fluorescent lamps, and mercury and xenon arc vapor lamps.¹ Manufacturers consideration was given to the inherent source characteristics, sensor compatibility, stage of development, and present availability of each lamp. A detailed discussion of these considerations is presented in the following paragraphs.

1. Incandescent Lamps

Incandescent lamps generally use tungsten filaments because of tungsten's low vapor pressure and high melting point (3655°K). For balanced performance the filament should operate at high temperature consistent with satisfactory life in order to radiate

(1) Numerous lamp manufacturers were contacted including General Electric Co., Grimes Mfg. Co., ILC Inc., McDonnell Douglas Astronautics Co., and Westinghouse Lamp Division.

maximum energy in the visible region. A large filament diameter, and consequently low voltage operation, is desirable for the vibration environment likely to be encountered in space. Incandescent lamps draw a high inrush current, 12 to 16 times normal current, when turned on, but the inrush current lasts only 100 ms for a typical 100 watt lamp.

The luminous efficacy of incandescent lamps (the ratio between emitted luminous flux and lamp input power) is lower than that of fluorescent lamps. However, the relatively small filament size permits much greater control of the light distribution and consequently allows more efficient use of the emitted light. The ability to focus the light into a closely controlled field of view is particularly important for long range illumination. Tungsten-halogen lamps provide a filament regenerative cycle which prevents the evaporation of tungsten onto the bulb, resulting in high illumination uniformity throughout the life of the bulb. Figure V-7 shows efficacy as a function of time for both standard and halogen tungsten lamps, and Fig. V-8 shows the spectral illumination distribution. The luminous efficacy can be increased by increasing the color temperature of the filament, but then the rated life of the lamp decreases sharply.

Efficacies for available incandescent lamps range from 10 lumens per watt typical of the 50 watt space qualified Apollo docking light, (Ref. 7), to 2-20 lumens per watt for a typical 100 watt aircraft lamp. These two lamps have a rated life of 1000 hours and 2000 hours respectively. If the teleoperator lamp life requirement is less than this, the efficacy of the lamp could be increased slightly by increasing the color temperature. Incandescent lamps can generally be operated over a wide power range for variable illumination requirements. Also, the illumina-

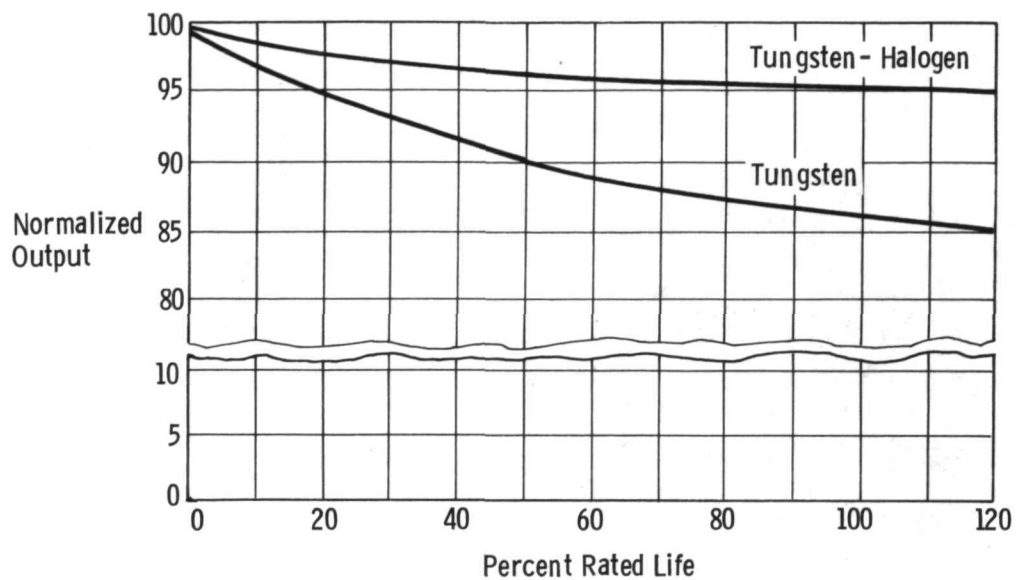


Fig. V-7 Tungsten Lamp Deterioration

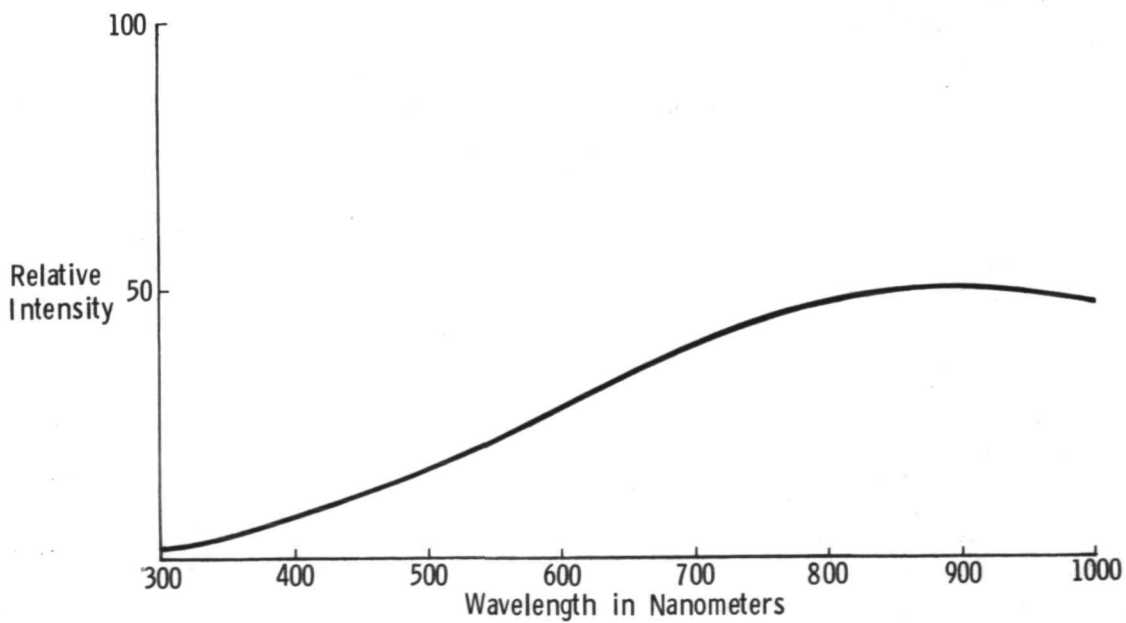


Fig. V-8 Tungsten Spectral Distribution

tion can be focused into a field of view ranging from a narrow 5 degrees to over 60 degrees. As the field of view increases the light per unit area incident on the worksite decreases proportionally.

A typical PAR 36, 250 watt aircraft lamp measures about 11.4 cm (4.5 inches) in diameter. The Apollo docking light shown in Fig. V-9 measures approximately 18.0 x 7.6 x 6.4 cm (7 x 3 x 2.5 inches) and has been designed to withstand the environmental conditions specified in Table V-1. The Apollo docking light would require design modification for teleoperator application because of its present narrow 8 degree field of view, but the basic existing configuration would require little change.

2. Fluorescent Lamps

Fluorescent lamps operate on the electric discharge principle. The low pressure mercury vapor arc generates ultraviolet energy which in turn activates fluorescent phosphor powders. These phosphor powders can be chosen to closely match the sensitivity spectrum of the selected TV camera. The lamps rely on an inert gas for starting and on a ballast which limits the current and provides starting and operating voltages of approximately 300 volts. The

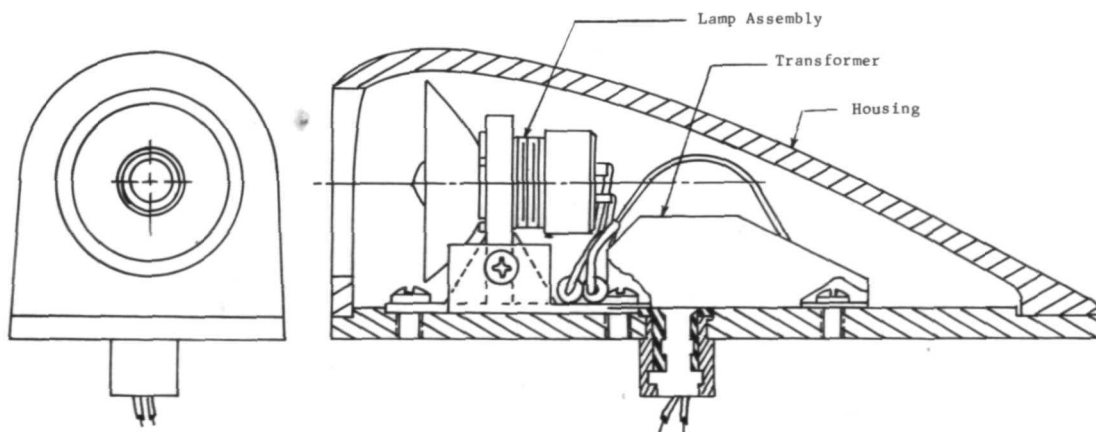


Fig. V-9 Apollo Docking Light

Table V-1 Environmental Requirements of Apollo
Docking Light

<u>Ascent Phase</u>		
Temperature	Up to +250 degrees F during launch	
Acceleration	Sustained acceleration level for 20g	
Vibration	<u>Frequency (Hz)</u>	<u>Level (g^2/Hz)</u>
	20-200	6 db/octave increase to 2.0
	200-600	Constant 2.0
	600-2000	3 db/octave decrease from 2.0
	Duration:	150 seconds on each of three mutually perpendicular axes
<u>Extra Atmospheric Phases</u>		
Temperature	Will vary from +250 degrees F when toward the sun to -200 degrees F on the shaded side	
Pressure	1×10^{-13} mm Hg for 255 hours	
Vibration	<u>Frequency</u>	<u>Level (g^2/Hz)</u>
	20-100	3 db/octave increase to 0.015
	100-2000	Constant at 0.015

most apparent disadvantage of fluorescent lights is their size. Because of its length the fluorescent lamp requires special mounting and packaging to withstand the space environment. The large size also accounts for the difficulty in focusing fluorescent lamps into a well defined field. The reason for lamp lengths on the order of 45 cm (18 inches) is apparent from Fig. V-10. As the length drops below 45 to 50 cm (18 to 20 inches) the efficacy decreases very rapidly. Consequently, unless relatively large dimensions are maintained, the advantages of fluorescent illumination are eliminated. Like incandescent lamps, the lumen output of a fluorescent lamp decreases with accumulated operation. Figure V-11 shows the normalized output of a typical fluorescent lamp as a function of hours operation. The life of fluorescent hot cathode lamps is determined by the rate loss of emissive coating on the

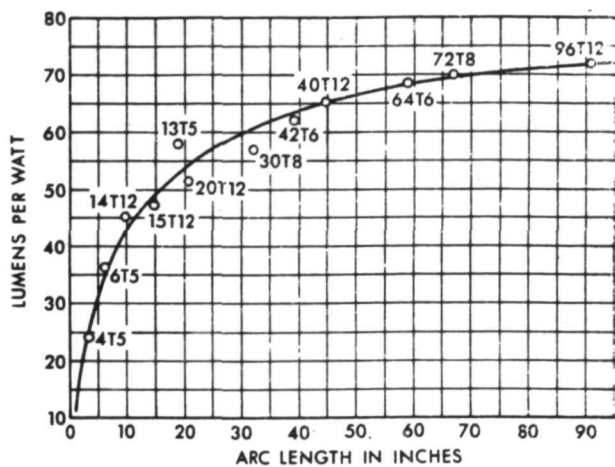


Fig. V-10 Fluorescent Lamp Efficacy Versus Length

electrodes. Starting cycles and evaporation during operation both contribute to this loss. The rated average life of fluorescent lamps is influenced by the number of starting cycles.

A space qualified high intensity fluorescent portable light (HIFPL) has been designed for Skylab (Reference 8). For space qualification the lamp requires teflon sleeves which reduced its effective candlepower, and indium is used to reduce the vapor pressure to a level compatible with the hard vacuum space environment. The circuitry required for the HIFPL consists primarily of a single transistor and capacitor. The efficacy of the space

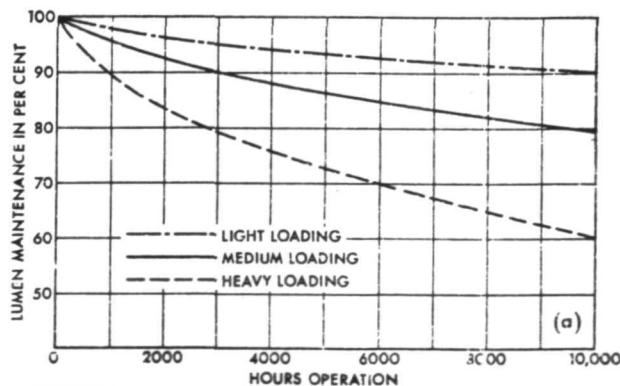


Fig. V-11 Fluorescent Lamp Deterioration

qualified HIFPL is approximately 26 lumens per watt at its optimum operating frequency of 20,000 Hz. The design life of the HIFPL lamp is 500 hours. The 5000°K color temperature of the lamp is correlated to specified film characteristics. Phosphors could be chosen to match the spectral curve of the lamp to the spectral sensitivity of nearly any TV tube. The spectral distribution is shown in Fig. V-12.

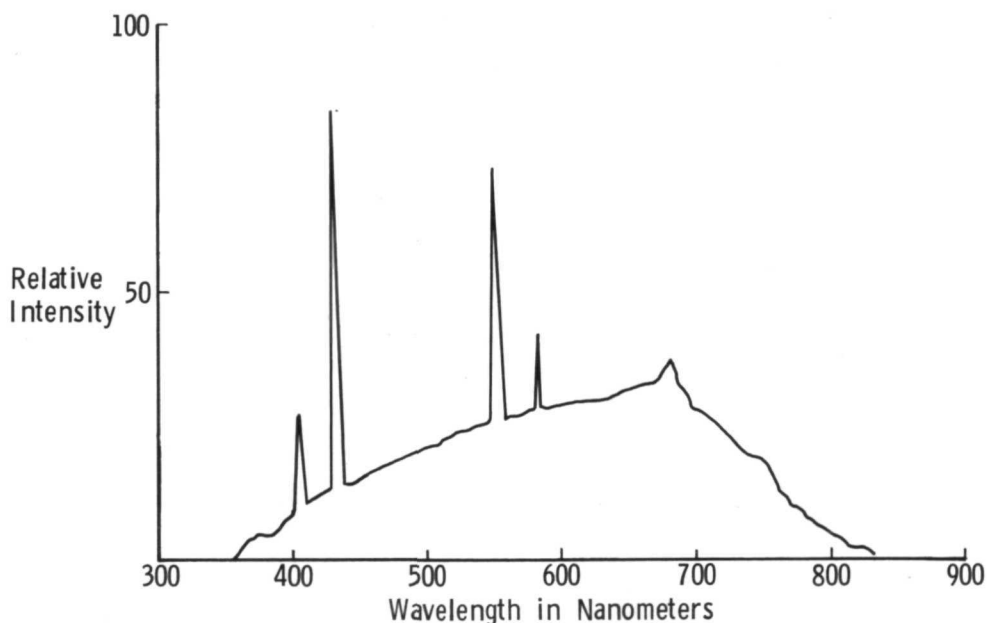


Fig. V-12 Spectral Distribution of Fluorescent Lamp

A cross-sectional diagram of the tube used in the HIFPL and its candlepower distribution are shown in Fig. V-13. A reflective coating within the fluorescent tube significantly improves the directivity of the emitted light, but even then the illumination field is broad and suited primarily for short range illumination applications. A drawing showing the construction of the Skylab light is shown in Fig. V-14.

Due to the inherently large size and high efficacy of fluorescent lamps, they lend themselves primarily to short range illumination

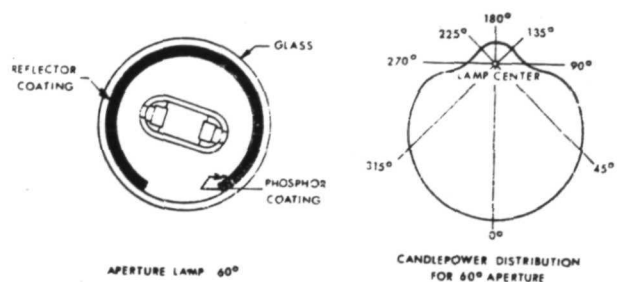


Fig. V-13 60° Aperture Fluorescent Tube

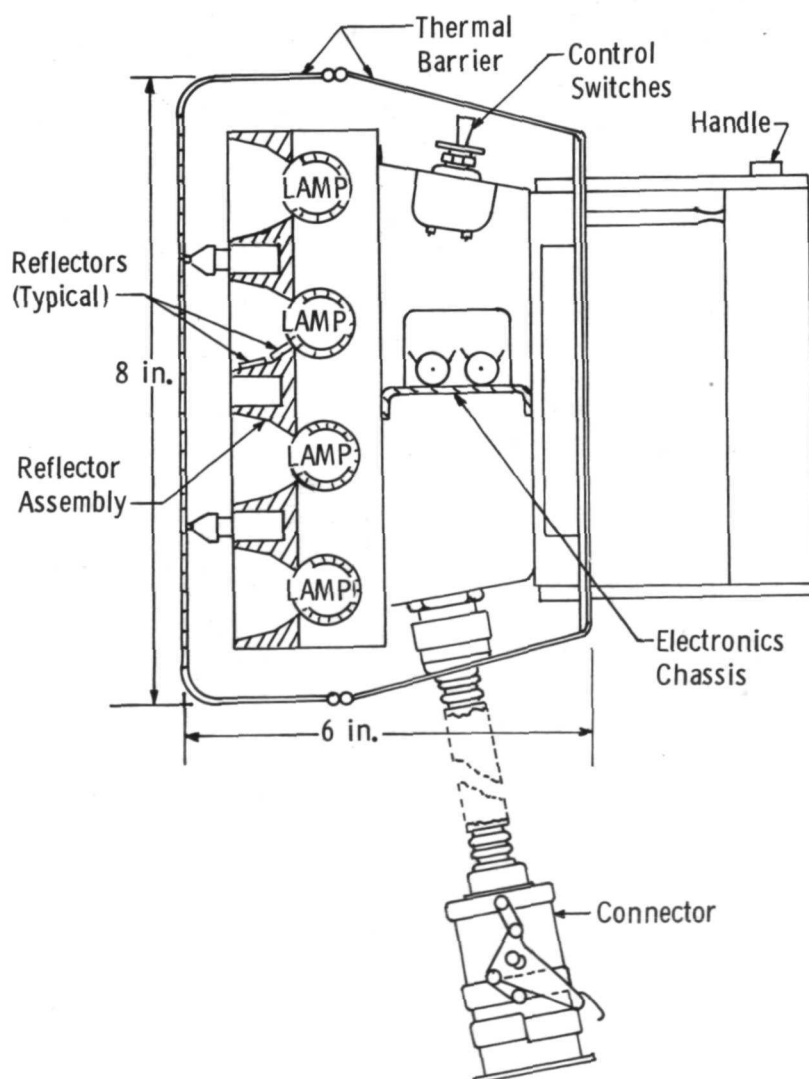


Fig. V-14 Skylab High Intensity Portable Fluorescent Light

applications. The resultant light is very diffuse and uniform and shadows are soft.

3. Mercury and Xenon Vapor Arc Lamps

Arc lamps, like incandescent lamps emit light from a very small area within the lamp enclosure making them easy to focus into a predetermined field. They generally require current limiters and high voltage starting circuits. Mercury vapor lamps have a relatively high 50 lumen/watt efficacy rating at 1000 watts operating power, but much of this illumination is in the form of ultraviolet radiation. Consequently, the mercury vapor arc lamp is poorly matched to the sensitivity of available television sensors. Another disadvantage of mercury arc lamps is its characteristically long warm-up time. The addition of xenon vapor to the mercury lamp reduces the warm-up time by about 50%, but the spectral distribution changes very little.

Xenon lamps differ sharply from mercury and mercury-xenon lamps in both operating pressure and warm-up time. Xenon lamps are filled with several atmospheres of gas and reach 80% of their final luminous output upon starting. The luminous efficacy of a typical xenon arc lamp is 30 lumens/watt at 1000 watts (40% less than mercury lamps) but the spectral distribution, shown in Fig. V-15, is more uniform throughout the visible region. Even so, much of the output power goes to useless ultraviolet and infrared radiation thereby reducing the effective efficacy for TV illumination. As with incandescent and fluorescent lamps, space qualification of a vapor arc lamp would probably reduce the efficacy even further. At present xenon arc lamps have not undergone the sophisticated development of incandescent and even fluorescent lamps.

4. Spectral Correlation Analysis

The relative efficiency of the light sources described above can

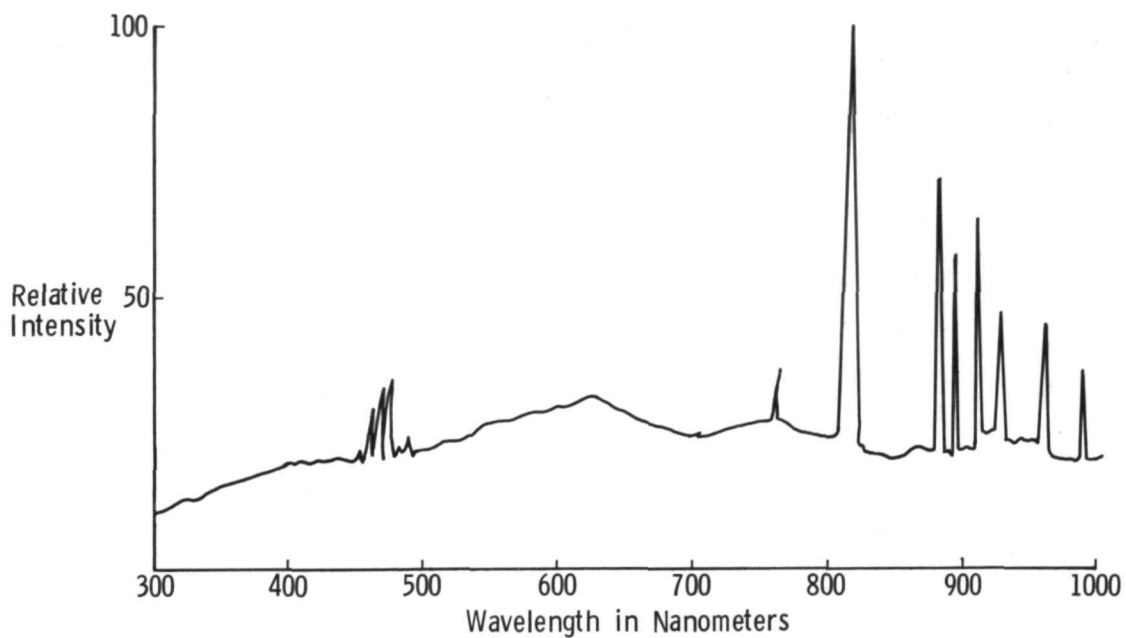


Fig. V-15 Spectral Distribution of Xenon Arc Lamp

only be determined through correlation of the spectral radiation of the lamps with the spectral sensitivity of the TV cameras under consideration. Figure V-16 shows the spectral distribution of

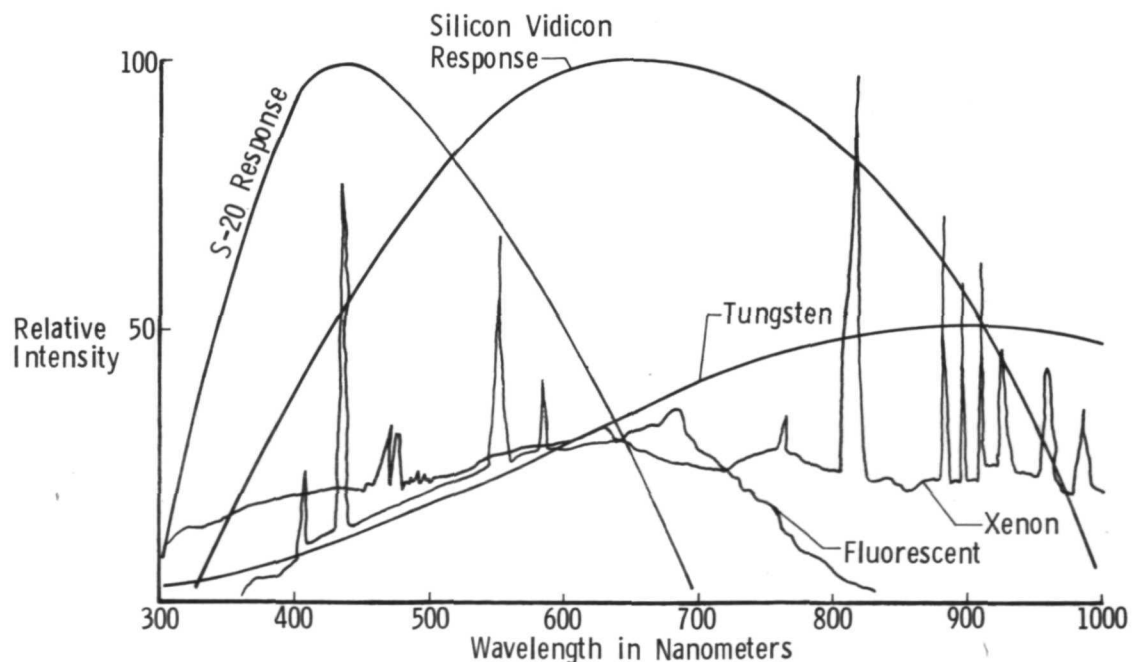


Fig. V-16 Spectral Correlation of Lamps and Cameras

typical tungsten, fluorescent, and xenon arc lamps, and the spectral sensitivity curves of the Apollo (RCA) SIT, the Skylab (Westinghouse) SIT, MSC/Lockheed, and RCA #4825 silicon vidicon TV cameras. In order to determine relative efficiencies of lamp and sensor combinations, a computer program was generated to correlate the spectral curves. The product of camera sensitivity and lamp illumination as a function of wavelength yields the TV camera signal current for a matrix of the 4 TV cameras and 3 light sources. Because only photometric data was available on the lamps, the photometric units had to be first transformed to radiometric units. This was accomplished by determining the constant K_L in Eq (1), and then substituting K_L into Eq (2) to determine a "Figure of Merit" for the various camera and lamp combinations.

$$I = K_L K_{\text{Phot}} \int_{\lambda_1}^{\lambda_2} H_L(\lambda) P(\lambda) d\lambda \quad (1)$$

Where: I = Measured photometric lamp output illumination
(lumens/ft²)

K_L = Peak lamp illumination (watt/ft²)

K_{Phot} = Peak photopic response (lumen/watt)

$H_L(\lambda)$ = Relative lamp illumination

$P(\lambda)$ = Relative photopic response

$$S = K_{\text{TV}} K_L \int_{\lambda_1}^{\lambda_2} R_{\text{TV}}(\lambda) H_L(\lambda) d\lambda \quad (2)$$

Where: S = TV sensor response (amp/ft^2)

K_{TV} = Peak TV sensitivity (amp/watt)

R_{TV} = Relative TV sensitivity

$d\lambda$ = Wavelength interval, 50 nanometers

The lamp distance, lamp power, illuminated area, and candle power versus angular distribution were held relatively constant for the lamps and cameras analyzed. Target reflectivity was assumed constant over the wavelength interval used, $\lambda_1 = 200 \text{ nm}$ to $\lambda_2 = 1150 \text{ nm}$. The camera and lamp combinations and the associated figure of merit of each is given in Table V-2.

Table V-2 Correlated Camera and Lamp Combinations

Camera	Lamp	Figure of Merit
RCA Silicon Vidicon	Incandescent	5.70
RCA Silicon Vidicon	Xenon	4.19
Apollo (RCA) SIT	Xenon	2.02
Skylab SIT	Xenon	1.82
Apollo (RCA) SIT	Incandescent	1.12
Skylab SIT	Incandescent	1.01
MSC/Lockheed	Xenon	0.55
MSC/Lockheed	Incandescent	0.36
Apollo (RCA) SIT	Fluorescent	0.25
RCA Silicon Vidicon	Fluorescent	0.25
Skylab SIT	Fluorescent	0.23
MSC/Lockheed	Fluorescent	0.07
Target Distance = 1.81 meters (6 ft); field of view = 30 degrees		

Since the spectral response peak of the RCA silicon vidicon falls at the high end of the visible spectrum, its combination with an incandescent lamp resulted in a figure merit higher than other camera and incandescent lamp combinations. Maximum response of

the Apollo, Skylab, and MSC/Lockheed cameras occurs at shorter wavelengths corresponding more closely to the intensity distribution of exnon lamps. Consequently, the xenon lamp combinations were rated higher in overall efficiency than incandescent lamps. This information alone would likely lead to the recommendation of a xenon-arc lamp for active illumination. However, in light of the dangerous high starting voltage requirement and lack of sophisticated development, the xenon arc lamp is not recommended. An extensive program to further develop and space qualify a xenon arc lamp may shed more light on this concept. It should be noted that the low fluorescent lamp ratings are partially due to the wide angular distribution of the light.

5. Summary and Recommendations

Incandescent lamps have several advantages over fluorescent and arc type lamps. Their intensity can be easily varied to meet illumination requirements and they can be easily focused for optimum efficiency at near and far ranges. They are simple, dependable, and relatively efficient for use with available TV cameras. Tungsten lamp technology in particular is very advanced with respect to fluorescent and arc lamp technology, and space qualified tungsten lamps are presently available. It is therefore recommended that incandescent lamps be used as the primary active illumination source for the teleoperator visual system. It is further recommended that two such lamps, each with a different field of view, be incorporated into the visual illumination subsystem. The reasons for this recommendation are numerous. Only the lamp with the field of view most closely matching the field of view of the camera would be needed at any given time, thereby optimizing the illumination efficiency, life, and reliability of the lamps. The multiplicity of lamps would provide illumination redundancy in case of lamp failure during critical tasks, and the

two could supply additional illumination for low reflectivity objects.

If the low sensitivity NASA/Lockheed color camera is used to view an adequately illuminated 54 degree (0.9 steradian) field at 6.1 m (20 ft), then about 1160 watts of electrical power would be required to illuminate the scene with a tungsten-halogen lamp (22 lumens/watt) similar to the space qualified Apollo docking light. Monochrome operation of this camera would reduce the requirement to 93 watts and use of the 32 degree (0.3 steradian) narrow field lamp would lower the figure to 31 watts. If the recommended Apollo GCTA camera is used, the respective requirements for the same 6.1 meter (20 ft) range would be about 5 watts for the wide field lamp and less than 2 watts for the narrow field lamp. A 24.5m(80 ft) target range would require 80 watts of electrical power for wide field illumination and 25 watts for narrow field illumination. These figures emphasize the power advantage of the second, narrow field lamp recommended above.

The above lamps will produce harsh shadows which may be disturbing or confusing during performance of dexterous tasks. It is therefore recommended that a fluorescent lamp be used to supplement the tungsten-halogen illumination system for close range work. Figure V-10 indicates that an arc length on the order of 30 inches provides an optimized tradeoff between lamp length and efficacy. By designing the fluorescent lamp in a circular configuration, the efficacy and volume requirements can be optimized. Because of its wide angular illumination distribution and its potential of being spectrally matched to the sensor, the fluorescent lamp would provide optimized illumination at ranges less than 3 m (10 ft). The use of such a lamp for performance of dexterous tasks within a 3 m (10 ft) range would require no more than 2 watts of electrical power for adequate illumination of the work site.

VI. DEPLOYMENT/ARTICULATION SUBSYSTEM

Phase I Summary: Limited effort was placed upon the visual system deployment/articulation subsystem during Phase I. The primary emphasis was to establish the visual system concept and the preferred location of the visual sensor(s) when performing satellite inspection, maintenance, and retrieval. However, the Phase I activity indicated that if general purpose visual coverage is required, the deployment/articulation subsystem becomes proportionately complex and significantly impacts the overall FFTO design.

Phase II Emphases: The primary sensor deployment/articulation effort was directed towards analyzing, in-depth, the subsystem requirements to establish a deployment/articulation technique which provides adequate flexibility while minimizing overall complexity.

A. PRELIMINARY REQUIREMENTS

The deployment/articulation subsystem requirements are strongly influenced by other FFTO systems. For example, the FFTO docking device can range from a simple probe and drogue in which the FFTO-to-satellite range at contact may be in the order of 0.3 to 1.8 meters (1 to 6 ft) in length to long booms or grappling devices where the satellite-to-FTFO range at contact exceeds 7.6 meters (25 ft). The angular offset of the initial contact point relative to the nominal (X-axis flight path of the FFTO can range from 0° for a direct docking situation to $\pm 90^{\circ}$ when a spinning/nutating satellite capture is required. Generally, as these mission requirements vary, the device used to effect the FFTO attachment is modified for the specific application.

In a similar manner, the FFTO manipulator subsystem varies from devices to perform satellite maintenance to those required to rescue astronauts stranded in space. Unfortunately, to date, no "universal" attachment device or manipulative device has been established. It is generally assumed that there will be two distinct categories of devices: general purpose and special purpose. Briefly, the general purpose device will provide adequate capability

to accomplish a large majority of FFTO missions and tasks while the special purpose will be required when unique situations arise.

The FFTO visual system, provided to enable a remotely located operator to view the task activity, must through its charter be flexible enough to visually cover the gamut of these "attachment and manipulative" devices. While a universal solution is desirable, in general, the solution results in an overly complex system and directly impacts the total FFTO system in the areas of weight, volume, control, power and so forth. Therefore, the major emphasis of the Phase II activity is to indicate the capabilities of various articulated visual sensor subsystem techniques, from extremely simple to complex, and based on technical judgement attempt to establish a general (or recommended) visual deployment/articulation subsystem, recognizing that as special tasks evolve, possible modifications to this subsystem may be required.

1. Visual Coverage

The visual coverage requirements, resulting from those identified in the statement-of-work and a review of related FFTO studies, have been generalized into three distinct working volume categories. As illustrated by Fig. VI-1, these volumes are ranked based upon anticipated FFTO activity as well as recognizing the visual coverage complexity required. The "primary" volume includes the satellite maintenance activity region, the docking interface between the FFTO and the satellite, and the satellite inspection surfaces. The "secondary" volume represents the visual coverage required for inspection of the FFTO and for viewing of the removal and stowage of satellite replenishable modules. The third volume includes two FFTO working categories; that required to view a large nutating satellite and that required to provide a "rear view" during the FFTO visual guidance phase or visual coverage of an alternate FFTO docking region.

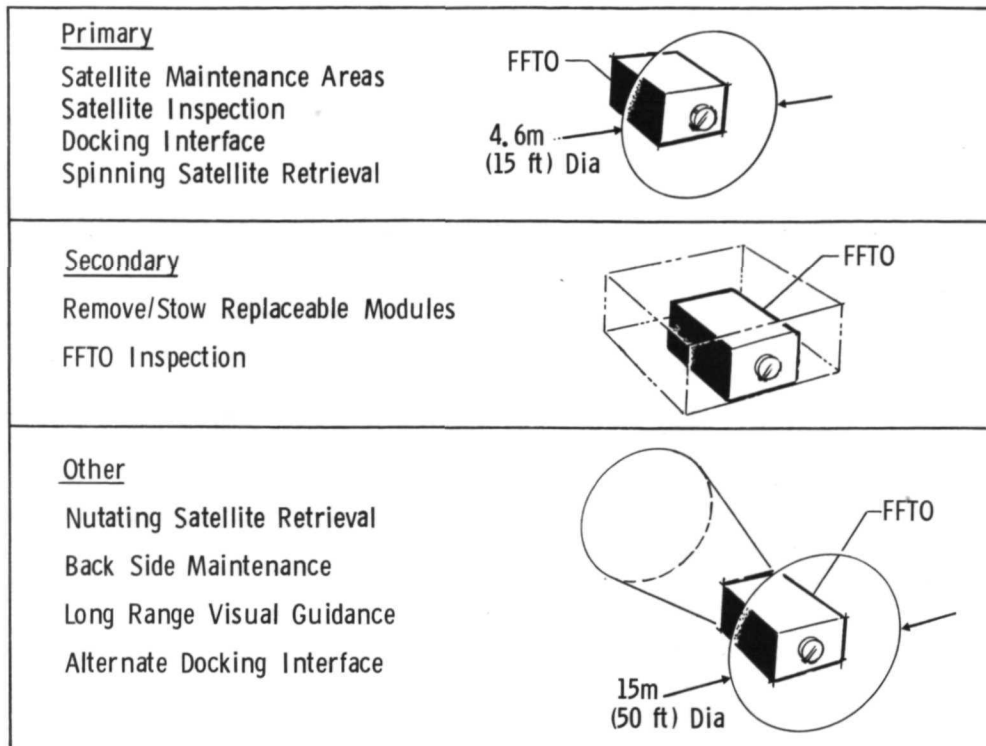


Fig. VI-1 Visual Coverage Working Volumes

The detailed analysis of the sensor deployment/articulation subsystem will initially consider only the "primary" volume and then be expanded to include the other working volume categories.

2. General Guidelines

The following guidelines will be used as a basis for analysis and selection of a general purpose deployment/articulation subsystem for the FFTO visual system:

- (a) The "general" purpose attachment device will be capable of positioning the FFTO within 0.3 to 1.8 meters (1 to 6 ft) of the satellite.
- (b) A typical "general" purpose manipulator will be approximately 1.9 to 3.0 meters (6 to 10 ft) long.

- (c) Satellites will range from the large 4.6 meter diameter, 18 meter long (15 ft by 60 ft) cylindrical class to spherical types approximately 1.2 meters (4 ft) in diameter.
- (d) The FFTO will be in the range of 1.2 meters wide, 1.2 meters high, and 1.8 meters long (4 ft x 4 ft x 6 ft).
- (e) The "front" and "rear" surfaces of the FFTO will be reserved for locating docking and/or manipulative devices.
- (f) A sensor located near and aligned to the docking device axis is desirable.
- (g) A sensor aligned with a FFTO control axis is preferred during inspection, docking, and long range visual guidance operations.
- (h) A sensor view will refer to visual coverage provided by a monoscopic or stereoscopic sensor.

3. Typical Sensor Characteristics

The primary sensor characteristic impacting the deployment/articulation subsystem is the available sensor field-of-view. The articulation analysis is based upon a sensor with the characteristic identified below:

- (a) Horizontal field-of-view: 6° to 48°
- (b) Vertical field-of-view: 4.5° to 37°
- (c) Minimum operating range: 0.61 meters (2 ft)

These sensor characteristics are based upon the average capabilities of television cameras used in or proposed for space environments. A graphic illustration of the visual coverage provided by a single sensor as a function of the sensor to object range is shown in Fig. VI-2. Based upon the maximum sensor field-of-view and assuming the sensor line of sight is normal to the work area, a general "rule of thumb" is the work area dimensions are approximately equal

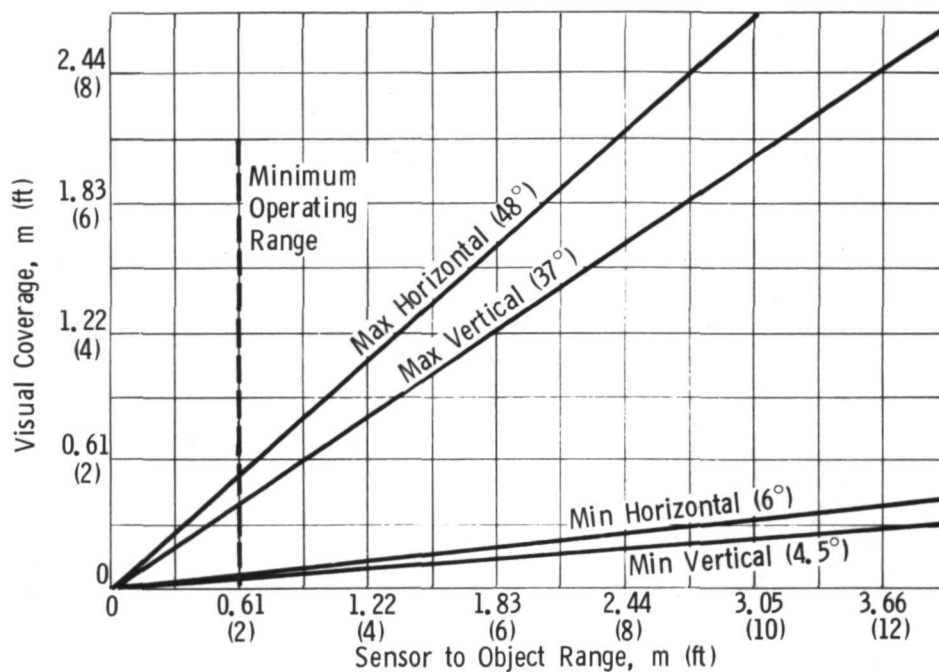


Fig. VI-2 Typical Visual Sensor Characteristics

to the sensor range (e.g. at 1 meter, using a 48° field-of-view, approximately 1 meter x 1 meter work sight is visually covered).

B. DETAILED ANALYSIS

A large number of possible sensor articulation configurations are available to provide the FFTO visual coverage. However, the objective of this analysis is to establish the minimum articulation requirements relative to the primary, secondary, and other visual coverage volumes. The sensor articulation devices have been classified into three distinct categories, ranging from simple to complex: unarticulated, articulated, and manipulator attached. Initially, only the primary visual coverage volume is considered and the articulation requirements for this coverage established. Subsequently,

the analysis will consider additional visual coverage volumes and more complex sensor articulation. Additionally, this analysis will be primarily based on the maximum available sensor field-of-view. Thus, it must be recognized that with an unarticulated sensor, the visual area coverage with respect to the central line of sight will be decreased as the sensor field-of-view decreases.

1. Unarticulated Sensor(s)

An unarticulated sensor is one in which the sensor is rigidly attached to the FFTO, either mounted directly to a FFTO surface or offset on a rigid, unarticulated boom. A number of sensor arrangements of varying location and typical visual coverage are discussed below.

a. Single Sensor, Front Mounted - A typical front mounted single sensor concept is shown in Fig. VI-3. In addition, a typical general purpose maintenance manipulator reach envelope is provided to illustrate the overall capabilities and limitations of this visual concept. Basically, the maximum visual coverage of the manipulator working volume occurs when the FFTO and satellite are separated by 1.5 meters. As the separation distance decreases, the visible work area in turn decreases. Thus, either an excessively long docking or attachment device is required, or additional sensors are required to provide adequate coverage. With reference to Figure VI-3, the single sensor is also limited in that it covers only a small percentage of a typical manipulator working volume. In summary, this concept offers the advantage of simple design implementation. However, the view near the FFTO is severely limited, the manipulator may occupy or block much of the sensor FOV during task performance and visual coverage of the available working volume is inadequate.

Figure VI-4 shows a similar concept however, the manipulator is off-

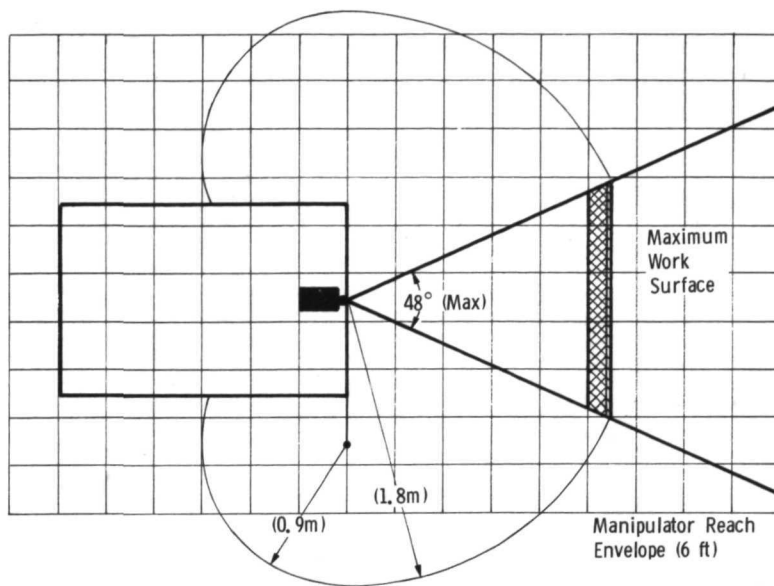


Fig. VI-3 Single Sensor, Front Mounted

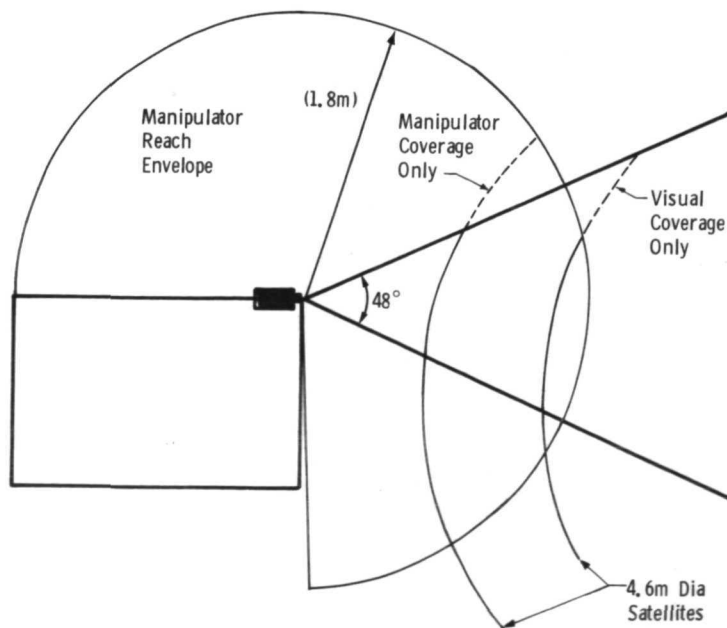


Fig. VI-4 Single Sensor, Front Mounted

set such that a different reach envelope is attained. Two views of a FFTO side docked to a 4.6 meter (15 feet) diameter satellite are shown to illustrate the inability of this concept to provide visual coverage and manipulator working volume compatibility.

b. Single Sensor, Rear Mounted - A typical rear mounted single sensor concept is shown in Fig. VI-5. The sensor is offset from the horizontal by one-half the maximum field-of-view such that the FFTO

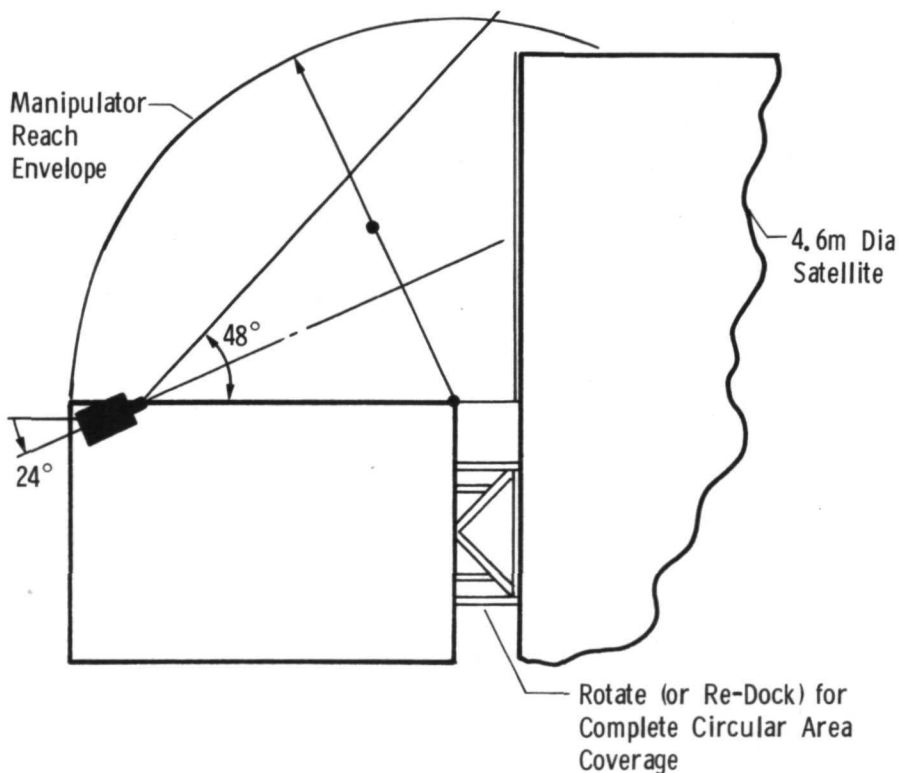


Fig. VI-5 Single Sensor, Rear Mounted

does not interfere with or reduce the available viewing area. Concepts of this class provide good visual coverage of large satellite maintenance regions above the area occulted by the FFTO. If the docking device rotates, or the FFTO re-docks to the satellite at a different angle, additional areas of maintenance become practical. However, for general purpose visual system applications, these con-

cepts lack the ability to view smaller satellites and, since the sensor is not aligned with the expected FFTO control axes, both satellite inspection and docking becomes difficult without additional sensors.

c. Dual Sensors, Front Mounted - Two concepts of front mounted dual sensors are shown in Fig. VI-6. The first maximizes the sensor separation while the second concept maximizes the visual field-of-view. In each case, the region of visual coverage has been increased over that of a single unarticulated sensor which is the only apparent advantage of these concepts, unless the second sensor is considered to provide a redundant feature. The disadvantages are numerous. The additional mass and increased power requirements for the additional sensor, in all likelihood, exceeds that required if a single yaw (pan) articulation gimbal were provided. The illumination subsystem is essentially doubled and inherent in these concepts is the requirement to continually switch TV monitor viewing as the task activity moves from one sensor FOV into the second FOV.

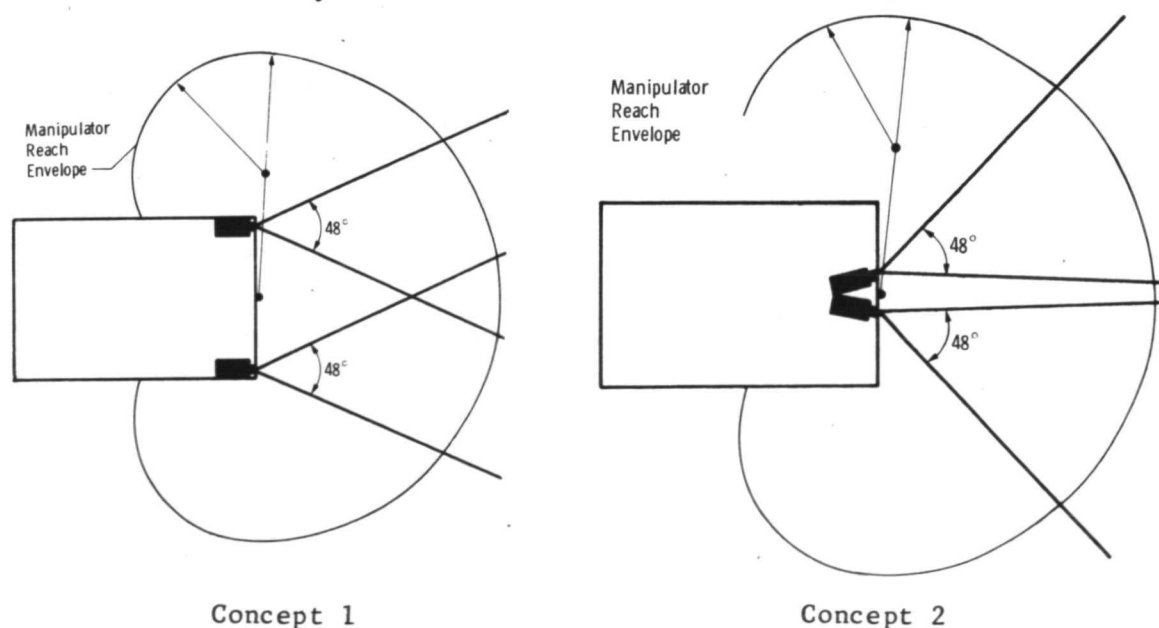


Fig. VI-6 Dual Sensors, Front Mounted

d. Single Sensor, Fixed Length Offset - Some of the limitations of a sensor fixed to the body of the FFTO can be overcome by the use of a rigid unarticulated boom to provide optimum placement of the sensor such that, for a given set of conditions, the visual coverage will be enhanced. Figures VI-7 thru VI-9 show the desirable sensor locations for relatively small, medium, and large satellites respectively. A fixed length, unarticulated boom would be used to position the sensor at the location selected. In Fig. VI-7, two loci are shown: one where the visual coverage includes a maximum

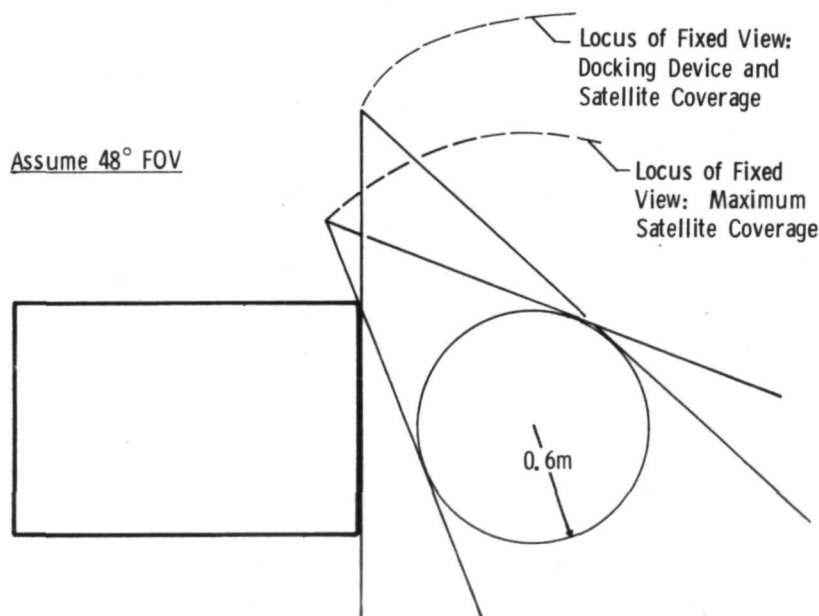


Fig. VI-7 Single Sensor, Fixed Length Offset
(Small Satellite)

satellite surface and the second where the docking device region is also included. The other two figures illustrate the typical loci for good visual coverage of larger satellites. An important observation established by these figures is that the preferred sensor location as the satellite size is increased is from the front of the FFTO to the rear. This basically results from the fact that with

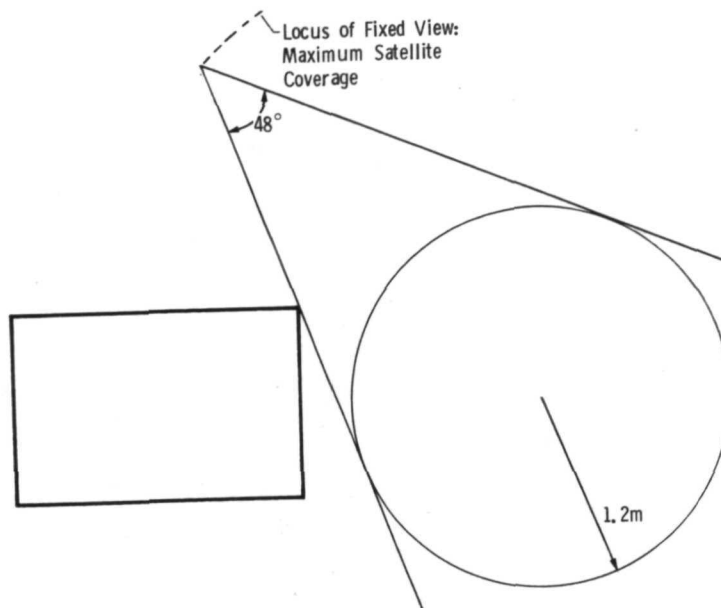


Fig. VI-8 Single Sensor, Fixed Length Offset
(Medium Satellite)

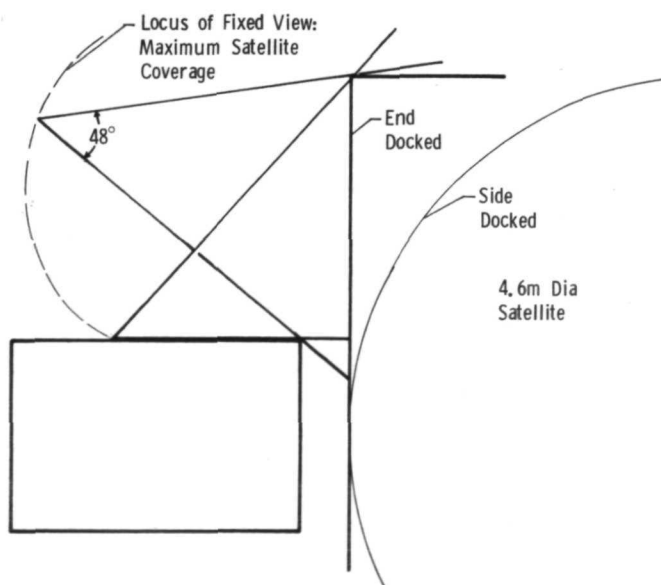


Fig. VI-9 Single Sensor, Fixed Length Offset
(Large Satellite)

a typical docking device, the sensor-to-satellite range must be increased to optimize the visual coverage as a function of satellite size. Hence, the primary advantage of the sensor-boom offset concepts is the ability to provide a good view if the docking device and satellite size are specified. The limitations of this conceptual class include the lack of sensor alignment with the FFTO control axis, the FFTO stowage complexity with an offset unarticulated boom, and, most importantly, the inadequate flexibility of these concepts for general visual system applications.

e. Unarticulated Sensor Summary - The unarticulated sensor analysis has shown that if all parameters of the FFTO system and mission are fixed (e.g. manipulator location and length, satellite size and work area, and docking device length) an optimum sensor location can be selected to provide visual coverage without articulation. However, using an unarticulated sensor, only the primary regions of the FFTO visual coverage requirements are satisfied and the work site area will be reduced as the sensor field-of-view is decreased.

A generalized summary of the unarticulated sensor analysis is illustrated by Fig. VI-10 and two significant conclusions have been established:

- (1) The initial sensor articulation must provide a variable sensor location and
- (2) A variable sensor line-of-sight is desirable.

2. Articulated Sensors

The results of the unarticulated visual sensor analysis has vividly demonstrated that to provide general coverage of the FFTO primary working area, at least one degree of articulation is required. This articulation must provide the sensor with a variable location (moveable base), and not merely a variable line-of-sight such as

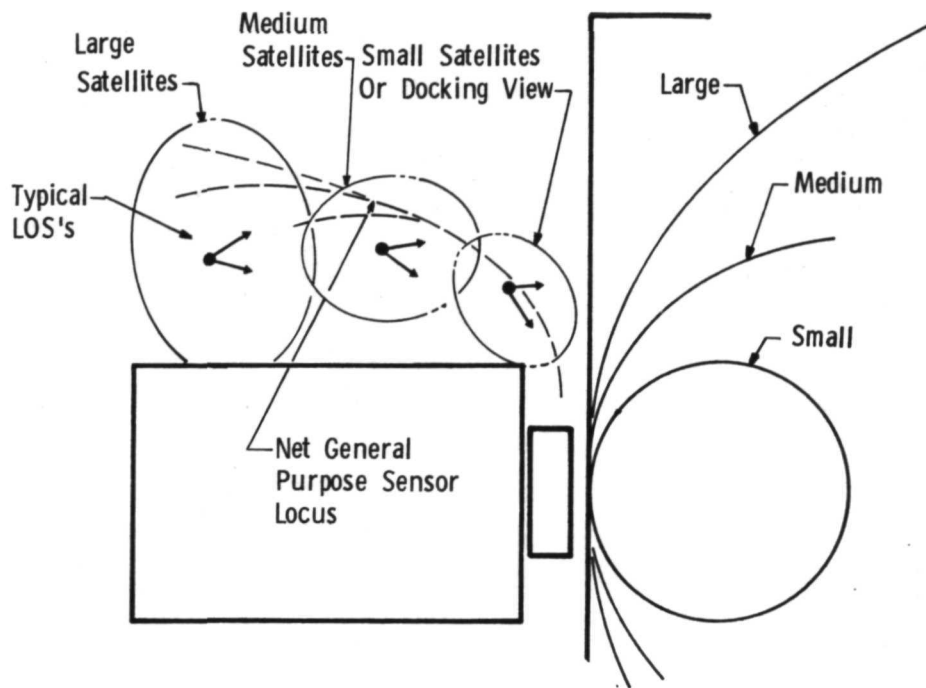


Fig. VI-10 Generalized Sensor Location

standard "pan-tilt" devices are capable of providing.

a. One degree-of-freedom Articulation - Two methods are available to provide variable sensor location: extendable booms and articulated booms. Only one extendable and two typical articulated boom concepts will satisfy the general purpose sensor location requirements established in Fig. VI-10. These concepts are shown in Figs. VI-11 and VI-12. While all three concepts provide about the same sensor-worksite range capability, it should be noted that the articulated booms provide a much greater area of visual coverage. The ability of the articulated boom concepts to view the FFTO docking region is another distinct advantage. Hence, the preferred articulation method, using a single degree-of-freedom, is an articulated boom which provides a maximum primary visual volume coverage with a

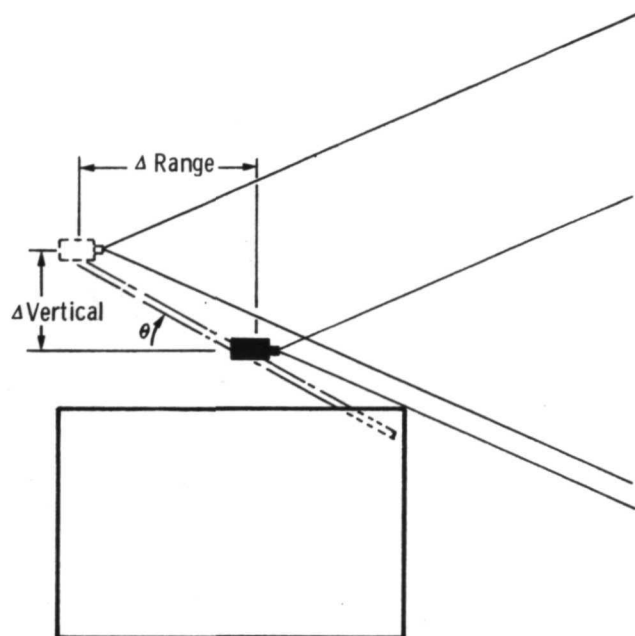


Fig. VI-11 One DOF Extendable Boom

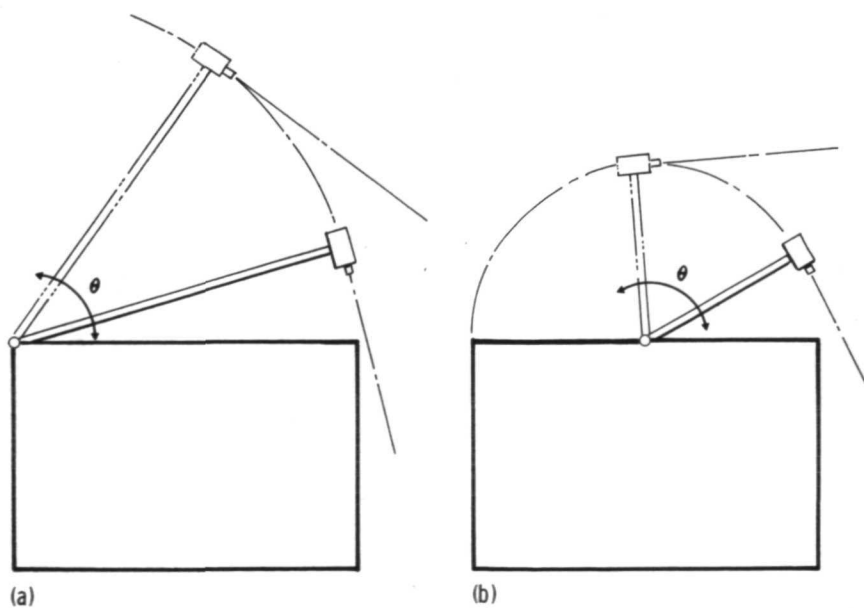


Fig. VI-12 One DOF Articulated Boom

minimum of articulation complexity. Concept (b) of Fig. VI-12 is recommended as a shorter boom is required.

b. Two Degrees-of-Freedom Articulation - The primary volume of FFTO activity was visually covered by a one degree-of-freedom articulated boom but additional degrees of articulation are required to view the secondary and other working volumes. Therefore, the articulation analysis was expanded to investigate the merits of additional articulation complexity.

Table VI-1 summarizes the large number of possible dual articulation methods with the one constraint established previously: one degree of articulation must provide variable sensor location.

Typical concepts of each method identified in Table VI-1 are shown in Fig. VI-13. It should be noted that none of the extendable concepts will provide secondary visual volume coverage, while Concept 5 of the articulated boom category is the only concept satisfying

Table VI-1 Two Degree-of-Freedom Sensor Articulation

		Articulation Location and Type	
Two DOF Concept	Boom Type	Base	Sensor
1	Extendable	Extend	Yaw
2	Extendable	Extend	Pitch
3	Extendable	Yaw-Extend	-
4	Extendable	Pitch-Extend	-
5	Articulated	Yaw-Pitch	-
6	Articulated	Pitch-Yaw	-
7	Articulated	Yaw	Yaw
8	Articulated	Yaw	Pitch
9	Articulated	Pitch	Pitch
10	Articulated	Pitch	Yaw

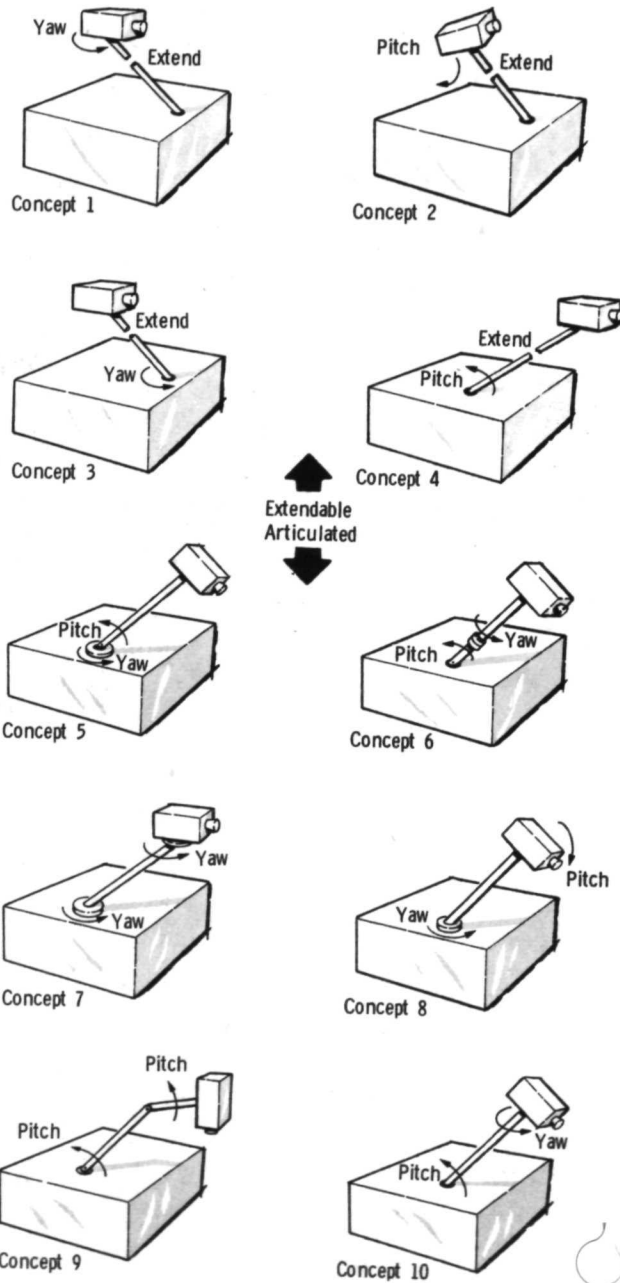


Fig. VI-13 Dual Articulation Concepts

the primary, secondary, and other visual volumetric requirements. Additionally, based upon both the single and dual articulation analysis, an extendable device generally requires one more degree of articulation to provide visual coverage equivalent to an articulated boom concept. Therefore, Concept 5 is the recommended two degree-of-freedom articulation method

c. Three Degrees-of-Freedom Articulation - Three degree-of-freedom articulation techniques are numerous. However, based upon the conclusion of the previous analysis, only a few candidates prove promising. For an articulated boom, the first two degrees-of-freedom must be yaw and pitch located at the base of the boom. For the extendable boom, the initial degree-of-freedom must be yaw. With these ground rules the possible candidates are listed in Table VI-2 and illustrated in Fig. VI-14. Again, it is important to recognize that the extendable concepts provide essentially no advantage over the two degree-of-freedom articulated boom concepts. Considering the two articulated concepts, Concept 4 is more desirable in that the two "yaw" degrees-of-freedom of Concept 5 are somewhat redundant. Concept 4 has some attractive features over the "best" two degree-of-freedom concept, with the only difference between them being the pitch gimbal located at the sensor. This is the recommended three

Table VI-2 Three Degrees of Sensor Articulation

Three DOF Concept	Boom Type	Articulation Location and Type	
		Base	Sensor
1	Extendable	Yaw - Extend	Yaw
2	Extendable	Yaw - Extend	Pitch
3	Extendable	Yaw - Pitch - Extend	-
4	Articulated	Yaw - Pitch	Pitch
5	Articulated	Yaw - Pitch	Yaw

degree-of-freedom concept.

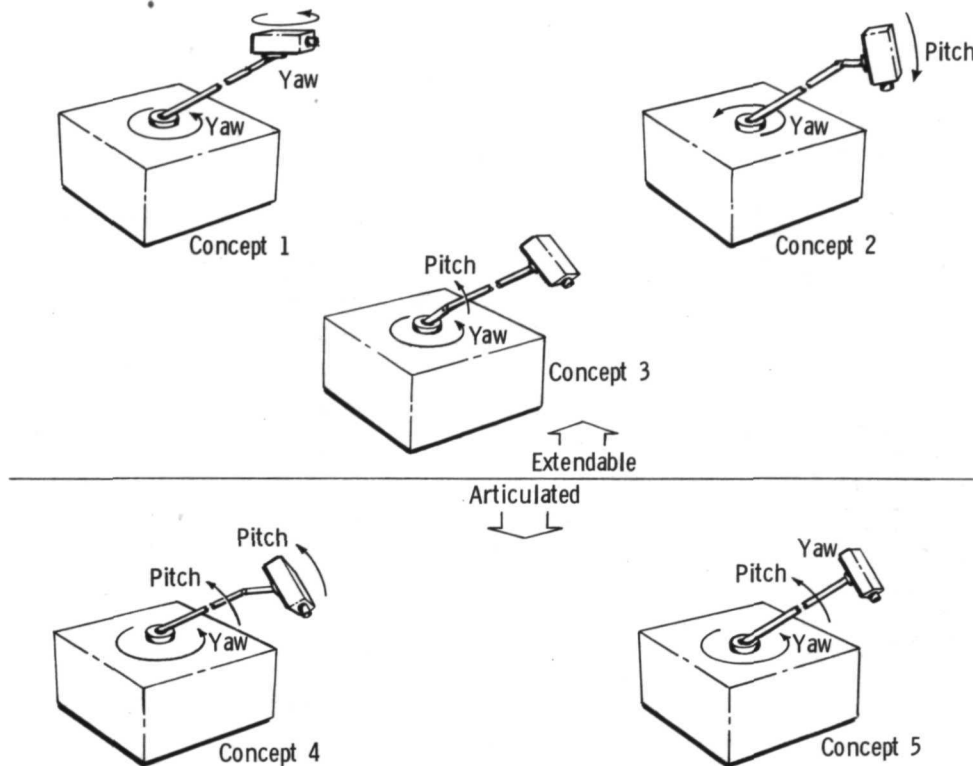
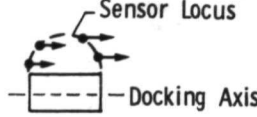
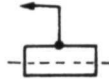
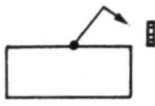
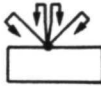


Fig. VI-14 Three Degrees of Articulation Concepts

3. Recommended Concept

The flexibility provided by the additional degree-of-freedom compared with the recommended two degree-of-freedom concept is illustrated by Fig. VI-15 and is summarized, related to FFTO activity, as follows:

a. Docking Phase - The three degree-of-freedom articulation provides a large number of views orthogonal with the FFTO docking axes, two ranges (forward and aft) per docking - FOV axis offset, and enables the sensor to be aligned as close as possible to the docking axis without requiring a sensor located on the front surface of the FFTO. The two degree-of-freedom device provides only a

Task	Two Degree of Freedom (5)	Three Degree of Freedom (4)
Docking Phase (Axis Aligned)		
"Aft" View (Axis Aligned)		
Maintenance		
FFTO Side View		
FFTO Top View		

→ = Typical FOV Central Line of Sight

Fig. VI-15 Comparative Flexibility of the Recommended Concepts

single location in which the docking - FOV axes are parallel and the offset is equal to the boom length.

b. "Aft" Viewing - Both concepts provide symmetrical fore and aft viewing. The advantages of the three degree-of-freedom concept are identical to those for the docking phase. This view is necessary where the FFTO is required to dock at both ends (e.g. satellite retrieval).

c. Maintenance - The three degree-of-freedom enables a variable sensor location with complete visual coverage, while the two degree-of-freedom has fixed field-of-view based upon the sensor location.

d. FFTO Side Views - Viewing of the FFTO sides can be accomplished with either concept. However, the two degree-of-freedom case is marginal in that the wide field-of-view must be used and the stowed modules are in the peripheral region. The three degree-of-freedom concept allows variable viewing angles and fields-of-view.

e. FFTO Top View - Only the three degree-of-freedom technique allows the top of the FFTO to be viewed.

The deployment/articulation analysis has shown, that where generalized FFTO tasks, manipulators, and docking devices are planned, a minimum of two degrees of sensor articulation is required. However, the three degree-of-freedom concept (Concept 4) is recommended as a "generalized" technique at this time based upon the additional flexibility available.

4. Special Considerations

The recommended sensor deployment/articulation technique provides the general overall visual coverage required by typical FFTO missions and tasks. This articulation system is considered to be the "general purpose" approach. However, special situations arise in which the FFTO will be implemented with a long manipulative or retrieval device to effect the large nutating satellite retrieval or where the satellite maintenance surface is on the reverse side ("back-side") of the satellite with respect to the general FFTO docking and maintenance areas. Unless these regions are coincidentally within the field-of-view of the recommended concept, additional articulation complexity is required. As indicated during the Phase I study and re-emphasized during Phase II, these categories of FFTO visual coverage will be considered "special" requirements (e.g. those FFTO missions requiring special purpose docking and/or manipulative

devices). As these situations arise, the most logical FFTO sensor deployment/articulation subsystem is one in which the sensor is attached to the manipulator. This approach provides a straightforward and reliable technique in that all regions reached by the manipulative device are identical to those visually covered. However, it must be recognized that as other FFTO subsystems approach specialization, so must the visual subsystem. Therefore, the visual sensor deployment/articulation preliminary design will be based upon the recommended "general" technique: three degrees of articulation - Concept 4.

C. SENSOR ARTICULATION MODEL EVALUATION

A full scale model of the recommended deployment/articulation subsystem was made and incorporated with an existing "FFTO type" manipulator to demonstrate the viewing capabilities of the system. Figure VI-16 illustrates the various locations of the sensors as a function of the typical FFTO task activity. As a result of this demonstration, the articulation subsystem was shown to provide adequate, flexible visual coverage of the FFTO operational areas.

D. PRELIMINARY DESIGN

The preliminary design requirements for the articulation system are an interdependent function of the sensor FOV, the working range, the work area, and the manipulator length and its operational rates. For example, if the work area is large and a narrow field of view is required to perform the task, the articulation control may be slaved automatically to continually view the end of the manipulator. Additionally, as the FOV is decreased, the desired operational rates must be decreased due to the increased display motion sensitivity presented to the operator with the narrow FOV. In many instances, the articulation system will be positioned and require no changes during the performance of the task. These cases represent the

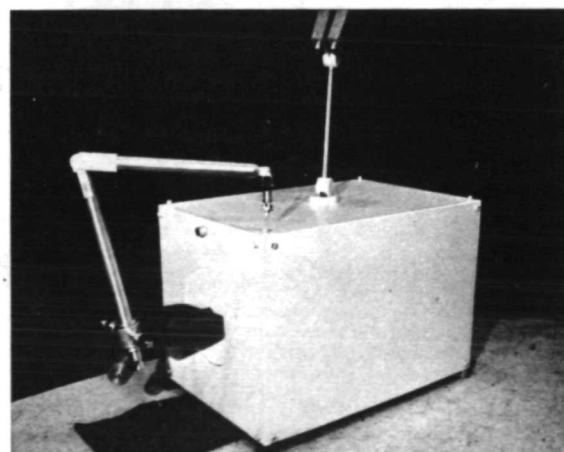
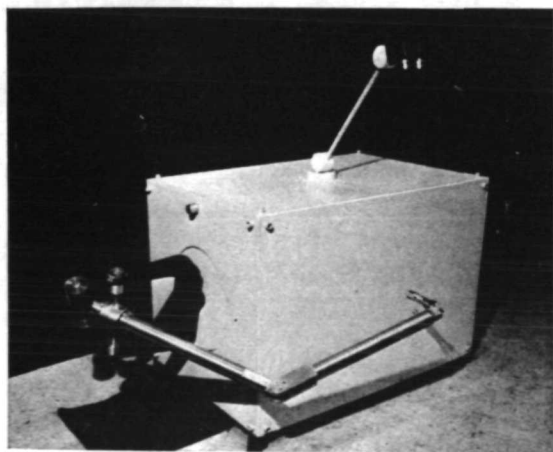
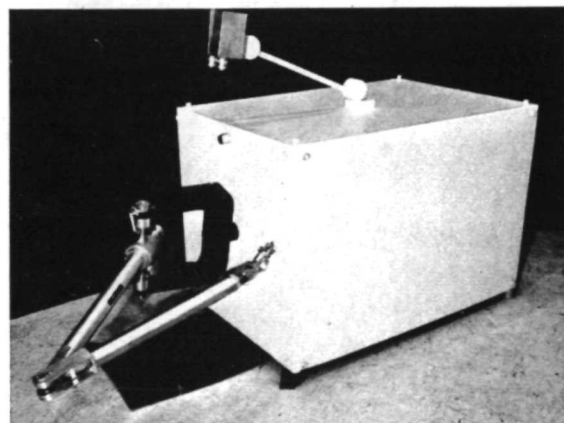
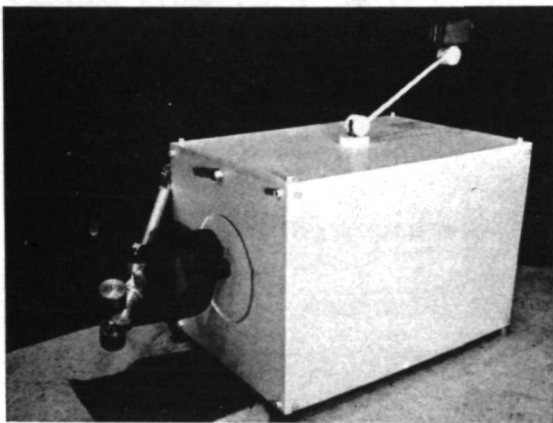
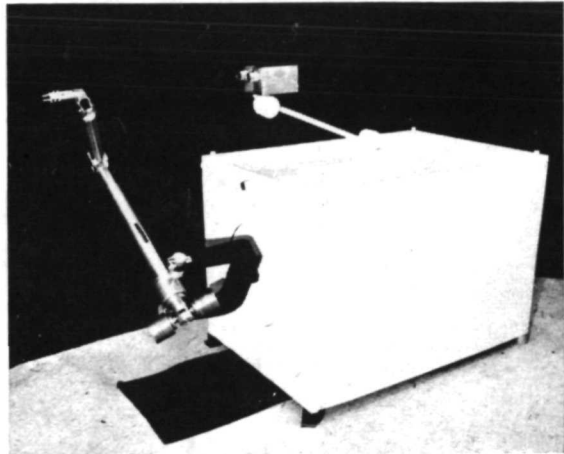
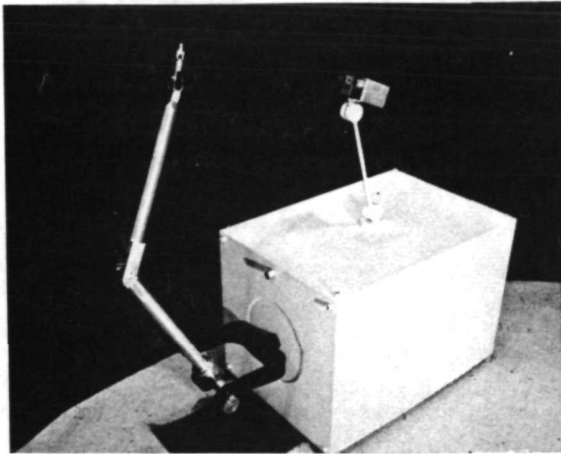


Fig. VI-16 Sensor Articulation Model Evaluation

lower limits of the articulation control. However, for the case of automatic (or manual) positioning, where it is desired to change the sensor view from scene "A" to scene "B" via preprogrammed positional information higher rates are acceptable in that time is the more critical parameter. This case imparts the upper limit on the articulation system control.

1. Control Rates

Ground based pan-tilt units used successfully in MMA teleoperator type operations were typically in the 3-5 degree/sec rotational rate range. Also, the Ground Command Television Assembly used on the lunar surface during the Apollo program contained a Television Control Unit providing azimuth and elevation control of the camera of 3.03 and 3.12 degrees/second respectively. Based upon a 5 deg/sec rate, the time required for a 180° positional change is 36 seconds, not including the time required for acceleration and deceleration. A time duration in the range of 10-15 seconds is more desirable to decrease the operational time. Fig. VI-17 shows the relationship between the total view reversal time, the peak angular rate, and the required angular acceleration assuming a constant acceleration followed by constant deceleration. Based upon this curve, the preliminary set of articulation design parameters established are to provide an angular acceleration of 0.1 rad/sec^2 and a peak angular rate of 0.5 rad/sec. A rate profile is also shown in Fig. VI-17 and indicates that with these parametric choices, a sensor reversal will take slightly over 11 seconds.

2. Motor Torque and Power Requirements

A conservative estimate of the maximum weight supported by the boom is shown in Table VI-3. Thus, in the "worst case", 19.5 kg. (43 lbs) must be articulated by the boom. The motor torque required is a function of the inertia reflected to the

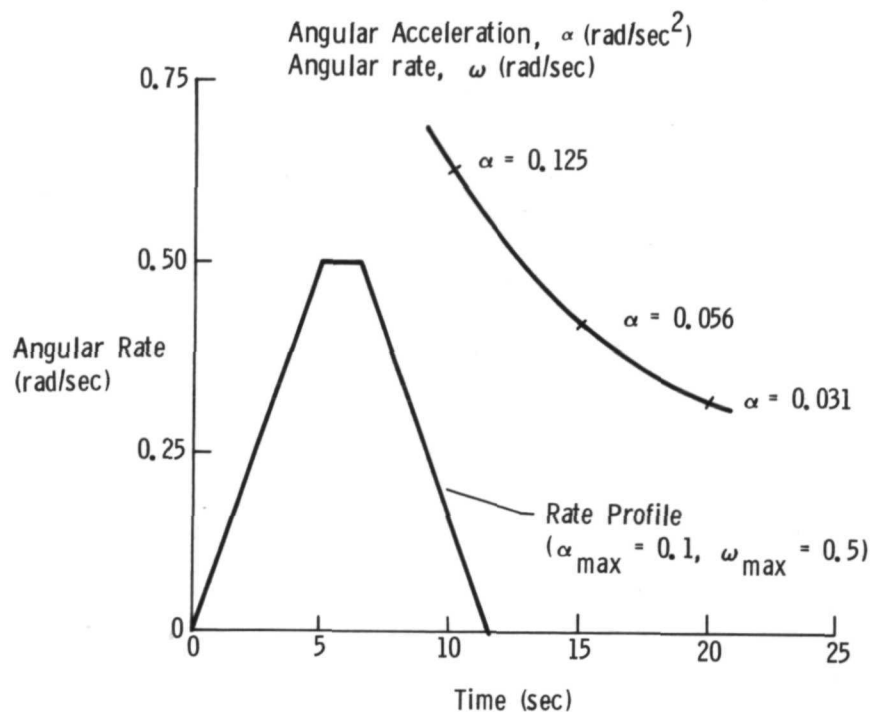


Fig. VI-17 Sensor View Reversal Characteristics

motor. The inertia, as seen by the motor gimbal is given by

$$I = I_o + Mr^2$$

where I_o is the inertia of the articulated mass about its center of mass, m is the articulated mass, and r is the distance from the mass center to the gimbal. Assuming the boom is approximately

Table VI-3 Estimated Articulated Weight

Component	Weight, Kg. (lb)
Two Apollo (RCA) Cameras	12.35 (27)
Active Lighting	2.27 (5)
Passive Illumination	0.45 (1)
Gimbal Motors and Boom Assy.	4.54 (10)
Total Maximum	19.5 (43)

0.9 m (3 ft) long (1/2 the overall FFTO length), the sensor pitch gimbal offset from the mass center by 0.15 m (0.5 ft), and the mass to be uniformly distributed within a 0.23 m (0.75 ft) cube, the reflected inertias at the base, I_b , and the sensor, I_s are respectively,

$$I_b = 12.1 \text{ slug-ft}^2 \text{ and } I_s = 0.44 \text{ slug-ft}^2$$

The output torque required at the base and sensor gimbals are

$$T_b = I_b \cdot \alpha_{\max} = (12.1)(0.1) = 1.21 \text{ ft-lbs}$$

$$T_s = I_s \cdot \alpha_{\max} = (0.44)(0.1) = 0.044 \text{ ft-lbs}$$

Assuming a gear-train is used with a worst case efficiency of 80%, and a gear ratio of K_g , the motor output torque, T_m , is related to the base and sensor torque by

$$T_{mb} = T_b / 0.8 K_{gb} = 1.51 / K_{gb} \text{ and } T_{ms} = T_s / 0.8 K_{gs} = 0.055 / K_{gs}$$

The power required to accelerate the gimbals at the maximum angular rate, W , of 0.5 rad/sec is given by

$$P_b = \frac{T_b}{0.8 K_{gb}} \cdot W K_{gb} = 0.75 \frac{\text{ft-lbs}}{\text{sec}} \text{ or } 1.0 \text{ watt}$$

$$P_s = \frac{T_s}{0.8 K_{gs}} \cdot W K_{gs} = 0.0275 \frac{\text{ft-lbs}}{\text{sec}} \text{ or } 0.037 \text{ watts}$$

To insure against commutator arcing which will lead ultimately to motor failure, the power rating of the motor should be at least four times the required output power. In addition, to remain within the motor operating temperature range, the required output

power, based upon the duty cycle, should be about 15-30 percent of the motor peak power rating. Therefore, the selected motor must typically meet the minimum specifications identified in Table VI-4.

Table VI-4 Motor Specifications

Gimbal	Peak Torque @ Stall (ft-lbs)	Power * (Watts)	
		Commutator Arc	Oper. Temp.
Base	1.51/K _{gb}	4.0	1.0/duty cycle
Sensor	0.055/K _{gs}	0.15	0.037/duty cycle
*Power required based upon the maximum rating			

3. Motor Considerations

In December, 1971, MMA completed a survey of motor usage in space. This survey, summarized in Appendix A, established that space qualified motors and components exist and, unless the requirements are extremely specialized or a completely new design is required, are not "long-lead" developmental items. Thus, based upon the visual system articulation requirements, space-qualified motors are assumed to be available but may require minor modifications.

4. Design Layout

A preliminary design layout of the sensor articulation boom was made to establish typical overall volumetric and mass properties this subsystem will require. This design is illustrated in Figs. VI-18 and 19 showing two candidate sensors, the Apollo (RCA) camera and the MSC (Lockheed) developmental camera. The boom assembly consists of azimuth (yaw) and elevation (pitch) gimbals at the base and an

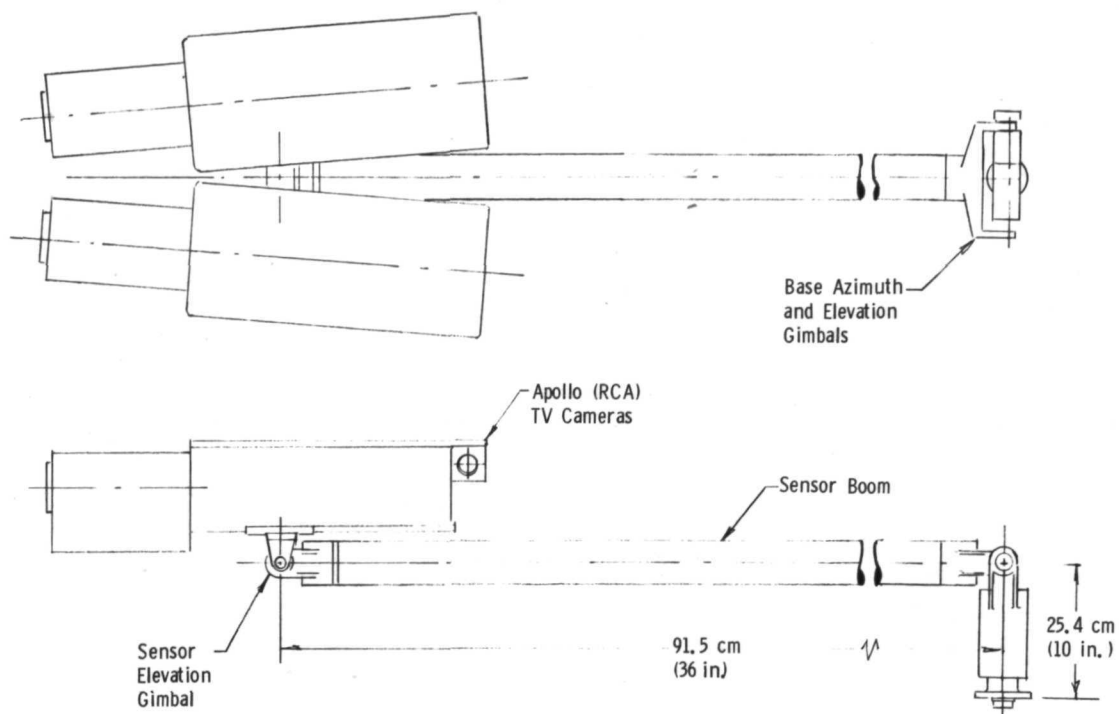


Fig. VI-18 Sensor Articulation Design Layout (Apollo Cameras)

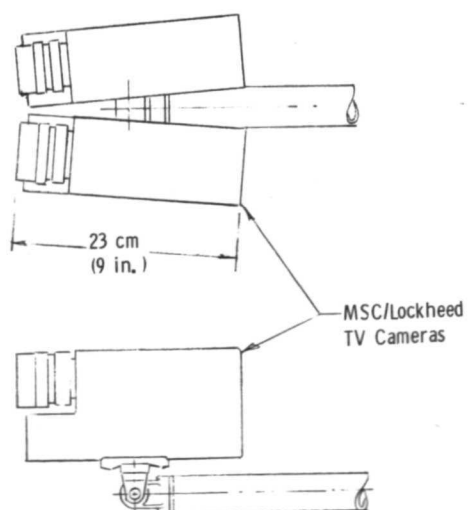


Fig. VI-19 Sensor Articulation Design Layout (MSC Cameras)

elevation (pitch) gimbal at the sensors. The elevation gimbals provide $\pm 90^\circ$ of rotation at accelerations up to 0.1 rad/sec^2 and the azimuth gimbal provides $\pm 180^\circ$ rotation with the same acceleration capability. The maximum mechanical backlash of each gimbal is approximately 2 minutes of arc.

The boom consists of 6061 T-6 aluminum tubing (2" o.d.; .050" wall thickness) which provides an interconnecting member between the base and sensor gimbals. The inner diameter of the boom provides a passage for electrical interconnections.

The gimbal details are shown in Fig. VI-20. The azimuth gimbal consists of a post with a mounted flange for attachment to the FFTO. The motor, a size 12 D.C. torquer with a harmonic drive gear reducer, is face mounted within the I.D. of the post. The gear reducer shaft extends thru the top of the post for connection to the azimuth gimbal yoke. A potentiometer shaft extends from the azimuth yoke thru a hollow motor shaft to the potentiometer mounted at the base of the post. The yoke is journalled to the post and is rotated about the post thru connection with the motor mounted within the post.

The base elevation motor, which is a duplication of the azimuth motor, is face mounted to one shoulder of the azimuth yoke. The elevation yoke is bearing mounted to the azimuth yoke at one end and connected to the elevation motor shaft at the other end. The potentiometer is mounted to the motor shaft and interconnected to the azimuth yoke to indicate angular motion imparted to the elevation yoke. A fitting is provided for mounting the camera boom to the elevation yoke.

The sensor elevation gimbal is basically identical to the base elevation gimbal. While a smaller motor could be used because of

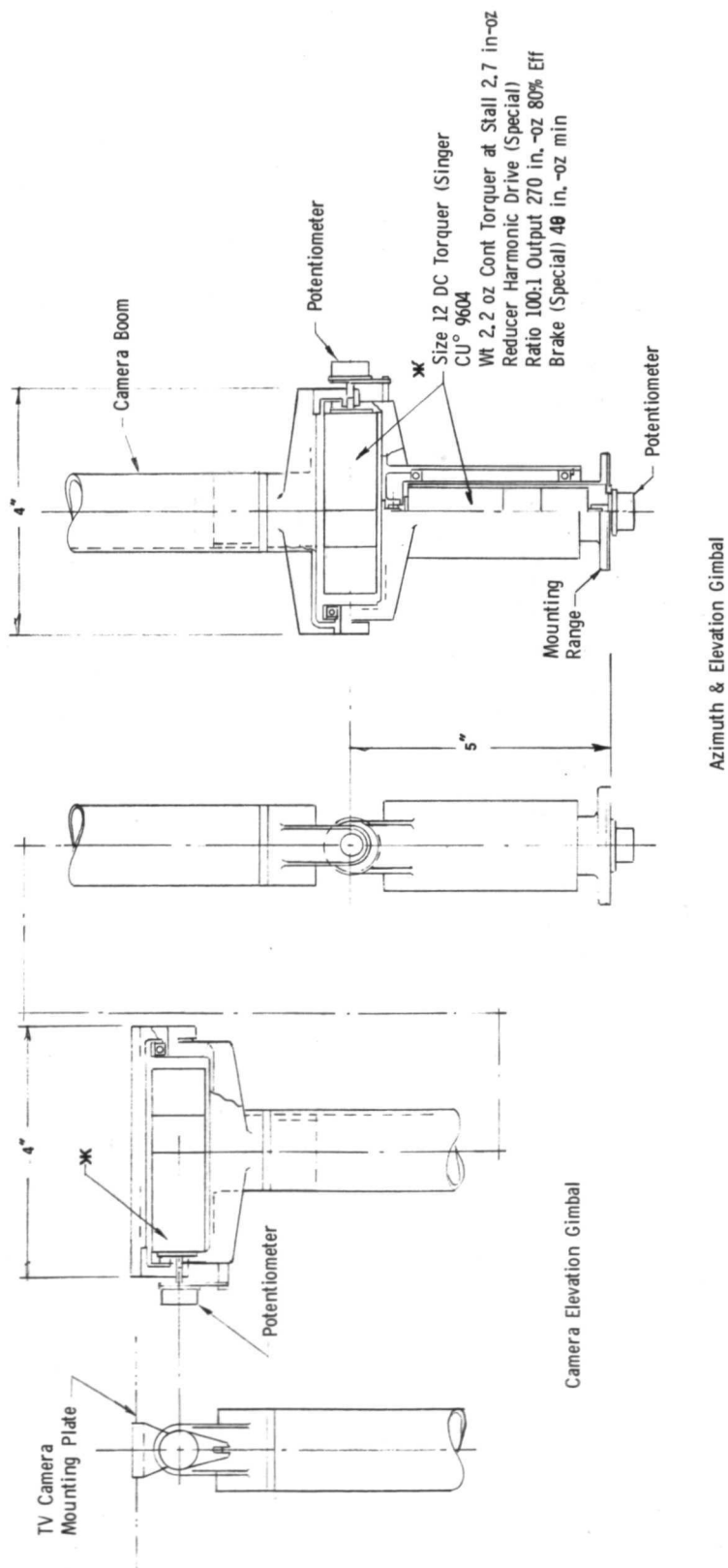


Fig. VI-20 Sensor Articulation Gimbal Detail Design

the reduced torque requirements, the motor is identical to the base motors for simplicity in the hardware procurement cycle to accommodate any minor motor modifications required.

The approximate weight of the articulated boom assembly is about 6 lbs not including wiring and electronics. (Base gimbal, 3.0 lbs; sensor gimbal, 1.25 lbs; and boom, 1.5 lbs).

A brake, providing 48 in oz. minimum, is provided at each gimbal to reduce the power consumption during the time the sensor view is not required to change.

5. Control Modes

The recommended stereo sensor deployment/articulation concept lends itself to three types of control techniques: automatic, manual, and hawk modes. The automatic mode, using pre-programmed viewing locations (e.g. docking, servicing, stowed modules, etc.), enables these locations to be readily placed automatically within the sensor visual coverage. This mode would also be used when it was desired to automatically track the manipulator end effector by deriving the articulation gimbal commands as a function of the manipulator joint angles. In the manual mode, operator actuated input control devices are used to position the visual coverage on an individual "joint by joint" basis, i.e., one input signal per joint is required. The hawk mode provides constant angular alignment of the sensor with respect to the FFTO in pitch. Driving the sensor pitch gimbal at an equal but opposite rate as the base pitch gimbal results in an elevation and range change while the sensor line of sight remains parallel to the initial line of sight at the time the hawk mode was selected. This enables a fine adjustment of the visually covered region without incurring an aspect angle change (sensor rotation), an important consideration during inspection or docking, in that adjustments may be made while maintaining the sensor line of sight parallel to the FFTO control axis.

VII. DISPLAY SUBSYSTEM

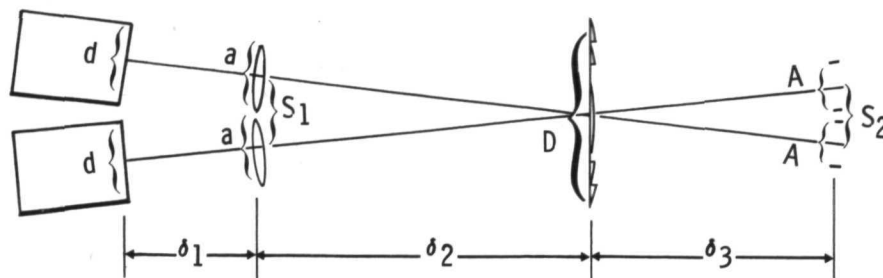
Phase I Summary: Based on statement-of-work specifications and optimization of human factors an approximate 30 cm (12 in) display size was recommended for both the monoscopic and stereoscopic displays. It was apparent that a standard CRT television monitor would provide the most practical display for the monoscopic TV system.

Analytical considerations, man-in-the-loop simulations, and display bench tests led to the recommendation of the fresnel stereoscopic display over other stereo displays because of its inherent high resolution capabilities, high illumination efficiency, and simplicity of design. Various techniques for stereoscopic-to-monoscopic display conversion were briefly considered, but required additional study. A prototype fresnel display using 7.6 cm (3 in) diagonal monitors was constructed and used successfully in visual system simulations.

Phase II Emphasis: The primary effort was directed towards an in-depth analytical analysis of the fresnel stereoscopic TV display parameters and investigating methods allowing additional viewer freedom to avoid the head restrictions inherent in the stereoscopic display. Emphasis was placed on augmented visual displays, alphanumeric and reticles, and stereo-to-monoscopic conversion techniques. Additionally, an engineering design drawing of the final stereo display, for installation at MSFC, was required.

A. DISPLAY PARAMETRIC ANALYSIS

The basic layout of a Fresnel stereoscopic display is shown in Figure VII-1. The viewer to display distance (δ_3) and the display diagonal dimension (D) have been baselined at 3.61 cm (24 in) and 30 cm (12 in) respectively. In addition to these requirements there are several desirable conditions which must be met to optimize the display. The separation (S_2) of the right and left projection axes at the prescribed viewing distance (δ_3) should be equivalent to an average interpupillary separation of the eyes (about 6.35 cm)(2.5 inches), and the exit pupil diameter (A) should approach the dimension S_2 so that the stereo viewing area is maxi-



δ_1 = Object distance

δ_2 = Image distance

δ_3 = Viewing distance

f_L = Transfer lens focal length

f_s = Fresnel screen focal length

M = Image magnification

D = Screen size (measured diagonal)

d = Monitor size (measured diagonal)

A = Exit pupil diameter

a = Transfer lens aperture

S_1 = Transfer lens separation

S_2 = Exit pupil separation

Figure VII-1 Fresnel Stereoscopic Display Parameters

mized. We then have

$$\delta_3 = 61 \text{ cm (24 in)}$$

$$D = 30.5 \text{ cm (12 in)}$$

$$S_2 = 6.35 \text{ cm (2.5 in)}$$

$$A = 6.35 \text{ cm (2.5 in)}$$

In light of the low f number (f/l) at which the Fresnel screen must operate to satisfy these dimensions, optical symmetry about the Fresnel lens is desirable to reduce the obliquity of the incident illumination. We therefore set δ_2 equal to δ_3 .

In addition to the above requirements, the following optical relations must hold:

$$\frac{D}{d} = \frac{\delta_2}{\delta_1} = M \quad (1)$$

$$\frac{A}{a} = \frac{\delta_3}{\delta_2} = \frac{S_2}{S_1} \quad (2)$$

$$f_L = \frac{\delta_1 \delta_2}{\delta_1 + \delta_2} \quad (3)$$

$$f_s = \frac{\delta_2 \delta_3}{\delta_2 + \delta_3} \quad (4)$$

since $\delta_2 = \delta_3$, Eq. (2) requires that

$$S_2 = S_1 = 6.35 \text{ cm (2.5 in)}$$

$$A = a = 6.35 \text{ cm (2.5 in)}$$

$$\delta_2 = \delta_3 = 61 \text{ cm (24 in)}$$

The Fresnel screen focal length is then defined by Eq. (4):

$$f_s = \frac{\delta_2 \delta_3}{\delta_2 + \delta_3} = \frac{(61)(61)}{(61 + 61)} = 30.5 \text{ cm (12 in)}$$

The remaining parameters are defined solely by the size of the monitors (d), or the desired magnification.

For example, if 7.6 cm (3 in) television monitors are used, then from Eq. (1) the magnification is

$$M = \frac{24''}{\delta_1} = \frac{12''}{3''} = 4$$

so

$$\delta_1 = 15.2 \text{ cm (6 in)}$$

From Eq. (3) the transfer lens focal length must then be

$$f_L = \frac{\delta_1 \delta_2}{\delta_1 + \delta_2} = \frac{(15.2)(61)}{(15.2 + 61)} = 12.2 \text{ cm (4.8 in)}$$

Figure VII-2 gives a graphic representation of the display parameters and their relationships to one another.

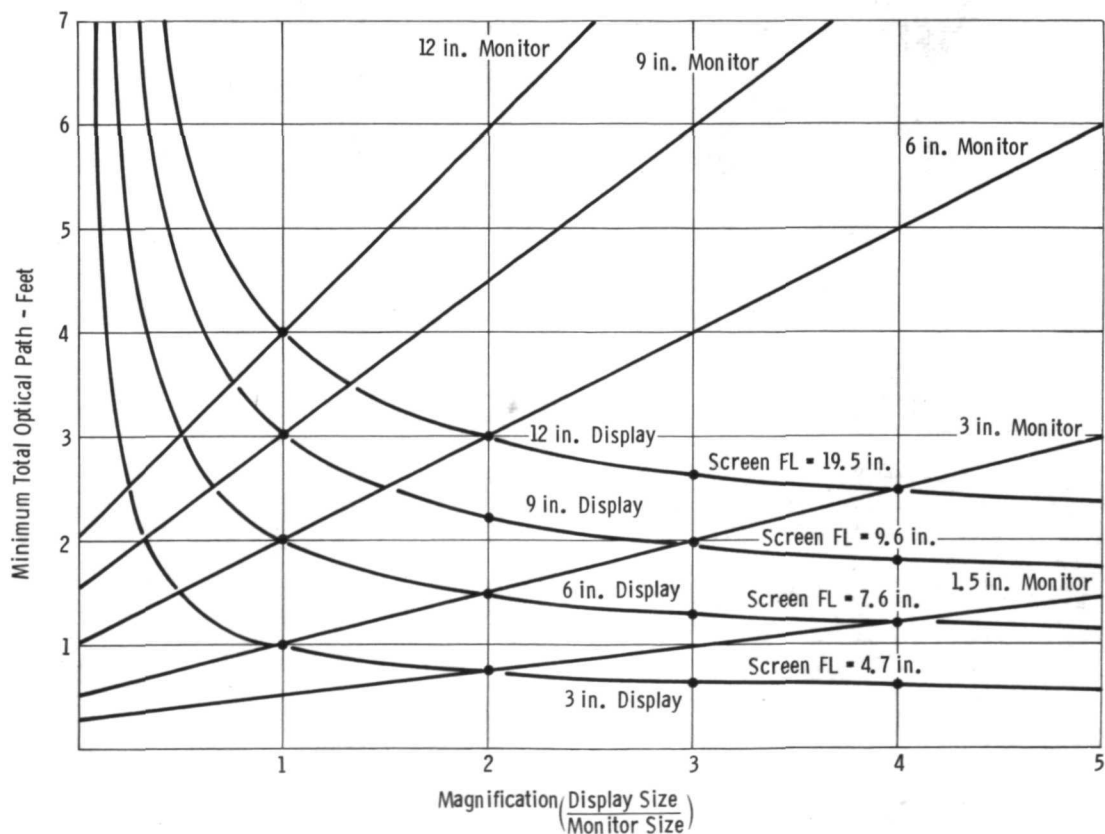


Fig. VII-2 Display Parameter Relationships

It can be seen from the above display analysis that an increased transfer lens aperture (a) will theoretically result in an increased exit pupil (A). However, if (a) is increased significantly beyond

the interpupillary distance of the viewer, then the optical axis separation must also increase. Unfortunately the performance of the Fresnel lens decreases rapidly with off-axis operation and both pupil and image distortion result. For this reason a transfer lens circular aperture (a) greater than 6.35 cm (2.5 in) provides little additional head movement in the horizontal direction. The allowable horizontal head movement for viewing stereoscopic displays without glasses is physiologically restricted to 6.35 cm (2.5 in) anyway unless an eye tracking device is used.

Since stereo information is obtained in the horizontal direction only, the allowable vertical head motion is not restricted by physiological parameters. Vertical motion is restricted only by the display subsystem parameters. An investigation into possible solutions to this problem resulted in the adaptation of the pupil spreading technique shown in Figure VII-3. The horizontal lens-lets on the surface of the screen spread the light vertically from

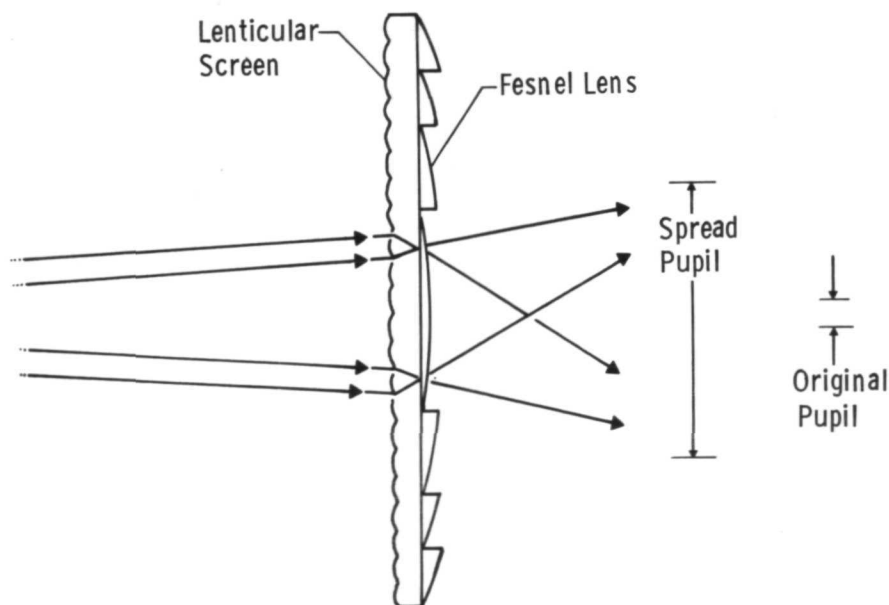


Fig. VII-3 Pupil Spreading Technique

each point on the screen through an angle prescribed by the screen design. Vertical head motion on the order of 30.5 cm (12 in) can be easily attained using this technique in conjunction with the Fresnel stereoscopic display. The illumination efficiency or brightness of the modified display is reduced, but is still greater than other types of displays. Also, ease of display acquisition is greatly improved.

The pupil spreading technique described above has additional versatility as a method of stereoscopic to monoscopic display conversion.

If both monitors in the display are operating, the right and left pupils are spread vertically for stereoscopic vision as described above. If one of the monitors malfunctions, the display can be seen only with one eye. In this situation the display can be converted to monoscopic operation by simply rotating the display screen through 90 degrees about its optical axis. The single exit pupil is then spread in the horizontal direction to allow normal viewing of the monoscopic display. Since the pupil is now spread in the horizontal rather than the vertical direction, the allowable vertical head movement is small, 6.35 cm (2.5 in), and horizontal head movement is large 30.5 cm (12 in). This technique of stereoscopic to monoscopic display conversion maintains constant display brightness with high illumination efficiency regardless of the mode of operation. If greater vertical head motion is desired for viewing in the monoscopic display mode, either the display brightness or horizontal head motion must decrease. It appears that vertical head motion would not be of prime importance since the monoscopic display conversion would be used primarily for redundancy in the case of unexpected component failure.

Results similar to those obtained by pupil spreading could be

achieved by using larger imaging lenses masked to provide the desired pupil shape. This technique would either require very expensive specially ground lenses or a beamsplitter which would reduce illumination efficiency by another 50 to 60%. Such a system would likely be proposed for actual use on space programs, but would be impractical as a preliminary laboratory tool.

B. POLARIZED DISPLAYS

Because of the great degree of viewer mobility associated with a polarized stereo display requiring polarized spectacles, the technique was investigated in parallel with pupil spreading for application to stereoscopic television systems. Various types of back projected diffuse screens were obtained and tested to determine the degree of depolarization at the diffusing surface. The most successful polarized display utilized an Eastman Kodak rear projection screen. This ground glass type screen provided moderate diffusion with high contrast and minimum depolarization. High quality cemented polarizers were used for cross polarizing the stereo images and also for the crossed polarized glasses. Standard 22.8 cm (9 in) television monitors were used for the image source.

The performance of the polarized stereoscopic display was disappointing. The illumination efficiency was so low that ambient light had to be eliminated and the monitor brightness had to be maximized before the displayed image could be seen. Even under these conditions the display was too dim for evaluation. In order to obtain a quantitative measure of the polarized display brightness, as compared to other stereoscopic displays, the displays were measured for effective brightness with a Honeywell Pentax illuminance meter. The results are shown in Fig. VII-4. The unmodified Fresnel display exhibits very nearly the same brightness as a standard television monitor of equal size. The pupil spreading technique reduced the brightness by about 75%. The polarized dis-

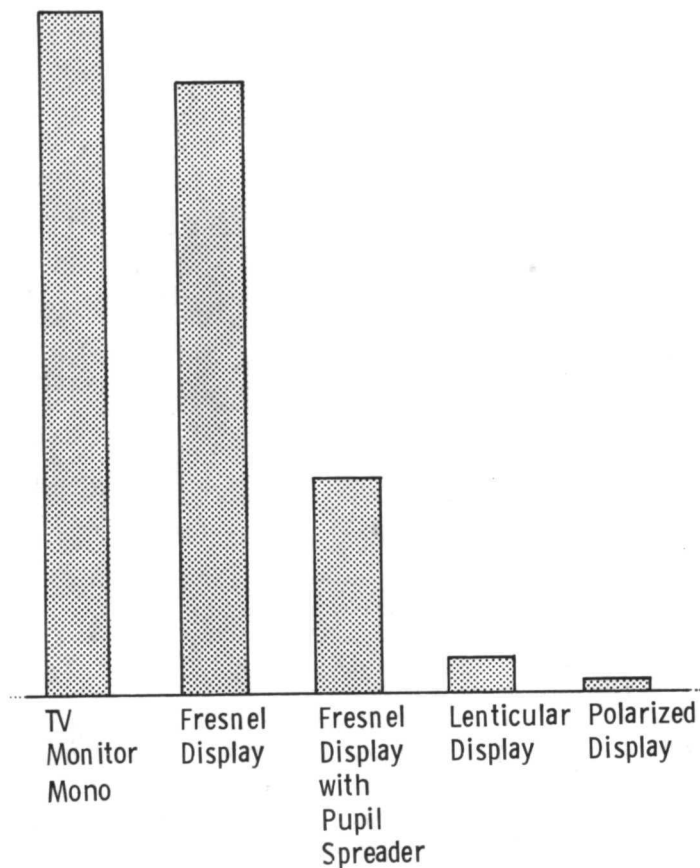


Fig. VII-4 Relative Display Brightness

play resulted in a brightness reduction of about 99% from that of the television monitor using the same transfer lenses as before.

The reasons for the substantial brightness reduction are as follows. Consider the polarized display diagram shown in Fig. VII-5. Light from each display monitor is collected by a transfer lens as in the Fresnel display. The light then passes through a polarizing filter. The estimated light losses due to the polarizing filter are (a) 50% due to polarization, (b) 8% due to reflection, and (c) close to 25% due to absorption resulting in a total transmission of $(50\% \times 92\% \times 75\%) = 35\%$. Consequently only 35% of the light from the lens reaches the display screen. An additional 25% is

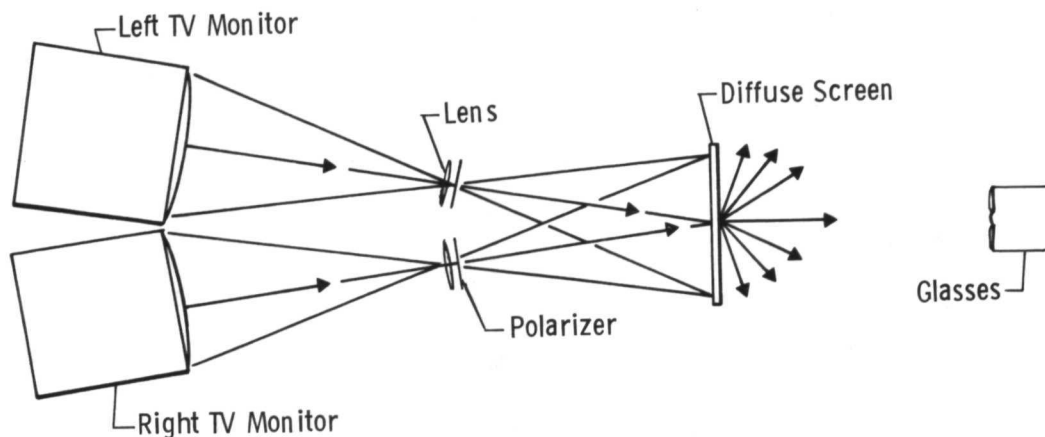


Fig. VII-5 Polarized Display Diagram

lost due to reflections and absorption in the ground glass screen leaving only 26% of the light which passed through the transfer lens to be displayed. The light from the display must again pass through a polarizer (the glasses) before reaching the eye. Since the light is already polarized, the only loss due to the glasses is the 31% due to absorption and reflection, leaving 18% of the original brightness. In addition to the above losses, the light is spread through some solid angle less than 2π steradians by the ground glass screen. It is this diffusion of energy that accounts for the additional decrease in brightness. It is quite possible that additional investigation and research would result in a polarized display brightness 4 or 5 times brighter than the display described above. However, an increase of at least an order of magnitude would be required to meet the display brightness requirements. A significant increase in brightness could be obtained with conventional projection techniques by simply using a brighter projection lamp. The brightness of a cathode ray tube display, however, is severely limited by the tolerance of the phosphor. For this reason the polarized display which has been so popular in stereoscopic film projection systems is not practical for stereoscopic television systems.

Additional problems with polarized displays include vision of peripheral objects through the cross polarized glasses. The degree of discomfort and eyestrain resulting from the use of cross-polarized glasses would likely depend on the duration of usage and the subject's environment. The subject's visual tolerance can only be determined through actual experimentation.

Recognizing the critical illumination efficiency associated with projected cathode ray tube displays and the possible discomfort and confusion associated with cross-polarized glasses, the polarized stereoscopic display described above is not recommended for use with television systems.

C. DISPLAY DESIGN LAYOUTS

Based upon the foregoing analysis the Fresnel stereo TV display system design shown in Fig. VII-6 was completed. This configuration

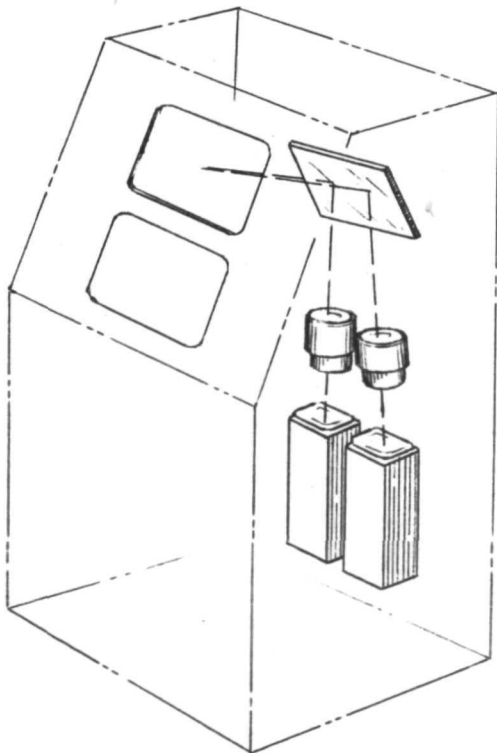


Fig. VII-6 Fresnel Stereo Display

was designed without regard to the layout of the subsystems controls and displays, which will be integrated as they are defined in Section IX, "Controls and Displays Subsystem".

Two 30.5 cm (12 in) diagonal, back-and-white TV presentations are provided. The Fresnel lens stereo unit is located above and a standard monoscopic monitor is below. The stereo display contains two monitors and therefore needs two standard controls.

The Fresnel stereo TV display contains two 7.62 cm (3 in) monitors, two 30.5 cm (12 in) focal length, $f/5.6$, lenses, one 20.3 cm (8.0 in) by 21.9 cm (8.625), 0.635 cm (.25 in) thick, $\frac{1}{4} \lambda$ front reflecting mirror, and a Fresnel lens system consisting of two 61 cm (24 in) F.L., 125 lines/inch Fresnel lenses mounted back to back and sandwiched between two sheets of 0.318 cm (.125 in) glass. The front glass is non-glaring. A detailed design drawing is shown in Fig. VII-7.

Figure VII-8 illustrates two alternative Fresnel stereo TV displays using 22.85 cm (9 in) monitors. These systems contain the two monitors, two 30.5 cm (12 in) F.L., $f/5.6$ lenses, 5 front reflecting

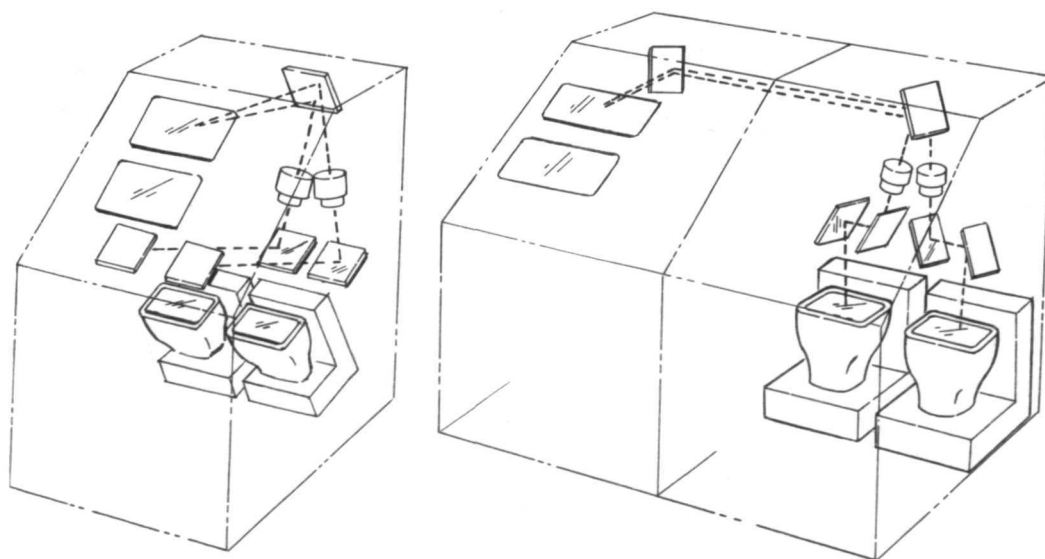


Fig. VII-8 Alternative Fresnel Stereo Displays

mirrors varying in size from 8.71 cm (6.8 in) by 25.4 cm (9.6 in), and a Fresnel lens system consisting of two 61 cm (24 in) F.L., 125 lines/inch Fresnel lenses sandwiched between two sheets of 0.318 cm (.125 in) glass. The front glass is non-glaring. A detailed design drawing of the single rack mounted unit is shown in Fig. VII-9.

The primary difference between the Fresnel stereo TV displays presented is the monitor size used. The size of the monitor dictates to a large extent the lenses used in the system and the optical distance between the monitors and lenses.

A one-inch television monitor utilizing a Ferranti micro-spot CRT is presently under development. It is possible that such a monitor could be used in a space qualified Fresnel display to reduce size, optical path, and power consumption.

D. AUGMENTED VISUAL DISPLAYS

The TV monitors in the control station can be utilized to display locally generated data either in place of or in conjunction with the remotely originated video. In this section two types of videographic data are discussed: 1) alphanumeric characters and 2) stereoscopic reticles.

1. Alphanumeric Characters

The basic advantage of character generation over using auxiliary displays is that data can be presented to the FFTO operator without his having to take his eyes from the screen. This is especially important for example, where the operator is flying the FFTO toward a satellite using both visual and range/range-rate data. If the data and the video appear simultaneously on the screen it is a simple matter to watch both. However, if range/range-rate utilizes a separate display, the operator must constantly glance back and

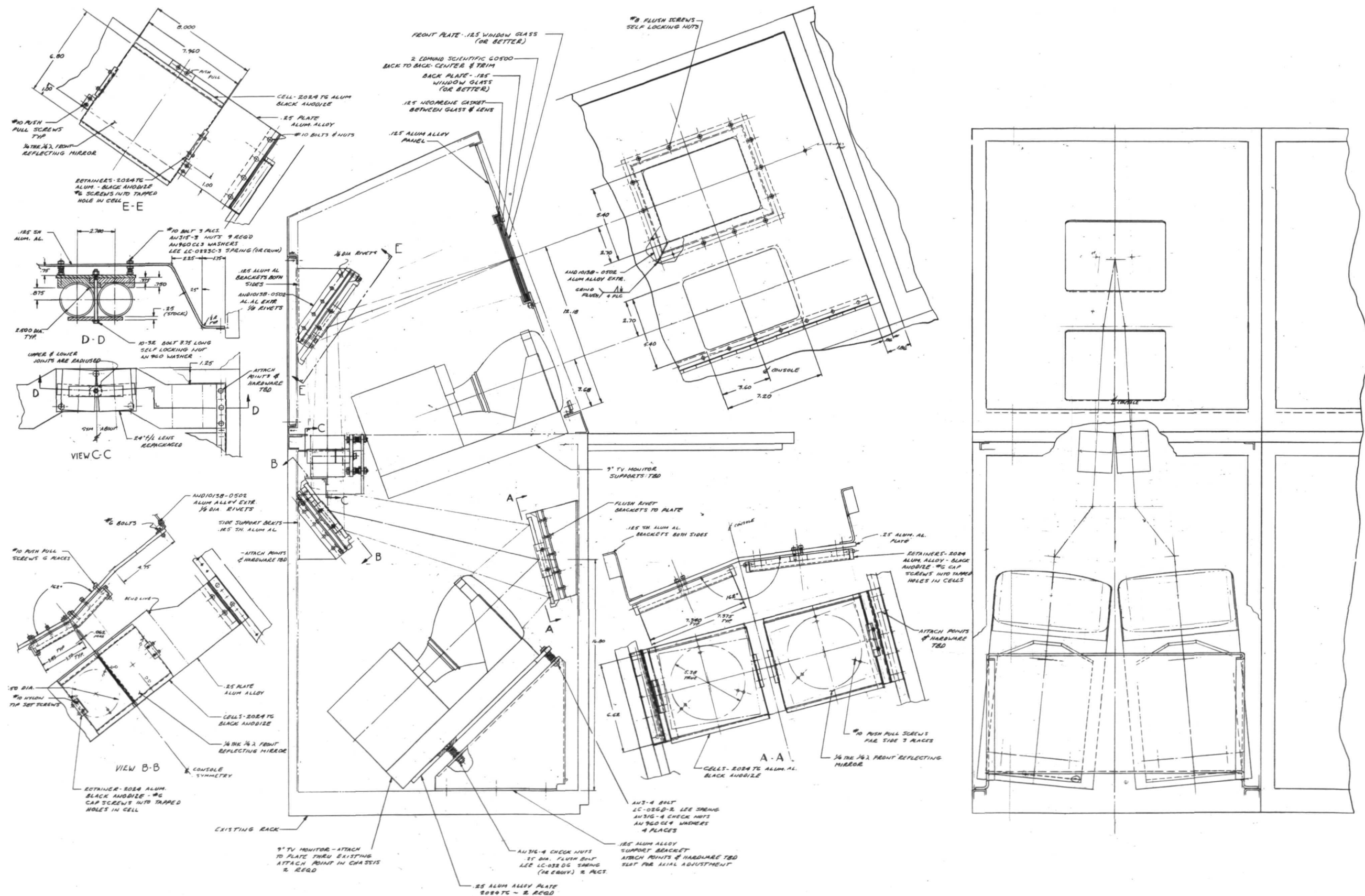


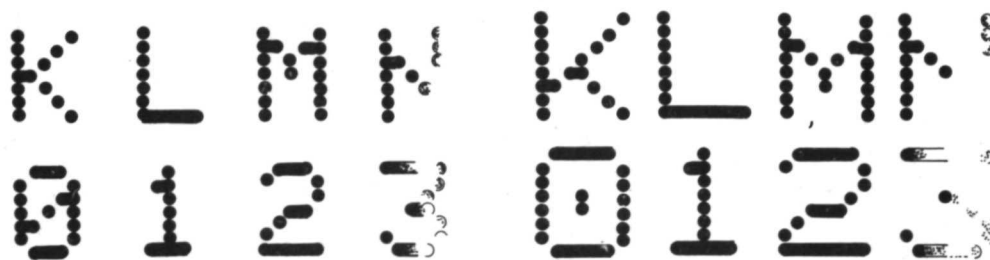
Fig. VII-9 Alternate Fresnel Stereo Display Design Drawing

forth and it will be more difficult to concentrate on either information.

The basis of videographic generation is that a video signal is produced by artificial means without camera involvement. The generated signal can be displayed alone or can be mixed with or used to modify camera video. The normal line and frame rates are used as the basic timing parameters for character generation on broadcast television. Since those standards have been recommended for the visual system, those rates apply here. A letter or number is produced by generating a series of properly timed pulses. The height of the pulse determines the screen brightness and the timing determines where the pulse appears on the screen. Fig. VII-10a shows several letters and numbers using a 35-dot character matrix: 5 dots horizontal, 7 dots vertical. This is generally the minimum requirement for displaying all common alphanumeric characters. Each dot represents a unit pulse which shows up as a short white line on the screen. A character is produced one horizontal line at a time as the horizontal sweep traces out one line on the display. Where there are two (or more) dots adjacent horizontally one pulse the length of two (or more) unit pulses is produced rather than two separate unit pulses.

The greater number of dots in the character generator matrix the more complex -- and in the case of alphanumerics, graphically correct -- the character which can be produced. The 7 x 8 matrix in Figure VII-10b shows some letters and numbers which appear more "normal" to the observer than those of the 5 x 7 matrix.

One difficulty of using generated characters in conjunction with video is that one cannot choose the background. If a white character appears over a white portion of a spacecraft in the picture, the graphics will be washed out. A number of methods have been devised to eliminate this problem. The simplest procedure is to merely blank the portion of the camera video in which the videographics



a) 35-Dot Matrix

b) 56-Dot Matrix

Fig. VII-10 Alphanumeric Character Examples

appear (a blanked spot appears black on the screen). Thus the character will always have a black background. This approach is inefficient, however, since more of the view is obstructed than necessary. A better way is to blank out a small area of the camera video just slightly larger than the character. The character will then appear white with a black outline and be visible on any background with minimal interference to the view. Fig. VII-11 illustrates this process.

Starting with a 5 x 7 dot matrix the letter F is generated, line by line as in Fig. VII-11a. In order to outline the letter, the video line must be blanked one line earlier than the beginning of the letter.

If the first line of the character is called line 0, then the outline must begin on line -1. Notice also that on each line the blanking begins before the leading edge of the character pulse and ends after the trailing edge by a small amount. This action produces the black outline to the left and right of the character. The video blanking will produce a black area in the video picture of the shape shown at the right in Fig. VII-11b. The result, when the generated F is superimposed on the blanked video signal, is shown in Fig. VII-11c.

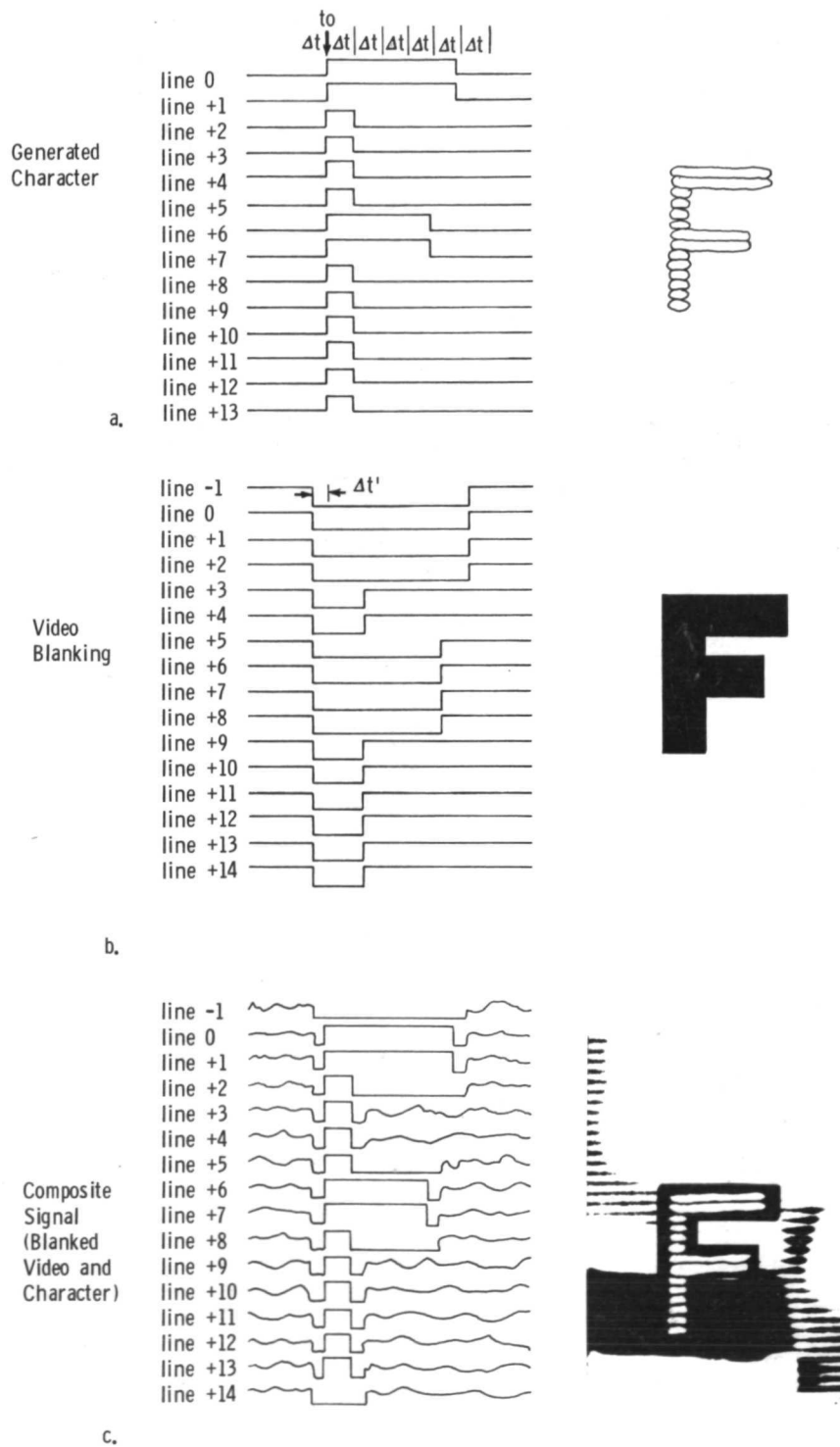


Fig. VII-11 Alphanumeric Character with Outlined Edges

Many other methods are used to make the alphanumerics visible on varying backgrounds. Some outline only the vertical edges, some outline only left or right vertical edges but not both. These incomplete outlines still seem to provide enough information to be legible and yet cause minimal interference to the viewed picture.

The information necessary to produce a specific character is normally stored in a type of integrated circuit called a read-only memory. A 5- to 8- binary-bit input code is used to call a specific character. The input codes can be applied by a computer, A/D converter or other digital source.

Alphanumeric character generation is well within the current state of the art. Most applicable techniques have been in practical use for years. All electronic components necessary have already been tested in previous space applications.

2. Stereoscopic Reticles

The stereoscopic television systems described earlier provide depth perception with varying degrees of stereo acuity. As with direct vision, these systems are more useful in discriminating depth or range differences than in actual quantitative range approximations. If a ranging capability associated with the visual system is desired, an operator controlled reticle which will vary in range can be generated on the display. Quantitative range information can then be obtained by simply aligning the stereo reticle (in depth) with the object of interest. The range accuracy of such a ranging device should be limited only by alignment tolerances and the stereoscopic depth resolution element (r) given in Eq. (15), Section IV. Consequently, visual ranging accuracies will correspond directly to the stereoscopic acuity curves in Figure IV-12 .

During the period of this contract a video synthesizer was designed

and built, as shown in Fig. VII-12, which has the capability to display a stereo reticle and two stereo dots which can move along three translational axes in response to computer commands or to manually applied dc voltages.

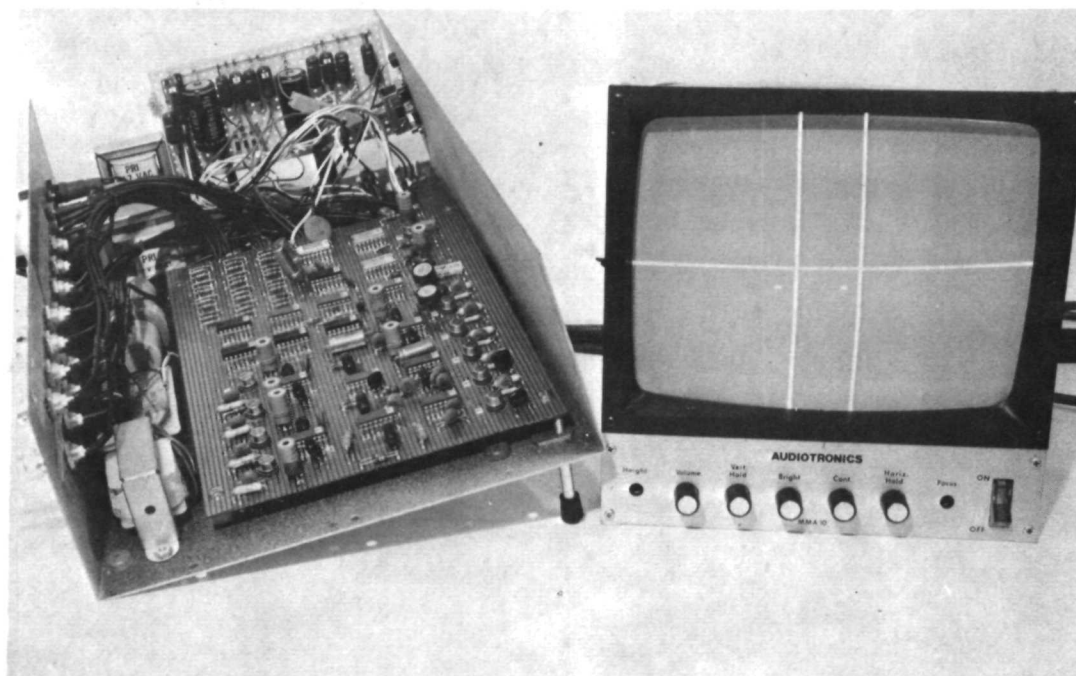


Fig. VII-12 Stereo Reticle Video Synthesizer

A stereo display is produced by presenting a different synthesized "scene" to each eye. Two separate images are transformed optically so that one image is presented to the left eye and the other to the right eye. The two images can be on separate monitors, or halves of a single monitor, or of different colors superimposed on one monitor. The video synthesizer will provide the proper monitor inputs for any of these presentation methods. The techniques for optical separation of the images will not be discussed here. Assume that the left image is presented to the left eye, the right image to the right eye. Referring to Fig. VII 13, if the images are exactly the same, it will appear as a single scene with all elements

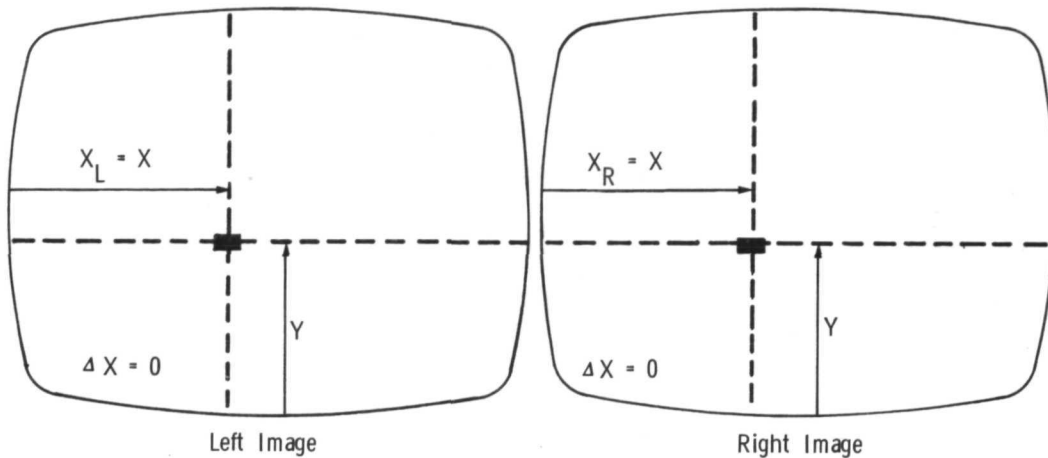


Fig. VII-13 Display with Dot in Plane of Screen

of the scene in the plane of the monitor. In this case the scene is two dimensional--flat. Now, assume one element, a dot for example, is moved to the right in the left image and to the left in the right image as shown in Fig. VII-14. Now, to focus on that dot the eye muscles must move the left eye in or to the right. Likewise the right eye must move in or to the left. In other words, the eyes must "cross" more and the dot will no longer seem to be in

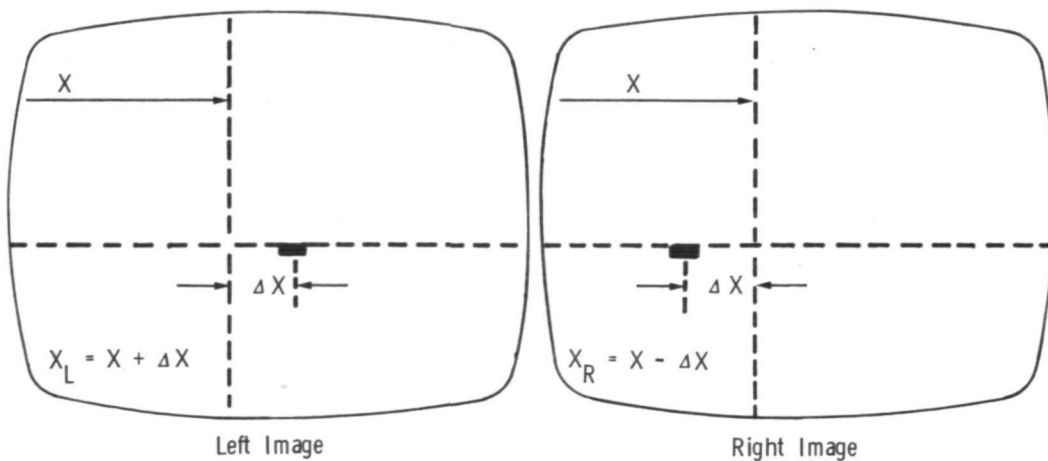


Fig. VII-14 Display with Dot Displaced Toward Viewer

the plane of the monitor but will appear closer to the viewer. Its horizontal or X coordinate remains the same but its Z coordinate varies, where a positive Z is defined as out of the screen toward the viewer. The Z displacement is thus determined by adding ΔX to the X coordinate in the left image and subtracting ΔX from the X coordinate in the right image. ΔX can be of either sign: positive is toward the viewer, negative is away from the viewer.

Fig. VII-15 is the video synthesizer block diagram. The X command

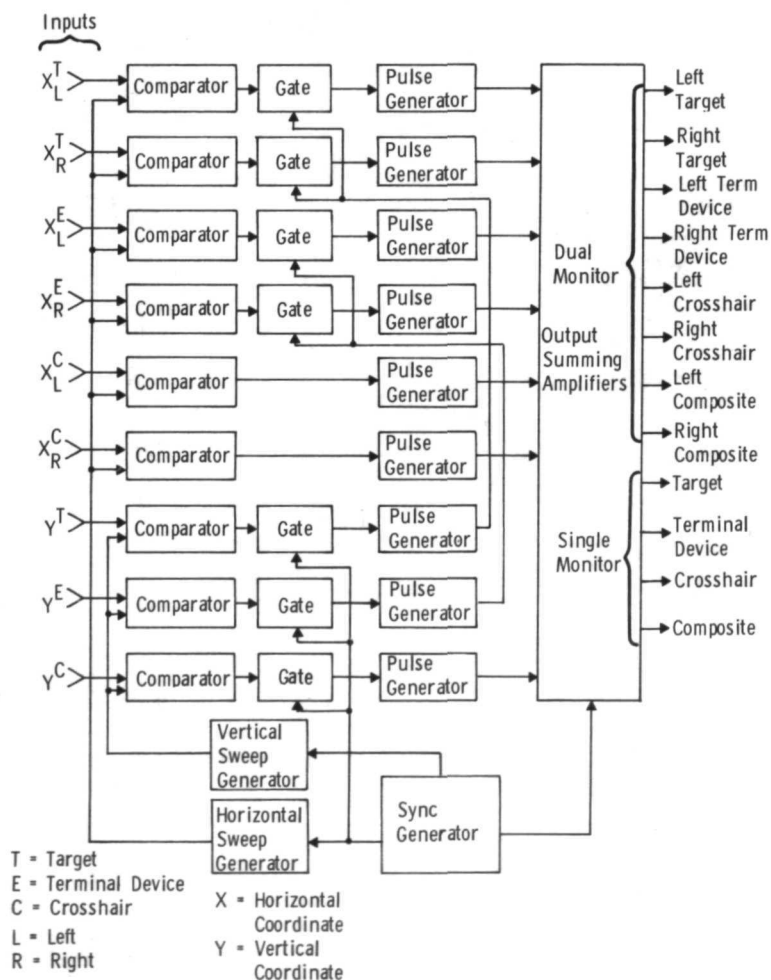


Fig. VII-15 Video Synthesizer Block Diagram

for the crosshair to be seen by the left eye is X_L^C . When the input from the Horizontal Sweep Generator is more negative than X_L^C the Comparator output is zero. The Horizontal Sweep Generator produces a linear sawtooth which starts at -10 volts and sweeps in a positive direction to +10 volts. This process is repeated 15,750 times per second. Each sweep corresponds to one horizontal line on the face of the monitors. Assume $X_L^C \approx 5.0$ volts. As soon as the output of the Horizontal Sweep Generator becomes more positive than 5.0 volts the Comparator output goes high and triggers the Pulse Generator. The pulse produced causes a white spot to appear on the otherwise dark monitor screen. Since this process occurs once during each horizontal line, at the same X displacement on each line, the result is a white vertical line on the screen.

Now let us see how the horizontal line of the crosshair is developed. A similar comparison is used to determine the Y component of the crosshair. The Vertical Sweep Generator produces the same kind of -10 volt to +10 volt sawtooth except that it occurs 60 times per second and corresponds to the monitor vertical scan. As soon as the sweep voltage goes positive with respect to the Y^C command the Comparator switches from zero to high. However, the Gate holds the Comparator output from triggering the Pulse Generator until the beginning of the next horizontal scan line, to avoid a scan line which is partially black, partially white. During the horizontal blanking interval the Gate opens and triggers the Pulse Generator. The pulse duration allows one scan line to appear white--the horizontal portion of the crosshair.

The dot generation is similar except that the output of the Y Pulse Generator is used to gate the X pulses. For example, the X_L^T Comparator will produce an output during each horizontal line. However, it does not trigger a pulse because the Gate is held

closed by the output of the Y^T Pulse Generator. When the Y^T Comparator goes high and the next horizontal line begins, the X_L^T Comparator output triggers the Pulse Generator and produces a dot on the monitor screen. At the end of that horizontal line the Y^T goes back to zero and closes the X_L^T gate. Thus only one dot appears on the screen rather than a whole sequence as in the case of the crosshair.

Timing for the Horizontal and Vertical Sweep Generators is provided by the crystal-controlled Sync Generator. A synchronizing signal which becomes part of the composite video is sent from the Sync Generator to the Output Summing Amplifiers.

The Output Summing Amplifiers are an array of 12 video amplifiers with an input matrix which provides the proper combination of signals--including sync--at the output. All the outputs can be used simultaneously or separately.

E. STEREO RETICLE SIMULATION

If a ranging capability associated with the visual system is desired, an operator-controlled stereo reticle such as the one described above may be used to determine the quantitative range information with respect to the object of interest in the stereo FOV by simply aligning the stereo reticle in depth with the object. Range is determined by the position of the reticle dial on the control console or by an auxiliary numerical display voltage readout. Fig. IV-12 was verified using the stereo reticle generator and stereo display system. The results demonstrated that ranging accuracy is limited only by the resolution and alignment tolerance of the TV system.

F. DISPLAY SUMMARY AND RECOMMENDATIONS

It was determined in Phase I of this study that a standard CRT

Display Monitor, approximately 30 cm (12 in) diagonal would be used for the monoscopic television display. Minimal modification of existing commercial TV monitors would be required for space qualification.

A thorough analytical study and associated laboratory investigations of the Fresnel stereoscopic display have resulted in further sophistication of the stereoscopic television display technique. Optical design parameters have been described in detail and an operational Fresnel display prototype was constructed and used in man-in-the-loop visual system simulations. Vertical head restrictions previously associated with the Fresnel display have been eliminated for improved display acquisition and retention. Other stereoscopic display techniques investigated proved impractical for use with television systems. Based on the simplicity, efficiency, and realism of the Fresnel display, it is recommended for the display of stereoscopic TV imagery. Existing mini-monitor development programs suggest additional miniaturization of the stereo display package for application to the teleoperator visual system.

The added capability of videographic generation on the control station TV monitors is also recommended. The monitors could then be used to display locally generated data either in place of or in conjunction with the remotely originated video signal. Laboratory simulations indicate that videographic generation can add alphanumeric displays and an accurate visual ranging capability to the display subsystem.

VIII. TELECOMMUNICATION SUBSYSTEM

Phase I Summary: Analysis and trade-off studies were conducted to identify, based upon a visual system employing three TV cameras, the antenna configuration, choice of frequency, power requirements, and video transmission techniques. The approach recommended was to use an omnidirectional circularly polarized antenna, a transmission frequency of 2100 MHz, and a separate-channel video link: one 5 MHz, 1.5 watt, transmitter per camera.

Phase II Emphasis: The primary telecommunication subsystem effort during Phase II was directed towards minimizing the total visual system bandwidth required by multiplexing, in some manner, the two stereo cameras. Additionally, the visual subsystem and the overall FFTO command and control requirements were to be identified and integrated such that a recommended telecommunication subsystem could be established.

A. TV TRANSMISSION BANDWIDTH ANALYSIS

To display video pictures with good resolution and motion rendition, the transmission link from the FFTO to the control station must possess adequate bandwidth. However, to minimize the transmission bandwidth, the spectrum required and methods for bandwidth reduction must be analyzed in depth.

1. Wideband Video Link System

Figure VIII-1 shows the most straightforward method of handling signals simultaneously from three television cameras: a single camera and a stereo pair. The only elements common to each of the three video channels are the summer, divider, and the antennas as each camera modulates a separate transmitter. At the receiving station, each channel is selected and demodulated by a separate receiver and sent to the proper monitor for viewing. The bandwidth required for this system is simply the sum of the bandwidths required for each of the three similar channels.

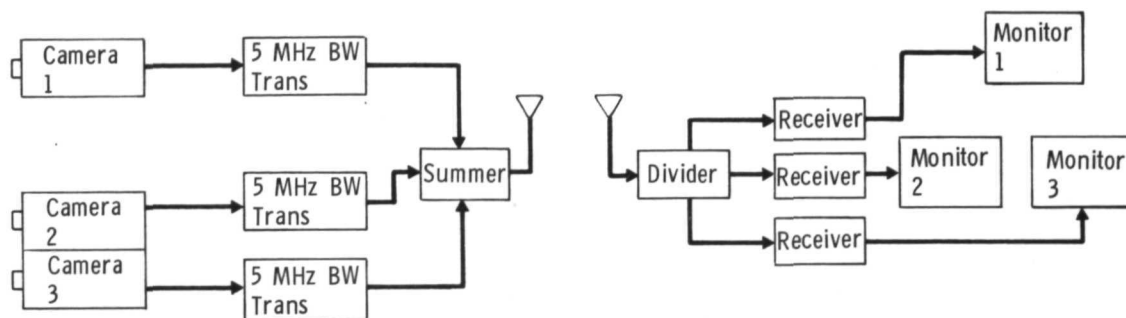


Fig. VIII-1 Wideband Video Link

Assuming the resolution required is approximately 350 lines, the frequency response of the transmission link must be great enough to allow 350 alternating black and white vertical lines to be distinguished on the monitor screen. In the standard 525 line, 30 frame per second format, a horizontal line is scanned in $63.5 \mu\text{sec}$. Allowing $10 \mu\text{sec}$ for overscan and retrace, the viewable portion of each horizontal scan line occurs in $53.5 \mu\text{sec}$. The width of each black or white line element therefore is $\tau = \frac{53.5}{350} = 0.153 \mu\text{sec}$. These elements will be distinguishable when the video cutoff frequency, $f_c \geq \frac{1}{2\tau}$. In this case $\frac{1}{2\tau} = 3.3 \text{ MHz}$. Thus, if the video circuit passes all frequencies below 3.3 MHz, the desired resolution will be maintained.

The corresponding RF bandwidth can be determined after selecting a modulation method to be used. For minimum bandwidth, the only acceptable candidates are amplitude modulation (AM) and narrow band frequency modulation (NBFM). Both systems require a bandwidth of twice the highest modulation frequency: $B_{\text{RF}} = 2f_c = 2 \times 3.3 \text{ MHz} = 6.6 \text{ MHz}$. However, in the case of AM, the bandwidth may be cut further by transmitting all of one sideband but only a portion of the other as the information contained in both sidebands is identical. Single sideband FM exists but is far less practical to generate. Assuming AM is the chosen modulation method with one

500 KHz sideband, the overall bandwidth for a single channel must be at least 3.8 MHz. In practice, a somewhat greater spectrum allowance is made to provide for frequency rolloff throughout the system. A practical bandwidth for each of the three channels would be 4.5 MHz and the spectrum required for all three wideband video channels is 13.5 MHz. These channels need not be adjacent in frequency but should be close enough to be well within the bandwidth of the antenna system employed.

It should be noted that the wideband video can be configured to use only one transmitter and receiver through frequency multiplexing or through pulse amplitude modulation (sampling). However, neither of these techniques would reduce the frequency spectrum without a sacrifice in resolution, and the redundancy attendant in two or more transmitters would be lost.

2. Non-multiplexed Reduced Bandwidth System

A number of methods can be used to reduce the transmission bandwidth, but each method requires some sacrifice in resolution or motion rendition, Fig. VIII-2 shows a system in which the bandwidth is reduced to 10 MHz. If 3 MHz is allowed for each channel, including 0.5 MHz for the vestigial sideband, the maximum resolution of each channel becomes approximately 270 lines. This method decreases the operator's ability to distinguish small objects in

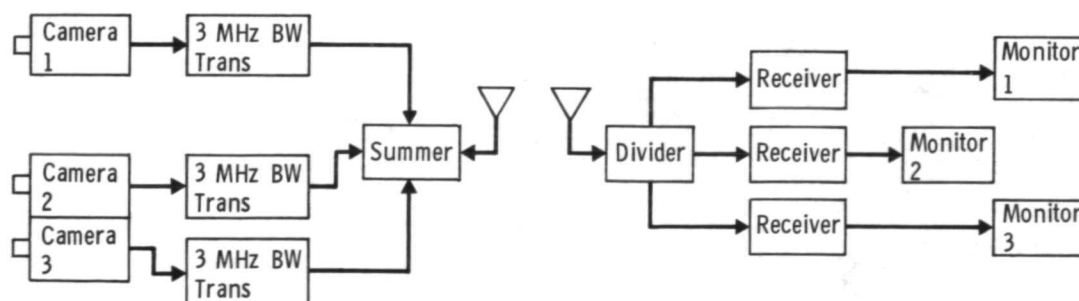


Fig. VIII-2 Non-Multiplexed, Reduced-Bandwidth Video Link

the field-of-view. However, 270 lines is conditionally acceptable provided other frequency limitations in the transmission path between the camera and the monitor do not further degrade the resolution. The primary drawback is the fact three separate transmitters must be used.

3. Multiplexed Systems

The multiplexed system analysis is primarily based upon reducing the bandwidth of the stereoscopic sensor to that required by a single monoscopic system. Several proposed techniques are discussed below.

a. Slow-Decay Monitors - A multiplexing scheme, alternately transmitting a video frame from the stereo sensor, Cameras 2 and 3, while the video from the monoscopic sensor, Camera 1, is transmitted normally, is illustrated in Fig. VIII-3.

The frame alternation is accomplished by a synchronous switch which also adds a digital code during the vertical blanking interval to identify whether the frame being transmitted is from Camera 2 or 3.

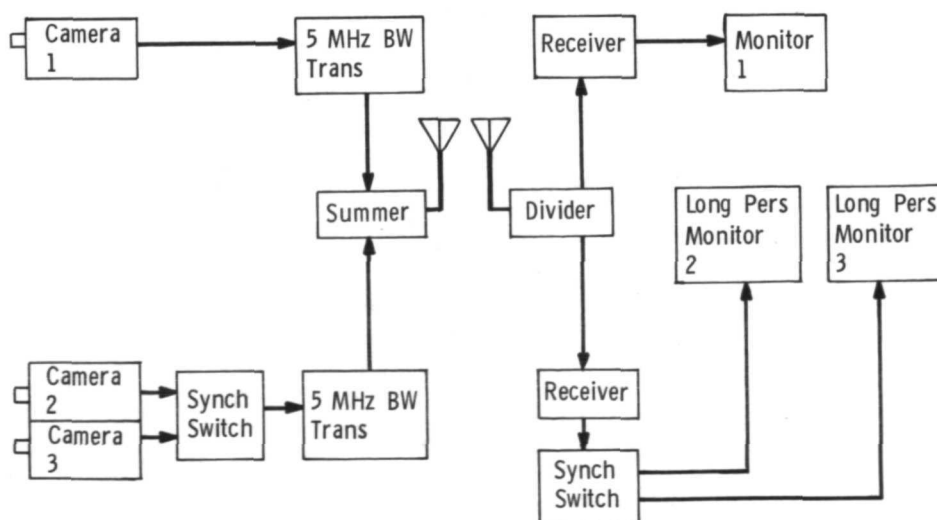


Fig. VIII-3 Frame Alternation with Slow-Decay Monitors

Hence, the encoded two-camera signal takes no more spectrum space than that of a single camera and can be transmitted by a single 5 MHz bandwidth transmitter without further treatment. However, the multiplexed signal must be decoded before display. The video output from the receiver, containing the alternate frames from Cameras 2 and 3, is sent to a second synchronous switch. This switch reads the coded identifier and routes each video frame to the proper monitor.

The basic difficulty with this approach is that a picture is traced out on Monitor 2 in 1/30 second but is blank during the next 1/30 second period while Monitor 3 is receiving its frame. While the eye tends to integrate the display during the blank frame, the effective 15 frame per second rate is too low to prevent objectionable flicker. Some method is needed to "store" the picture and keep it on the monitor screen until it can be updated. The simplest storage mechanism is to use a cathode ray tube with a "longer-than-normal" persistence phosphor. The scene, once painted on the screen by the electron beam, does not die away immediately but fades more slowly and helps the eye to integrate during the alternate frame. It is obvious that any rapid motion in the scene will be subject to smearing and any 30 frame-per-second video displayed on the screen will smear even more.

b. Scan Converters - The disadvantage of slow-decay monitor tubes can be overcome, while maintaining the same basic system, through the use of scan conversion, as illustrated in Fig. VIII-4.

The scan converter acts as a one-frame storage device which replays the same frame to the monitor during the time it would not ordinarily receive an input. For example, assume a frame from Camera 2 is being transmitted. At the receiver, the synchronous switch is allowing the video to enter the scan converter associated with

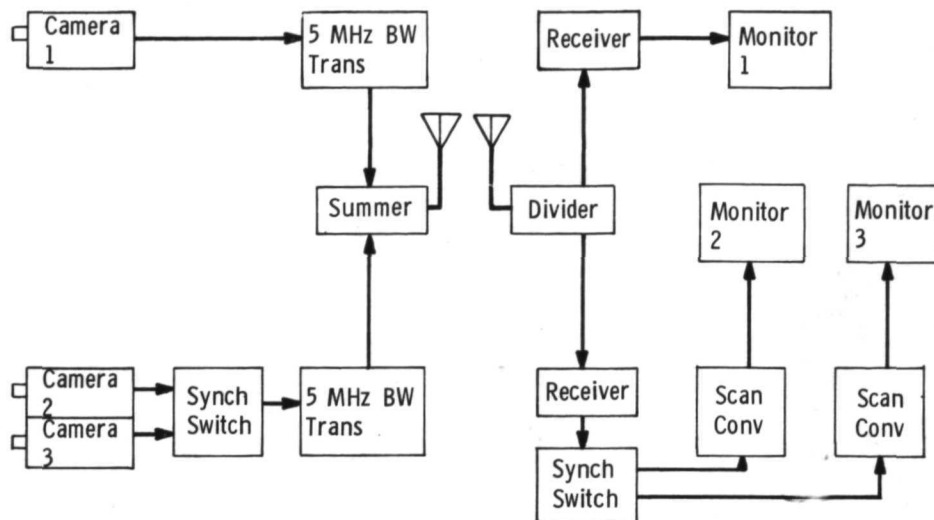


Fig. VIII-4 Frame Alternation with Scan Conversion

Monitor 2. During this frame two things are happening: the video is displayed "live" on Monitor 2 and the scan converter is recording this video signal. Upon completion of the frame, the synchronous switch sends the video to the scan converter associated with Monitor 3. During this frame, Monitor 2 does not receive a "live" input but instead receives the recording of the previous frame from its scan converter. Thus each monitor sees the same frame twice and, while the update rate remains at 15 frames per second, the monitor receives a video input at the normal 30 frame per second rate and flicker is eliminated. Three scan conversion methods are described: storage tubes, disc memories and charge coupled device (CCD) arrays.

Storage Tubes: The storage tube is a special purpose cathode ray tube (CRT) possessing one or more electron guns with a beam collimating system and a dielectric disc at the faceplate which acts as a charge storage area. The beam, intensity modulated and deflected as in a conventional CRT, establishes a stored charge

pattern on the disc rather than exciting a luminescent phosphor. The charge pattern may be retained "indefinitely" until deliberately erased or may be designed to dissipate in a fraction of a second. The stored information may be read out either by the same electron gun and deflection system or by a separate system. Storage tubes have been used for many years for a wide variety of scan conversion applications. However, it suffers from certain limitations in the alternate field storage application presently considered. The first problem area is the relatively long time required to erase a stored image. It normally requires a full frame time, and preferably two, for erasure. This length of time means that it is not possible to write a frame, read it during the next frame period and then write a new frame. No time remains for the erase operation. Therefore, it would be necessary to employ two storage tubes for each of the monitors, or a total of four tubes for the stereo system. Fig. VIII-5 shows the sequencing of the scan converter required to decode and display a dual camera signal, indicating that the sequence repeats after four frames.

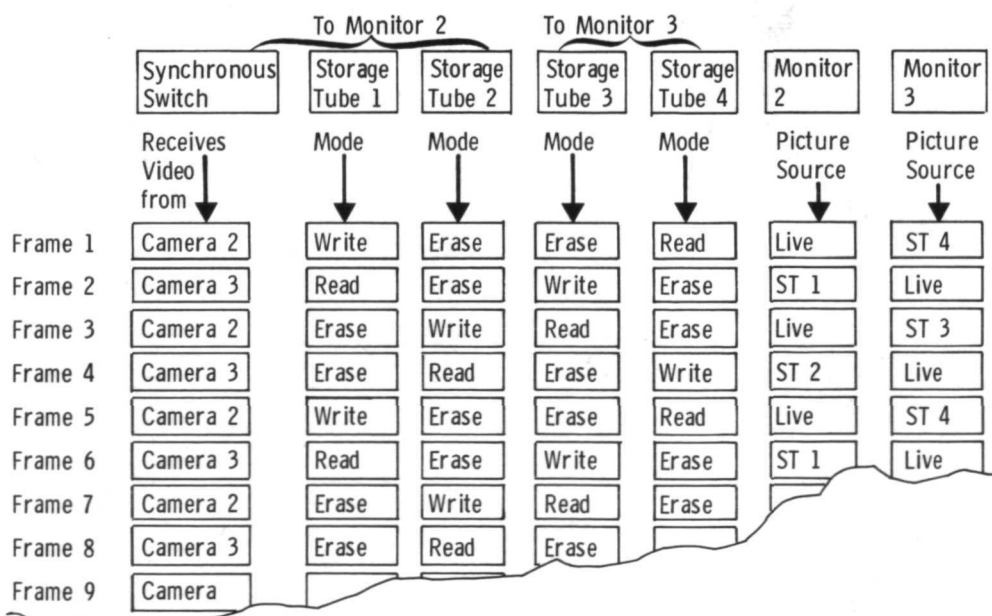


Fig. VIII-5 Storage Tube Scan Converter Sequencing

Besides the weight and bulkiness caused by four separate scan tubes, it is difficult to eliminate nonlinearities in sweeping the electron beam across the dielectric disc. These nonlinearities vary with time, temperature, voltage, and magnetic fields and may be different between tubes. The effect will be misregistration in the display which makes the picture appear to "jiggle" in certain areas of the screen or generally over the screen as the monitor input is switched between live video and its two converter tubes. These negative factors outweigh the one advantage the storage tube system has over the magnetic disc recorder: no moving mechanical parts.

Magnetic Disc Recorder: Scan conversion can also be accomplished by a magnetic disc. A video frame can be recorded on a disc coated with a magnetic oxide which rotates at high speed. The principles involved are the same as those for recording and playback of magnetic tape. That is, a record head may be preceded by an erase head to clear the disc of previously recorded information. There is no frame/two-frame delay to deal with and two frames may be placed on the same disc and recorded or played back independently. Thus, only one multiple-head mechanism is needed. As long as the angular velocity of the disc is constant there can be no registration problem between the live and the recorded images. The primary drawback of the disc recorder is that it contains moving parts. In addition, the disc mechanism must remain pressurized during operation since the disc and head are kept separated by a cushion of air while spinning. It is also possible that vibration and gyroscopic effects on the spinning disc during spacecraft attitude maneuvers could affect the picture. Although some developmental efforts have been made to produce a space qualified scan converter for sequential color, no such equipment has yet been qualified.

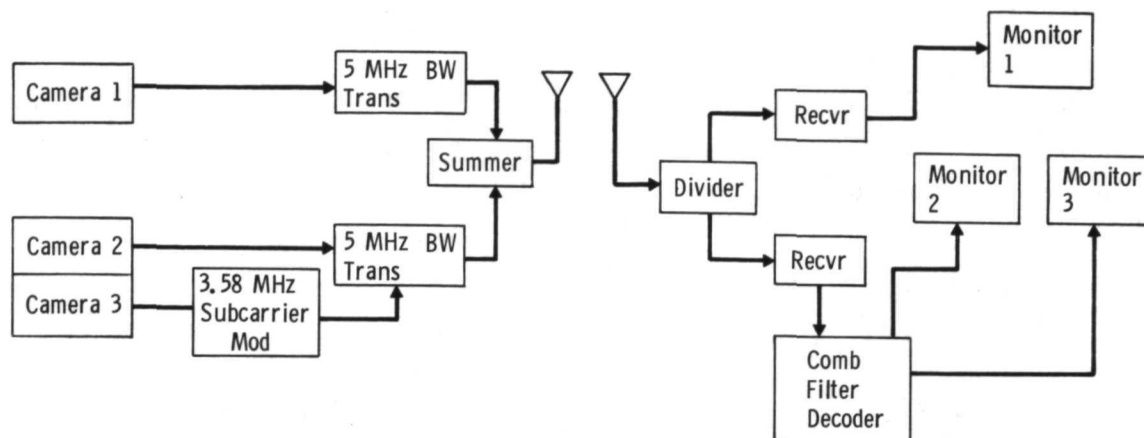
Charge-Coupled Device (CCD): The CCD was described in Phase I as a possible sensor for a TV camera. The only disadvantage compared to other "space-ready" cameras is that it is developmental and no array large enough to give the required resolution has been produced. In all other respects it is superior. In addition to its value as a sensor, the CCD can also function as an analog shift register.

The CCD consists of a silicon substrate insulated from tungsten electrodes by a thin layer of silicon dioxide. In the case of a photo-sensor, light impinging on the substrate is converted into a quantity of charge which is stored in potential wells. The magnitude of the charge depends on the number of photons hitting the surface. When the CCD is used as a shift register, a diffusion into the silicon at the input allows the entry of charges to form the potential wells from an analog input signal. These potential wells are moved along from cell to cell until they reach a second diffusion where the charge again appears as a voltage signal. If the CCD consists of n cells and the clock frequency is $\frac{1}{t}$, the CCD acts as a delay line of nt seconds. The delay time can be easily varied by adjusting the clock frequency and can store the information indefinitely if the clock frequency goes to zero. Because the shift operation is performed digitally there is no problem with misregistration of the images. For image storage an array of 400 by 500 elements is required: 400 elements in the horizontal direction to slightly exceed the 350 line resolution requirement and 500 in the vertical direction to provide line-by-line storage. It is not necessary to store lines in the vertical blanking interval. Only one such array is needed for the current scan conversion application. As a line from the first frame is read out to one monitor, the corresponding line from the second frame can be read into the array. It is only necessary to switch the CCD array output between monitors.

Because an image is not being formed on the silicon substrate when the CCD is being used as a shift register, it is not necessary to form the device on a single silicon chip. For example, 16 area arrays of 128 by 106 elements could be connected together to perform the desired function, as could 400 line arrays of 500 elements. Although the CCD is still in the early developmental stages, the technology is already sufficiently advanced to produce the CCD scan converter today.

Three methods have been presented for demultiplexing of the alternate frame video. Storage tubes are not recommended due to the need for four tubes and attendant weight, size, power and possible registration problems. The disc recorder can produce a sharp well-registered display but requires a pressurized case and contains many moving mechanical parts. The CCD shift register is simple, all electronic, and requires little power. CCD's should be given serious consideration for alternate frame multiplexing if development continues rapidly. If CCD's are not obtainable during the visual system design phase, the disc recorder is recommended as the best alternative.

c. Phase Modulated Subcarrier - A novel technique for two-camera multiplexing is shown in Fig. VIII-6. This system, borrowed from the NTSC standards for color broadcasting, allows two pictures to be transmitted on a single carrier. One picture is sent with full resolution while the other is restricted to about 2 MHz, equivalent to a resolution of 210 lines. The video from Camera 3 phase modulates a 3.58 MHz subcarrier and the frequency spectrum of the modulated subcarrier is filtered to resemble that shown in Fig. VIII-7(a). The video from Camera 2, shown in Fig. VIII-7(b), is mixed with the Camera 3 video and amplitude modulated on a single 5 MHz bandwidth transmitter. The resultant signal,



Functional Flow Diagram

Fig. VIII-6 Phase Modulated Subcarrier Video Link

Fig. VIII-7(c), contains the interlaced sidebands from both cameras, maintains the desired resolution of one camera without sacrificing motion rendition, and occupies the same bandwidth as a single camera. At the control station end of the link, the video output from the receiver contains both the Camera 2 video and Camera 3 modulated subcarrier.

Due to the nature of television scanning, most of the energy in the video signal is concentrated at multiples of the horizontal scanning frequency. The 3.58 MHz subcarrier frequency was chosen so that its sidebands would fall at odd multiples of one-half the

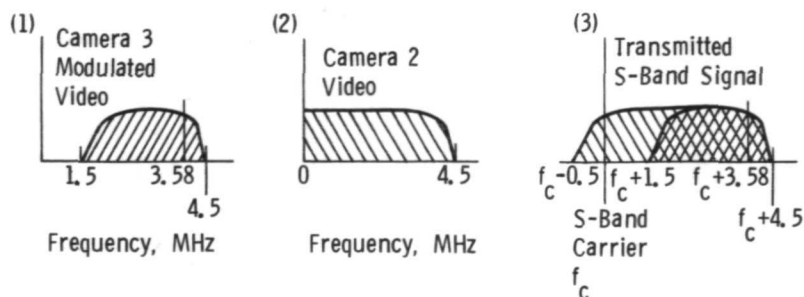
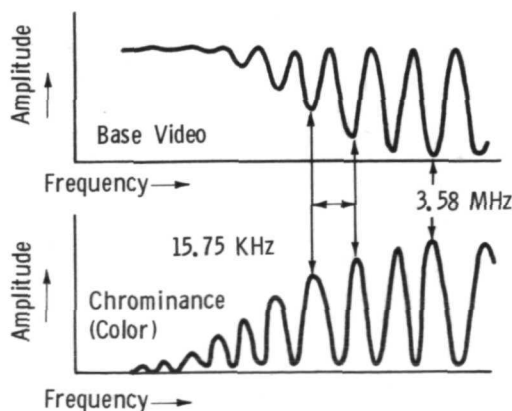
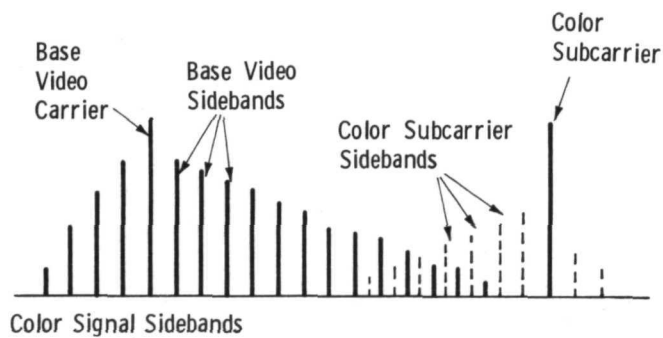


Fig. VIII-7 Phase Modulated Subcarrier Spectra

scanning frequency. In other words, each subcarrier sideband falls between the energy concentrations in the baseband video signal, as shown in Fig. VIII-8. By relating the frequencies of the two signals in this fashion, there is minimum interference and cross-talk between the camera signals. This same principle makes the signals easy to separate as the frequency response of a "comb" filter, also illustrated in Fig. VIII-8, is ideally suited to pass one component of an interlaced composite signal and reject the other. One output of the comb filter decoder would be the Camera 2 video which is sent to Monitor 2. The other comb filter output is the Camera 3 video still modulated on the 3.58 MHz subcarrier. The



Comb Filter Characteristics

Fig. VIII-8 Standard Color Television Frequency Spectrum and Comb Filter Response

subcarrier is then removed, restoring the 2 MHz Camera 3 video, and sent to Monitor 3. The entire modulation/demodulation process, except for the comb filter, reflects the standard method used in color TV broadcast studios and home television receivers. The difference is that the encoded color information is replaced by the Camera 3 monochrome video.

As the merits of this bandwidth reduction technique appeared promising, it was decided to conduct a short simulation with differentially degraded stereo images (e.g. one stereo sensor providing a "maximum bandwidth" view, the other degraded by bandwidth limitations). Thus, an experiment was conducted to determine whether an acceptable stereo view can be obtained when one of the views, transmitted as if it were an NTSC chrominance signal, is degraded by the bandwidth limitations.

Fig. VIII-9 is a block diagram of the experimental setup. The monitors and cameras were aligned for the best view of a three dimensional scene using the Fresnel display technique. The scene was first observed without any filter. Then filters, consisting of low pass L-networks with cutoff frequencies of 3, 2, 1, and 0.4 MHz, were inserted.

The results, although subjective, are extremely interesting. It is possible to degrade one image to the minimum bandwidth with little apparent change in the picture quality. This effect is true even

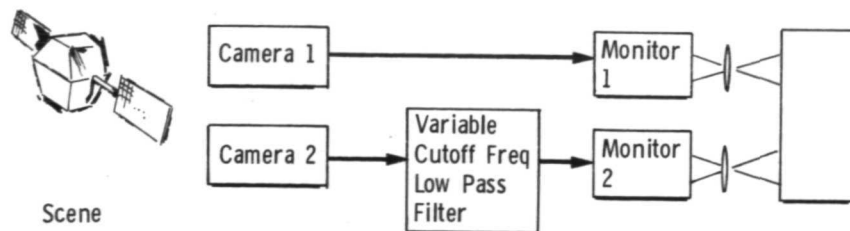


Fig. VIII-9 Differential Stereo Resolution Simulation

though the degraded video, viewed alone, is of very poor quality (30 - 40 lines). Apparently, the "good" picture furnishes the brain with the necessary detail for an overall high-resolution picture while the more poorly detailed picture is still sufficient to provide the necessary depth information.

The primary drawback to the pictures of varying resolution is a psychological one in that the eye subjected to the poorer view "feels funny."

This effect, while very prominent when the image is severely bandwidth limited, is barely noticeable at a 2 MHz bandwidth.

The differentially degraded stereo image is deserving of further study to verify these preliminary findings and to obtain task performance data. Also, it is recommended that a system, complete with these modulation and demodulation techniques, be constructed to determine the effects of mutual interference between the two video signals.

4. Bandwidth Analysis Summary

Methods for obtaining three video pictures for simultaneous viewing, utilizing an overall bandwidth no greater than 10 MHz, have been presented. The first method merely reduces the bandwidth of each video signal and is unsatisfactory because resolution is marginal and use of three transmitters is excessive. The second method transmits alternate frames from each of two cameras and uses long-persistence phosphors in the monitor. Besides decreasing the motion rendition the picture tends to smear in the presence of motion. The third method also uses alternate frames but each "live" frame is stored and replayed during the time between "live" frames thus eliminating flicker. The primary drawback is that no acceptable scan conversion equipment is presently available. The fourth me-

thod uses the NTSC system with the color signal replaced by video from one of the stereo cameras. This approach allows normal motion rendition in all cameras, full resolution on two cameras, and reduced resolution on the third camera. Experiments showed that the lowered resolution was acceptable for stereo viewing when used in conjunction with a high resolution view, and hence, this technique appears most feasible with present technology. However, additional experiments should be performed to verify that the theoretical performance can actually be achieved. In the event that solid state scan converters, such as those utilizing charge-coupled devices, reach a practical state of development by the time the FFTO visual system hardware designs are required, these devices represent a desirable alternative.

B. FFTO COMMAND, CONTROL AND TELEMETRY ANALYSIS

The FFTO command, control and telemetry analysis is performed in two parts to establish the data requirements between the FFTO and the control station. The first part discusses telemetry data from the FFTO to the control station while the second discusses the command and control data transmitted to the FFTO.

1. General Considerations

A substantial percentage of the standard 525-line, 30-frame-per-second television format is used for synchronizing and sweep retrace. During this portion of the sequence, the picture is blanked and no video is present. Only a small part of this interval is used for synchronization. A portion of each horizontal line and the greatest part of several horizontal lines in the vertical blanking interval can be conveniently utilized as a transmission medium. If all the desired FFTO telemetry data can be placed into these horizontal and vertical intervals, it can be transmitted along with the video with no mutual interference and

no additional data transmitters and receivers will be required.

Figure VII-10 shows the standard NTSC horizontal sync/blanking pulse. The sync pulse contains a 3.58 MHz reference signal ordinarily used to phase lock an oscillator in the receiver for color demodulation. If video from a second camera replaces the color information in the NTSC format, the 3.58 MHz reference fixes the demodulation axis for the second picture. For a normal monochrome camera signal, the reference burst does not appear. When the burst is present, the remaining space on the sync pulse is small and only 1 μ sec. two-level data pulse added to the sync pulse can be used to transmit telemetry data at the rate of one bit per $\frac{1}{15,750}$ sec. Therefore, the maximum data rate is 15,750 bits per second. The pulse is rather narrow and is affected by rolloffs and synchronization "jitter".

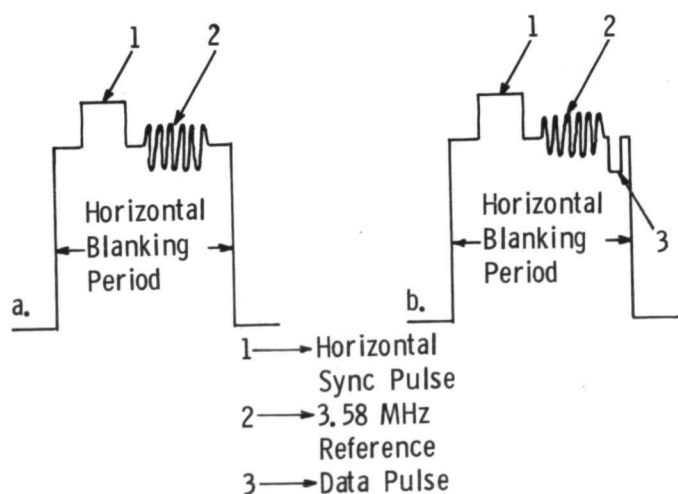


Fig. VIII-10 Horizontal Sync Pulse as Data Carrier

A much greater block of unutilized data capacity exists in the vertical interval. In this interval, whole lines are available free of conflicting video. Figure VIII-11 shows the vertical blanking interval (VBI) and includes lines with video on either

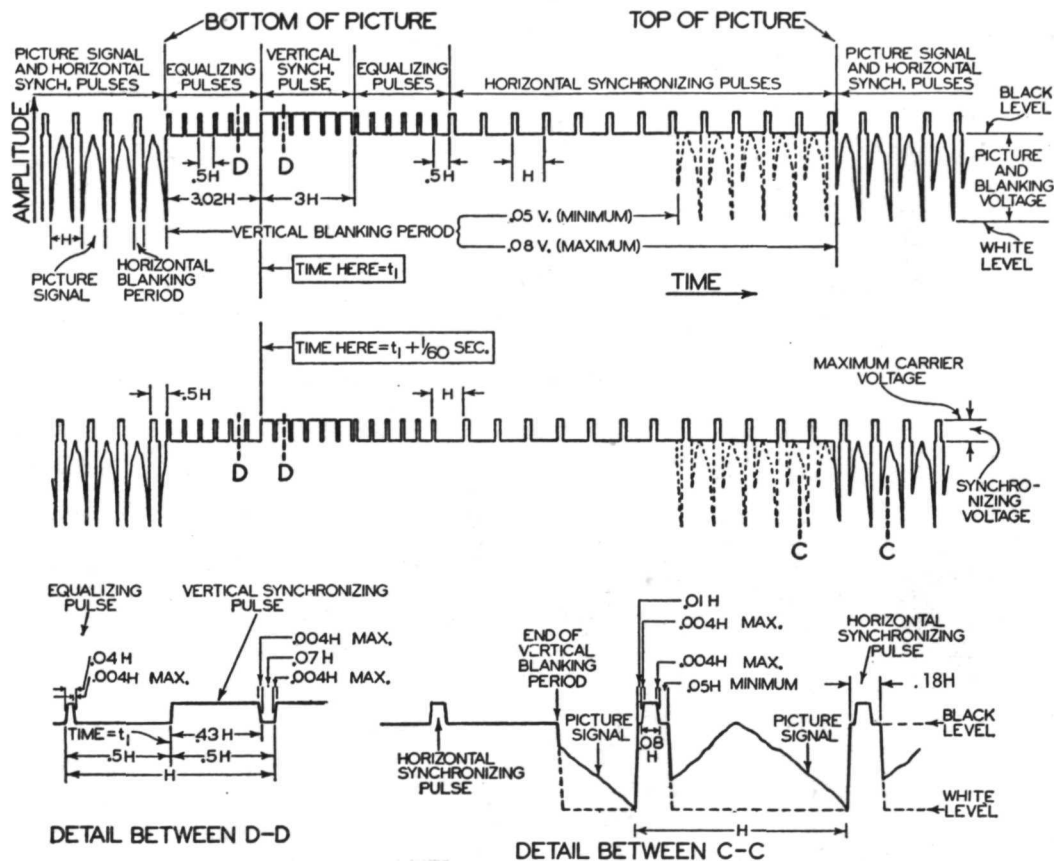


Fig. VIII-11 NTSC Standard Synchronizing Waveforms (from Ref. 13)

side of the VBI. The total length of the VBI is at least 18 lines. However, the first 10 lines of each field are occupied by signals involved with frame synchronization and are not easily used for data. Lines 11 through 18, except for the portion occupied by the horizontal sync pulse, are available as a data carrier.

To determine the maximum data rate, consider the highest practical bit rate during the VBI to be one half the video cutoff frequency. Therefore,

$$R_m = \frac{4.5 \times 10^6}{2} = 2.25 \times 10^6 \text{ bits/sec.}$$

The usable portion of each line, τ_d , is given by $\tau_d = H - \tau_s$ where H is the time from the start of one line to the start of the next and τ_s is the length of the sync pulse. Then

$$\tau_d = \frac{1}{15,750} (1-0.18) = 52 \text{ } \mu\text{sec.}$$

The total number of bits per line, I_L is given by

$I_L = R_m \tau_d = (2.25 \times 10^6)(52 \times 10^{-6}) = 117$ bits and, allowing for some margin, $I_L = 100$ bits. Based upon 8 usable lines per field and 60 fields per second, the total information capacity, C, is therefore

$$C = 8 \times 60 \times 100 = 48,000 \text{ bits per second.}$$

If the total bit requirement of the FFTO telemetry does not exceed 48 Kbps and no more than 60 samples per second is required of any parameter, the vertical blanking interval can be utilized to give the data essentially a "free ride".

2. FFTO/Control Station Telemetry Requirements Summary

The approximate telemetry data required from systems aboard the FFTO are summarized in Table VIII-1. This table is primarily based upon the total FFTO system requirements, established in Reference 10 and Section IX: Controls and Display Subsystem. However, these requirements have been updated to include MMA developmental work in both the visual and manipulative subsystem areas and, as a result, represent a more realistic situation.

The table is set up for a data frame rate of 30 frames per second

Table VIII-1 FFTO to Control Station Telemetry Function Summary

CHANNEL NUMBER	CHANNEL FUNCTION	NUMBER OF IDENTICAL CHANNEL	SCALE RANGE	UNITS	RESOLUTION	BITS/ CHANNEL	SAMPLE RATE/ SEC	BITS/ SECOND/ CHANNEL	TOTAL RATE BIT/SEC
1	Synchronization (Forward & Inverse 11-Bit Barker Sync Code)	1	-	Digital	-	22	30	660	660
2-5	Spare	4	-	Digital	-	12	1	12	48
6	Gas Pressure, Fuel Tank Blowdown	1	0 to 500	PSI	+ 4 PSI	7	0.1	0.7	0.7
7	Propellant Quantity	1	0 to 110	Percent	+ 0.86 Percent	7	0.1	0.7	0.7
8-23	Thruster On/Off	16	Off/On	Discrete	2 State	1	10	10	160
24	Propellant Temperature	1	0 to 150	Deg F	2.3 Deg F	6	0.1	0.6	0.6
25-28	Propellant Valve Position	4	Off/On	Discrete	2 State	1	1	1	4
29	Safe/Arm System Status	1	Safe/Arm	Discrete	2 State	4	1	4	4
30-34	Vehicle Skin Temperature	5	-100 -+500	Deg F	9.1 Deg F	6	0.1	0.6	3
35-39	Vehicle Inside Temperature	5	0 to 100	Deg F	3 Deg F	5	0.1	0.5	2.5
40	Battery Bank No. 1 Voltage	1	0 to 32	Volts DC	0.5 Volt	6	1	6	6
41	Battery Bank No. 2 Voltage	1	0 to 32	Volts DC	0.5 Volt	6	1	6	6
42	Critical Load Bus Current	1	0 to 30	Ampere	0.12 Ampere	8	1	8	8
43	Non-Critical Load Bus Current	1	0 to 30	Ampere	0.12 Ampere	8	1	8	8
44	Power System Operating Status	1	-	Discrete	-	3	1	3	3
45	FFTO Pitch	1	+ 90	Degrees	0.09 Degree	11	10	110	110
46	FFTO Roll	1	+ 180	Degrees	0.09 Degree	12	10	120	120
47	FFTO Yaw	1	+ 180	Degrees	0.09 Degree	12	10	120	120
48-50	FFTO Attitude Rates ($\dot{\theta}$, $\dot{\phi}$, $\dot{\psi}$)	3	+ 50	Deg/Sec	0.1 Deg/Sec	10	10	100	300
51-53	FFTO Translational Acceleration ($\ddot{X}$, $\ddot{Y}$, $\ddot{Z}$)	3	+ 2	Ft/Sec	0.008 Ft/Sec	9	10	90	270
54	Control System Operating Status	1	-	Discrete	-	3	1	3	3
55,56	Hard Dock Sense	2	-	Discrete	-	1	1	1	2
57-64	Equipment Operating Status	8	-	Discrete	-	1	0.1	0.1	0.8
65	Sensor Articulator Base Yaw	1	0 to 360	Degrees	1.4 Degree	8	5	40	40
66	Sensor Articulator Base Pitch	1	+ 90	Degrees	1.4 Degree	7	5	35	35
67	Sensor Articulator Wrist Pitch	1	0 to 360	Degrees	1.4 Degree	8	5	40	40
68-75	Visual System Status	8	-	Discrete	-	3	1	3	24
76,77	Stored/Updated Program Readout	2	-	Digital	-	12	0.1	1.2	2.4
78,79	Test Message/Results Readout	2	-	Digital	-	12	0.1	1.2	2.4
80	Command Mode/Status	1	-	Discrete	-	4	1	4	4
81,82	Command Message Repeat/Verify	2	-	Digital	-	12	1	12	24
83,84	Command Channel Designation	2	-	Digital	-	8	1	8	16
85	Command Message Decode Rate	1	0 to 30	Message/ Second	1.0 MPS	5	1	5	5
86	Command Message Parity Failure	1	-	Discrete	-	7	1	7	7
87-90	Spare	4	-	Digital	-	12	1	12	48
91	Manipulator Shoulder Yaw	1	0 to 270	Degrees	0.53 Deg	9	30	270	270
92	Manipulator Shoulder Pitch	1	0 to 270	Degrees	0.53 Deg	9	30	270	270
93	Manipulator Elbow Roll	1	0 to 360	Degrees	0.7 Deg	9	30	270	270
94	Manipulator Elbow Pitch	1	0 to 300	Degrees	0.6 Deg	9	30	270	270
95	Manipulator Wrist Yaw	1	0 to 240	Degrees	0.5 Deg	9	30	270	270
96	Manipulator Wrist Pitch	1	0 to 240	Degrees	0.5 Deg	9	30	270	270
97	Manipulator Wrist Roll	1	0 to 360	Degrees	0.7 Deg	9	30	270	270
98	Terminal Device Closure	1	0 to 45	Degrees	0.35 Deg	9	30	270	270
99-106	Manipulator Operating Status	8	-	Discrete	-	3	1	3	24
107	Address (Terminal Designation)	1	-	Discrete	-	3	30	90	90
108	Label (Message Type/Content)	1	-	Discrete	-	3	30	90	90
109	Parity (1 Parity per 16 Bit Segment)	1	-	Discrete	-	7	30	210	210
110	Target Range	1	3 - 12,000	Feet	3.0 Feet	12	5	60	60
111	Target Range Rate	1	+ 40	Ft/Sec	0.3 Ft/Sec	8	5	40	40
112-114	CMG Measured Vehicle Rates (3 Axes)	3	+ 50	Deg/Sec	0.1 Deg/Sec	10	10	100	300
115-117	CMG Desaturation Event	3	-	Discrete	-	2	1	2	6
118-121	Vehicle Body Strain Gages	4	0 to 1000	Lb	7.8 Lb	7	1	7	28
122-124	High Response Accelerometers	3	+ 100	Ft/Sec ²	0.4 Ft/Sec ²	9	1	9	27
125-130	Gyro Spinup Sense	6	0 to 100	Percent	0.8 Percent	7	1	7	42
131-139	Spare	9	-	Digital	-	12	1	12	108
140	End of Message	1	-	Discrete	-	1	30	30	30
Total Bit Rate:									5303.1

to coincide with the TV video frame rate. In the event a higher sample rate is needed, the frame rate can be changed to 60 frames per second synchronized with the TV field rate or two equally-spaced samples can be taken at the 30 frame rate. Real time sampling at rates above 60 per second cannot be realized utilizing the VBI.

FFTO type manipulator experiments, conducted at MMA, have shown a rate of 20 samples per second is sufficient for good controllability of a manipulator joint. The typical joints under study utilize "force feedback" through measurement of the master/slave position error. Without this feedback the sample rate required is lower. Assuming, in the worst case, force feedback is a desirable feature, a sample rate of 30 samples per second for the manipulator telemetry, and for the manipulator command channels, is specified.

Hence, the total bit rate requirement of 5,303.1 bits/second, as identified in Table VIII-1, is well within the 48,000 bits/second VBI capacity. By reducing the number of bits per line from the allowable maximum of 100 to 16, the required VBI capacity becomes 7,680 bits per second. This information density allows all telemetry data to be transmitted and provides for a reasonable system expansion. It should be noted that the telemetry data originating in the visual system comprises only a very small portion of the total data required by the FFTO.

3. FFTO Command/Control Function Summary

The FFTO command and control link is based upon two separate channel groups: a primary system and a backup system.

a. Primary System - The primary system, identified in Table VIII-2, summarizes the FFTO command and control functions. With respect to the visual system, the sensor articulation commands, a discrete 2-bit signal, orders the articulation gimbal motor to run in either the forward or reverse directions. A second command, consisting of a single bit, selects the high or low articulation rate. A 3-bit command selects which TV camera is transmitted over the video channels available. Each TV camera lens receives a 2-bit command for off, forward, and reverse action of the stepper motors controlling

Table VIII-2 Primary FFTO Command Function Summary

CHANNEL NUMBER	CHANNEL FUNCTION	NUMBER OF IDENTICAL CHANNEL	SCALE RANGE	UNITS	RESOLUTION	BITS/ CHANNEL	SAMPLE RATE/ SEC	BITS/ SECOND/ CHANNEL	TOTAL RATE BIT/SEC
1	Synchronization (Forward & Reverse 11 Bit Barker Code)	1	-	Digital	-	22	30	660	660
2	Address (Terminal Designation)	1	-	Digital	-	3	30	90	90
3	Label (Message Type/Content)	1	-	Digital	-	3	30	90	90
4	Parity (1 Parity per 16 Bit Segment)	1	-	Discrete	-	7	30	210	210
5-11	Spare	7	-	Digital	-	12	1	12	84
12	Attitude Hold Mode Select	1	-	Discrete	-	2	1	2	2
13	FFTO Pitch Rate	1	+50	Deg/Sec	0.1 Deg/Sec	10	10	100	100
14	FFTO Roll Rate	1	+50	Deg/Sec	0.1 Deg/Sec	10	10	100	100
15	FFTO Yaw Rate	1	+50	Deg/Sec	0.1 Deg/Sec	10	10	100	100
16-18	FFTO Translational Acceleration (X, Y, Z)	3	+2	Ft/Sec ²	0.008 Ft/Sec ²	9	10	90	270
19	Test Mode Initiate/Results Request	1	-	Discrete	-	4	1	4	4
20,21	Test Message	2	-	Digital	-	12	1	12	24
22	Range Hold Mode Select	1	-	Discrete	-	2	1	2	2
23	Range Hold Value	1	3 to 10,000	Feet	1% of Scale	7	1	7	7
24	Parity Override, Command Accept Code	1	-	Discrete	-	3	1	3	3
25	Command Initialize, Zero or Offset	1	0 to + 100	Percent	0.1 Percent	11	1	11	11
26	Command Hold/Cancel	1	-	Discrete	-	2	1	2	2
27	Command Delay Time	1	0 to 90	Minutes	0.02 Minute	12	0.1	1.2	1.2
28	Command Channel Designation	1	-	Digital	-	8	1	8	8
29	Command Execute	1	-	Discrete	-	2	1	2	2
30	Command Repeat/Verification/Read	1	-	Discrete	-	3	1	3	3
31	Program Advance/Hold/Retard	1	-	Discrete	-	3	0.1	0.3	0.3
32	Program Execute/Start/Stop	1	-	Discrete	-	3	0.1	0.3	0.3
33	Program Update/Enter Data	1	-	Discrete	-	2	0.1	0.2	0.2
34	Program Repeat/Verification/Read	1	-	Discrete	-	2	0.1	0.2	0.2
35	Program Data Item Identity	1	-	Digital	-	10	0.1	1	1
36	Program Data Channel Value	1	0 to + 100	Percent	0.1 Percent	11	0.1	1.1	1.1
37	Telemetry Message Request	1	-	Digital	-	8	1	8	8
38	Telemetry Mode Command	1	-	Discrete	-	4	1	4	4
39-58	Equipment On/Off	20	-	Discrete	-	1	1	1	20
59	Command System Mode Control	1	-	Discrete	-	4	1	4	4
60,61	Docking Latch/Unlatch	2	-	Discrete	-	1	1	1	2
62	Thruster Arm/Safe Mode Select	1	-	Discrete	-	3	1	3	3
63	Control System Mode Select	1	-	Discrete	-	3	1	3	3
64,65	Thruster Manifold Vent A and B	2	-	Discrete	-	1	1	1	2
66	Thruster Individual and Group Check	1	-	Digital	-	6	1	6	6
67-69	CMG Desaturate/Zero	3	-	Discrete	-	2	1	2	6
70	Thruster Bank A/B/Both Select	1	-	Discrete	-	3	1	3	3
71	Sensor Articulator Base Yaw	1	-	Discrete	-	2	5	10	10
72	Sensor Articulator Base Pitch	1	-	Discrete	-	2	5	10	10
73	Sensor Articulator Wrist Pitch	1	-	Discrete	-	2	5	10	10
74	Camera/Transmission Channel Select	1	-	Digital	-	3	1	3	3
75	Stereo Camera Zoom Control	1	-	Discrete	-	2	5	10	10
76	Mono Camera Zoom Control	1	-	Discrete	-	2	5	10	10
77	Stereo Camera Focus Control	1	-	Discrete	-	2	5	10	10
78	Mono Camera Focus Control	1	-	Discrete	-	2	5	10	10
79	Stereo Camera ALC Mode Select	1	-	Digital	-	2	1	2	2
80	Mono Camera ALC Mode Select	1	-	Digital	-	2	1	2	2
81	Stereo Camera Iris Control	1	-	Discrete	-	2	5	10	10
82	Mono Camera Iris Control	1	-	Discrete	-	2	5	10	10
83	Stereo Camera Illumination (Off/Low/High)	1	-	Discrete	-	2	1	2	2
84	Mono Camera Illumination (Off/Low/High)	1	-	Discrete	-	2	1	2	2
85	Sensor Articulator High/Low Rate Select	1	-	Discrete	-	1	1	1	1
86-95	Systems Startup/Warmup/Standby/Operate	10	-	Discrete	-	3	1	3	30
96	Range Sensor Scale/Mode Select	1	-	Discrete	-	3	1	3	3
97	Range Gate Set Control	1	3 to 11,000	Feet	1% of Scale	7	1	7	7
98	Electric Power Bus Mode Select	1	-	Discrete	-	3	1	3	3
99	Manipulator Shoulder Yaw	1	0 to 270	Degrees	0.53 Degrees	9	30	270	270
100	Manipulator Shoulder Pitch	1	0 to 270	Degrees	0.53 Degrees	9	30	270	270
101	Manipulator Elbow Roll	1	0 to 360	Degrees	0.7 Degrees	9	30	270	270
102	Manipulator Elbow Pitch	1	0 to 300	Degrees	0.6 Degrees	9	30	270	270
103	Manipulator Wrist Yaw	1	0 to 240	Degrees	0.5 Degrees	9	30	270	270
104	Manipulator Wrist Pitch	1	0 to 240	Degrees	0.5 Degrees	9	30	270	270
105	Manipulator Wrist Roll	1	0 to 360	Degrees	0.7 Degrees	9	30	270	270
106	Terminal Device Closure	1	0 to 45	Degrees	0.35 Degrees	9	30	270	270
107	Manipulator Stow/Activate	1	-	Discrete	-	2	1	2	2
108-116	Spare Digital	9	-	Digital	-	12	1	12	108
117	End of Message	1	-	Discrete	-	1	30	30	30
Total Bit Rate:									4282.3

zoom, iris, and focus. The camera automatic light control (ALC) circuits are commanded in a similar fashion except that the 2-bit command is digital, rather than discrete, to allow four ALC levels to be chosen. A 2-bit discrete command is used to furnish 2 levels of illumination control. Except for the sensor articulator, the visual system commands are provided at a one-sample-per-second rate.

b. Backup System - An emergency backup system, summarized in Table VIII-3, is recommended and utilized solely to return the FFTO safely to the Shuttle. Basically, the manipulator terminal device can be commanded to release and be returned to its stowed position. All visual system elements remain controllable as well as the ability to maneuver the FFTO.

Table VIII-3 Emergency Backup Command Function Summary

CHANNEL NUMBER	CHANNEL FUNCTION	NUMBER OF IDENTICAL CHANNEL	SCALE RANGE	UNITS	RESOLUTION	BITS/ CHANNEL	SAMPLE RATE/ SEC	BITS/ SECOND/ CHANNEL	TOTAL RATE BIT/SEC
1	Synchronization	1	-	Digital	-	11	10	110	110
2	Label (4 Message Types)	1	-	Digital	-	2	10	20	20
3	Parity (1 Parity Bit Per 16 Bit Seg Segment)	3	-	Discrete	-	3	10	30	30
4	FFTO Pitch Rate	1	+ 13	Deg/Sec	0.1 Deg/Sec	8	10	80	80
5	FFTO Roll Rate	1	+ 13	Deg/Sec	0.1 Deg/Sec	8	10	80	80
6	FFTO Yaw Rate	1	+ 13	Deg/Sec	0.1 Deg/Sec	8	10	80	80
7	FFTO X Translational Acceleration	1	+ 2	Ft/Sec ²	0.016 Ft/Sec ²	8	10	80	80
8	FFTO Y Translational Acceleration	1	+ 2	Ft/Sec ²	0.016 Ft/Sec ²	8	10	80	80
9	FFTO Z Translational Acceleration	1	+ 2	Ft/Sec ²	0.016 Ft/Sec ²	8	10	80	80
10	Thruster Arm/Safe Mode A/B/Both Bank	1	-	Discrete	-	4	1	4	4
11	Docking Latch/Unlatch	1	-	Discrete	-	2	1	2	2
12	Control Mode Select (CMG/RG/MIB)	1	-	Discrete	-	3	1	3	3
13	Terminal Device Release	1	-	Discrete	-	1	1	1	1
14	Manipulator Stow	1	-	Discrete	-	5	1	5	5
15	Test Mode Select	1	-	Discrete	-	1	1	1	1
16	CMG Desaturate Zero	1	-	Discrete	-	3	1	3	3
17	Sensor Articulator Base Yaw	1	-	Discrete	-	2	1	2	2
18	Sensor Articulator Base Pitch	1	-	Discrete	-	2	1	2	2
19	Sensor Articulator Wrist Pitch	1	-	Discrete	-	2	1	2	2
20	Camera/Transmission Channel Selector	1	-	Digital	-	3	1	3	3
21	Stereo Camera Zoom Control	1	-	Discrete	-	2	1	2	2
22	Mono Camera Zoom Control	1	-	Discrete	-	2	1	2	2
23	Stereo Camera Focus Control	1	-	Discrete	-	2	1	2	2
24	Mono Camera Focus Control	1	-	Discrete	-	2	1	2	2
25	Stereo Camera ALC Control	1	-	Digital	-	2	1	2	2
26	Mono Camera ALC Control	1	-	Digital	-	2	1	2	2
27	Stereo Camera Iris Control	1	-	Digital	-	2	1	2	2
28	Mono Camera Iris Control	1	-	Digital	-	2	1	2	2
29	Stereo Camera Illumination (Off/Low/High)	1	-	Discrete	-	2	1	1	1
30	Mono Camera Illumination (Off/Low/High)	1	-	Discrete	-	2	1	1	1
31-33	Spare Digital	3	-	Digital	-	8	1	8	24
34	Spare Discrete	1	-	Discrete	-	8	1	8	8
35-38	System Startup/Warmup/Standby/Operate	4	-	Discrete	-	3	1	3	12
39	Electric Power Bus/Mode Select	1	-	Discrete	-	3	1	3	3
40	End of Message	1	-	Discrete	-	1	10	10	10
Total Bit Rate:									743

C. REDUNDANCY CONSIDERATIONS

The telemetry link is vital to the accomplishment of any FFTO task. Thus the reliability of the transmitting system aboard the FFTO must be extremely high. The system proposed in Phase I of this contract, where two or more identical video transmitters were used, is one valid approach.

The TV camera configuration requires that, in some cases, the 3 cameras be active simultaneously and require a bandwidth less than or equal to 10 MHz. Both video signals can be modulated onto a single transmitter with a 10 MHz bandwidth. However, a single-point failure in the transmitter would interrupt all data returned from the FFTO. Instead, two identical transmitters can be used, one returning a two-camera multiplex signal, the other sending the single-camera simplex signal, and possessing an input switching matrix to allow any camera to be associated with any transmitter. A single-point transmitter failure will then reduce the simultaneous capability from three cameras to two which will still allow completion of most FFTO missions. All cameras can still be viewed, two at a time, by switching transmitter inputs. The increased reliability of a dual video transmitter system outweighs the slight power and weight increase required.

An additional consideration is that a separate transmitter for FFTO data would normally be required if only one video transmitter is used. It was suggested in Phase I that a modulated data subcarrier be added to one of the video transmitters as a backup for the primary data transmitter. However, it was shown that the video signal itself contains ample unused "space" which can be conveniently used to transmit all telemetry data. There is no penalty--in fact, an advantage--in adding telemetry data to all video signals transmitted and thereby eliminate the need for a separate

data transmitter.

From redundancy consideration, it is recommended that two S-band transmitters, each having a bandwidth of 5 MHz be employed for returning both video and telemetry data from the FFTO to the control station.

D. RECOMMENDED TELECOMMUNICATION SUBSYSTEM

A description and block diagram of the recommended telecommunication subsystem is presented in this section in two parts:

1) Free-Flying Teleoperator Visual System and 2) FFTO Control Station. The diagram of the FFTO onboard electronics consists of components peculiar to the visual system as well as elements of other subsystems which are shared by the visual system. The Control Station block diagram is complete for all components involved in the operation of the FFTO. This is in keeping with the design of an integrated control panel for all FFTO functions. However, only those functions relating to the visual system are discussed.

1. Visual System Block Diagram, FFTO Onboard - The block diagram given by Fig. VIII-12 includes the visual system elements physically located aboard the FFTO. The elements which are primarily the responsibility of the visual system are indicated by an asterisk.

Commands to the FFTO visual system include in the primary mode

- 1) video sensor articulator motion commands, 2) camera/transmission channel select, 3) camera zoom, focus, iris and ALC controls, 4) illumination control and 5) video sensor articulator rate mode.

The emergency backup mode contains the same capability except for illumination control and sensor articulator rate. The command signal is intercepted by the S-band omnidirectional antenna array and routed through the Diplexer to the Primary Command Receiver

and Backup Command Receiver inputs.

The demodulated output of each receiver is sent to a command decoder. Besides furnishing the control signals to the onboard subsystems the decoders also check parity and verify the incoming data. The Command Mode Selector is controlled by a signal from either the Primary Command Decoder or the Backup Command Decoder. The Command Mode Selector determines which command decoder will be in control of the FFTO.

Additional processing is normally required before the raw command data can be utilized by the visual system elements. The Visual System Command Processor contains D/A converters, power amplifiers, solid state relays, etc. to convert commands into usable form.

The three television cameras are basically identical. They are similar to those flown on the later Apollo missions for use with the Lunar Roving Vehicle. The primary differences are that zoom and focus are decoupled so that they are separately controllable, and the color wheel and motor are removed. The drive motors for focus, iris and zoom and the ALC switching are commanded in tandem for the two cameras (Cameras 2 and 3) which produce the stereo view. Separate control of these variables is provided for the mono camera, Camera 1.

Camera 1 remains in a fixed position relative to the FFTO structure. The stereo pair, Cameras 2 and 3, can be positioned by the Sensor Articulator, a 3 degree-of-freedom remotely-controlled boom. The three Sensor Articulator joints can be controlled by individual rate commands generated by manual switches in the FFTO Control Station or by simultaneous rate commands from the FFTO Computer. Forward/off/reverse discrete commands from the Primary or Backup Command Decoders are converted by the Visual System Command Processor into motor drive signals for the Sensor Articulator.

The Sync Generator provides the timing reference for all FFTO functions. It contains its own high-stability oscillator which can be synchronized with the incoming data frame rate or function separately. It derives the composite sync for the TV cameras, the video line and field reference for the Data Encoder and the 3.58 MHz reference for the Phase Modulator.

The Video Switching Network routes each camera signal to one of three transmission channels upon command from the Control Station.

Video inputs to Video Mixer 1 are transmitted simplex over Video Transmitter 1. Video applied directly to Video Mixer 2 is the base band multiplex video. The third video signal is modulated on a subcarrier by the 3.58 MHz. Phase Modulator and interlaced with the base band video in Mixer 2. The Mixer 2 output is transmitted over Video Transmitter 2.

The data telemetered back to the Control Station consists of 1) Sensor Articulator joint position information 2) Visual System equipment status and 3) data from other FFTO subsystems. The Data Encoder processes the information from the various data sensors and encodes it onto lines 10 through 17 of each video field. The output of the Data Encoder is added to both the simplex and composite video signals in Video Mixers 1 and 2. Use of this parallel channel concept allows reception of telemetry data in the event of failure of one Video Transmitter.

The Video Transmitter outputs are combined in the Adder and sent through the Diplexer to the Antenna Array and thus to the receiving antennas at the FFTO Control Station.

2. FFTO Control Station Block Diagram

Figure VIII-13 shows the complete block diagram of the integrated FFTO Control Station. However, only those elements which apply

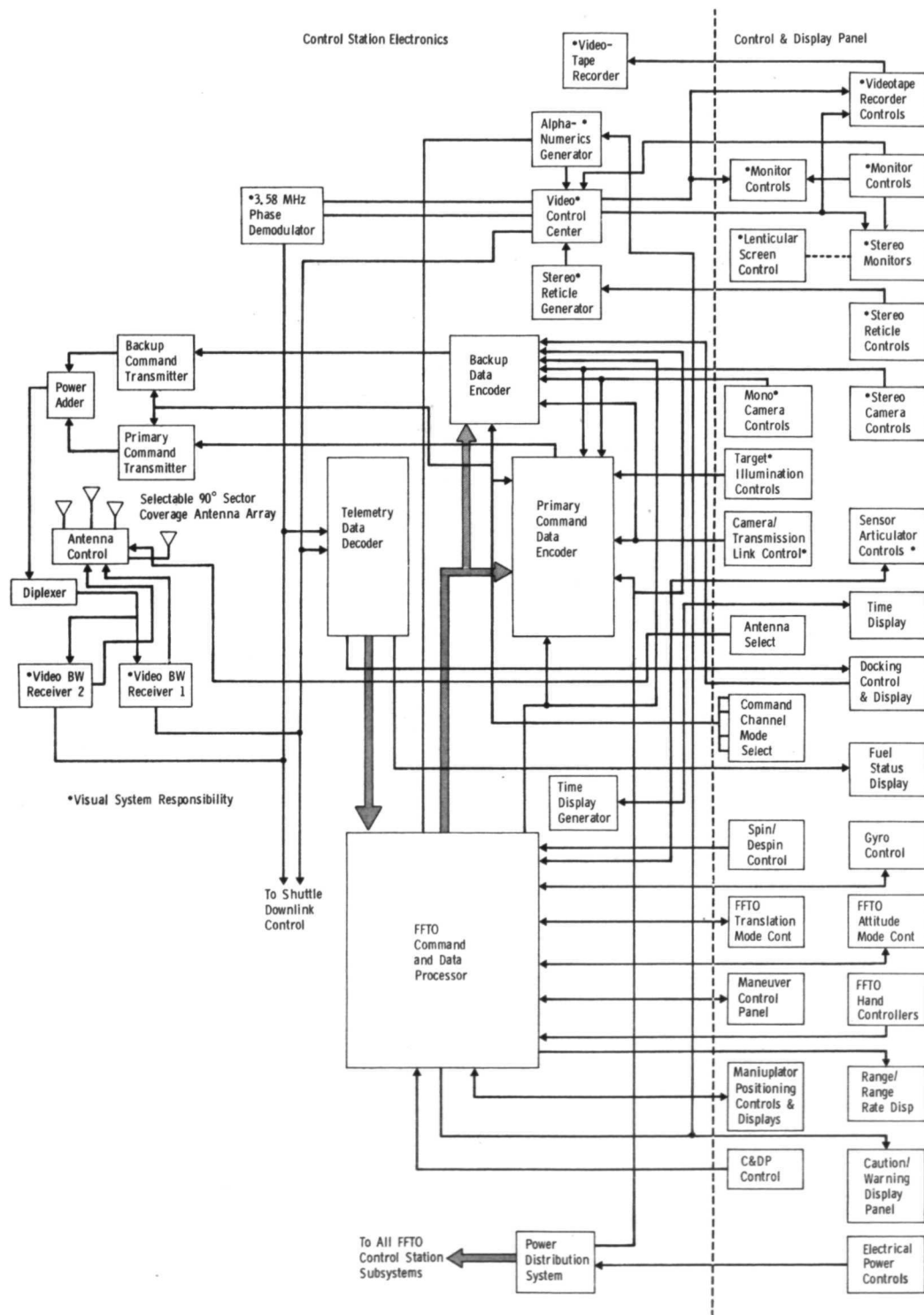


Fig. VIII-13 FFTO Control Station Block Diagram

directly to the functions of the FFTO Visual System will be addressed.

The received signal from the FFTO is intercepted by one or more of the 90°-Sector-Coverage Antennas. The automatic gain control (AGC) voltage from the Video Bandwidth Receivers (VBR) is utilized by the Antenna Control circuits to select the antenna producing the maximum signal strength. The antenna may also be selected manually by the Antenna Controls. The selected signal is routed through the diplexer and to the two VBR's where the camera signals are demodulated. The output of VBR1 is the simplex video. The output of VBR2 is the composite signal which must be further processed in the 3.58 MHz Phase Demodulator to extract its two components, normally the stereo pair from Cameras 2 and 3. The same two VBR outputs are also routed to the Telemetry Data Recorder where the video is removed and the data is decoded and processed.

The three video signals are applied to the Video Control Center. The Video Control Center serves as a general purpose mixing and distribution matrix. The input from the Monitor Controls determine which video is displayed on which monitor. Here the data from the Alphanumeric Generator is added to the video as is the stereo reticle.

The Alphanumeric Generator converts digitally coded outputs from the FFTO Computer to properly timed and spaced pulses which, when added to the video, produce a character on the monitor screen. It is also capable of producing a visual caution/warning indication to alert the operator to a malfunction.

The Stereo Reticle Generator provides pulses which, when added to the video, appear on the Stereo Monitor screens as a vertical

black/white line pair in three dimensions.

Each of the three monitors has the normal setup controls: brightness, contrast, horizontal and vertical hold, on/off. The brightness and contrast are clutch-type dual-concentric controls for the stereo monitors to allow them to be adjusted simultaneously. The Stereo Monitor can be used in a mono mode by mechanically moving the lenticular screen via the Lenticular Screen Control and turning off one of the monitor pair.

A Videotape Recorder is provided for storage and later analysis of FFTO missions. The Videotape Recorder Controls are used to switch the recorder on and off and select which scene is to be recorded.

Telemetry data pertaining to the Visual System is separated by the Telemetry Data Decoder and routed to the FFTO Command and Data Processor. Here the Sensor Articulator Controls determine whether the camera boom position readouts will be used for automatic positioning or if the manual mode is to be used. The FFTO C and DP provides the Sensor Articulator commands to the Primary and Backup Command Data Encoders. The visual system status data is also routed to the computer for analysis and potential application to the Caution/Warning Display Panel in event of an out-of-tolerance condition or malfunction.

Controls are provided for commanding the TV cameras on the FFTO. The zoom, focus, and iris are rate controlled. That is, the motor is commanded to move when the control switch is in an actuated position and is commanded to stop when the switch is in the neutral position. Again, these control signals are applied in parallel for the stereo camera pair. The Stereo and Mono Camera Controls also provide the camera on/off commands.

The Target Illumination Controls operate two lighting circuits associated with the mono camera and the stereo cameras. Each circuit is capable of producing two levels of illumination upon command of the operator.

The Camera/Transmission Link Controls furnish a digital signal to operate the Video Switching Network onboard the FFTO. This function has been previously discussed.

The command inputs from the various controls and from the FFTO Computer are processed in the Primary and Backup Command Encoders. The encoded data modulates the Primary and Backup Command Transmitters. The S-band output is summed and routed through the Diplexer to the Antenna Array.

IX. CONTROLS AND DISPLAYS SUBSYSTEM

Phase I Summary: The primary goal of Phase I was the development of visual system concepts and their evaluation for system selection. During this phase very little effort was expended on defining the controls and displays required to operate a FFTO visual system. A preliminary Control and Display Panel layout was prepared with little regard to the free-flyer subsystems other than the visual. The configuration selected used two, 30.8 cm (12.5 in) diagonal, black and white TV displays. A Fresnel lens stereo was located on the right, with a standard mono display on the left. The associated controls required to operate the visual system were located around the two display screens.

Phase II Emphasis: This section presents the results of the work performed by MMC in Phase II on the free-flying visual system control and display elements. The two prime objectives during this period were to establish control and display requirements and to define a preliminary FFTO Control and Display Station (CDS). In doing this the primary emphasis was placed on first developing a CDS concept within the visual system requirements and secondly the investigation of the visual control and display elements with the other control and display elements required to operate a FFTO. The emphasis was then placed on the integration of these elements into a total FFTO Control and Display Station.

A. GENERAL PHILOSOPHY

The Control and Display Station (CDS) will provide the on-orbit crew-machine interface necessary to operate a FFTO vehicle. The main crew-machine interface includes the operator interface for the directed performance of selected FFTO missions; the coordination required between the FFTO operator tasks and the Shuttle flight control station; the crew interface for manual override of the automatic system control functions; and the crew interface required during a caution and warning or emergency situation.

1. Functional Description

The functional objective of the FFTO is to provide a transitional

link between the prime Shuttle vehicle and free flying target. In order to service this link a remotely located CDS on either the Shuttle vehicle or ground base is required to control the FFTO mission tasks.

2. Physical Configuration

The FFTO Control and Display Station will be located in the Shuttle or at a ground based station. The visual portion of this system will be comprised of: sensors, illumination devices, displays, monitors, camera deployment and articulation and telecommunications. The primary crew-machine related equipment include: TV displays, console/panel configuration, operators seat, panel lighting and communication links with the shuttle flight station and ground stations. The physical parameters for these subsystems will be specified in the following paragraphs.

a. Displays - Based on simulations, a two display concept is considered adequate to provide the FFTO operator the necessary views to conduct basic mission tasks. One of the two displays in this concept presents a monoscopic image from any of the three selected camera sensors. The other display presents a stereo image which relies on a fresnel display screen to direct the right and left images to the corresponding eyes of the viewer. The unit is designed to accommodate nearly full peripheral vision. No glasses or other viewing aids are required, so random viewing of peripheral controls and displays is natural and effortless. The one limitation of the fresnel display screen is the restriction of head movement. However, the incorporation of a lenticular faceplate over the fresnel screen, increases the horizontal head movement to approximately ± 6 inches. It also provides a monoscopic view by rotating the lenticular faceplate 90 degrees.

The following display design requirements are considered to have

The greatest impact on the FFTO Control and Display Station:

- . Total display area shall not exceed 0.26 sq. m. (400 sq. in)
- . Viewed from 46 to 61 cm (18 to 24 in)
- . Ambient light of 40 ft candles

As indicated in the Phase I Report (Ref. 1) a typical monitor display height based on the average viewing distance would be 19.0 ± 2.5 cm (7.5 ± 1 in) minimum. On this information it is assumed that the diagonal dimension of the display screen would be 28 to 33 cm (11 to 13 in).

b. Console/Panel - The Control and Display Console design will be compatible with both ground based and Shuttle operation. Provisions will be provided to accommodate flight personnel, at the FFTO Control and Display Station, having anthropometry dimensions of the seated to standing male for the 5th to 95th percentile as per MSFC-STD-267A. A restraint system will be used to accommodate one crewman in a shirtsleeve environment. This requirement establishes a preliminary panel area available within the 5th percentile reach range.

c. Operator Seat - A seat or restraint system will be provided at the FFTO Control and Display console. The system will provide a restraint device for both the lap and feet. The adjustment capability of the seat will depend on the anthropometric data of the 5th to 95th percentile male, using the eye as the fixed reference point to define the seat - height - and arm rest height. A viewing distance of 45.6 to 61 cm (18 to 24 in) will be used as a design guide in establishing the distance from the operators eyes to the stereo display screen.

d. Panel Lighting - Console floodlighting, electroluminescent panel lighting and numeric displays will be controllable in intensity steps at the panel or console. Lamp testing capability will be

provided for panel displays.

e. Emergency Lighting - Control and Display panels will provide control capability for manual or automatic emergency lighting of the panels. This requirement may be satisfied through the use of the redundant overhead lighting.

f. Voice Communications - Controls and Displays for voice communication with the shuttle flight deck will be provided at the FFTO Control and Display Station as requirements are defined.

g. Ground Communication - Controls and Displays for control of voice communication to ground station will be provided at the FFTO Control and Display Station as requirements are defined.

B. PHYSICAL REQUIREMENTS

The actual location and volume available in the Shuttle for the FFTO Controls and Displays Station (CDS) has not, as yet, been specifically identified. However, it is recognized that the potential locations will have volume and dimensional restrictions. Therefore, a decision was made to first define a CDS configuration using overall dimensions compatible with the operator/console requirements and secondly, employ a modular concept in which panels may be added or deleted depending on the surface area and volume required for the FFTO controls and displays.

1. General Requirements

The general requirements for the CDS were selected to act as a guideline in developing system concepts and in establishing criteria limits. The general requirements having the greatest impact on system configuration were reviewed and summarized as follows:

- a. Controls will be located within the operators functional reach.

- b. The FFTO operator may either be standing or sitting.
- c. Primary displays will be located within a viewing distance of 45.6 to 61 cm (18 to 24 in).
- d. The design concept will reflect state-of-the-art technology applicable to a 1975 time frame.
- e. All manual controls will be activated by hand operation.

2. Specific Requirements

The following specific requirements were used in defining the console and panel configuration:

a. Visual system criteria:

- 1) A hybrid stereo-mono concept
- 2) Over-under image display, with stereo on top
- 3) Operator's eyes fixed in position perpendicular to the fresnel display along the standard line of sight

b. Control and Display Operator's Size:

- 1) The console will accommodate the 5th to 95th percentile male
- 2) The console will be designed using a functional arm reach of 63.7 cm (25 in) from the shoulder pivot point.

c. Number of Control and Display Station Operators:

One operator positioned at station

d. Head Movement Angles that Operator can Accomplish with Ease:

- 1) Head can tilt forward, from vertical body axis 15 degrees (normal head tilt)
- 2) Head can tilt back from vertical body axis 25 degrees

e. Viewing Angles While Keeping Head Stationary:

- 1) A horizontal optimum angle of 15 degrees both right and left

- 2) A horizontal maximum angle of 30 degrees both right and left
- 3) A vertical optimum angle of 30 degrees down from standard line of sight
- 4) A vertical maximum angle of 60 degrees down from standard line of sight

f. Viewing Distance Between Operator's Eyes and Console Panels:

- 1) A viewing distance of 45.6 to 61 cm (18 to 24 in) will be considered for display screen viewing
- 2) A viewing distance of 33 to 75 cm (13 to 29½ in) will be considered for displays other than the TV display screens. (Ref. 9, Human Engineering Guide).

C. FUNCTIONAL/DIMENSIONAL ANALYSIS

A functional analysis was prepared to define the maximum dimensions and envelope shape for a control and display console using the limits and ranges as listed in IX-B.2. The analysis was separated into a top view and side view analyses. From this evaluation both the horizontal and vertical dimensions and the three dimensional configuration was defined.

1. Top View Analysis

The top view as shown in Fig. IX-1 indicates the horizontal relationship of the operator to the console panels. In this layout the interaction of the horizontal functional arm reach, the fixed head viewing angles and the fresnel-stereo screen depths have been compared for both a 5 percentile and 95 percentile male. An evaluation of this layout indicated that the following dimensional criteria be observed in designing for the horizontal section of the Control and Display Station (CDS).

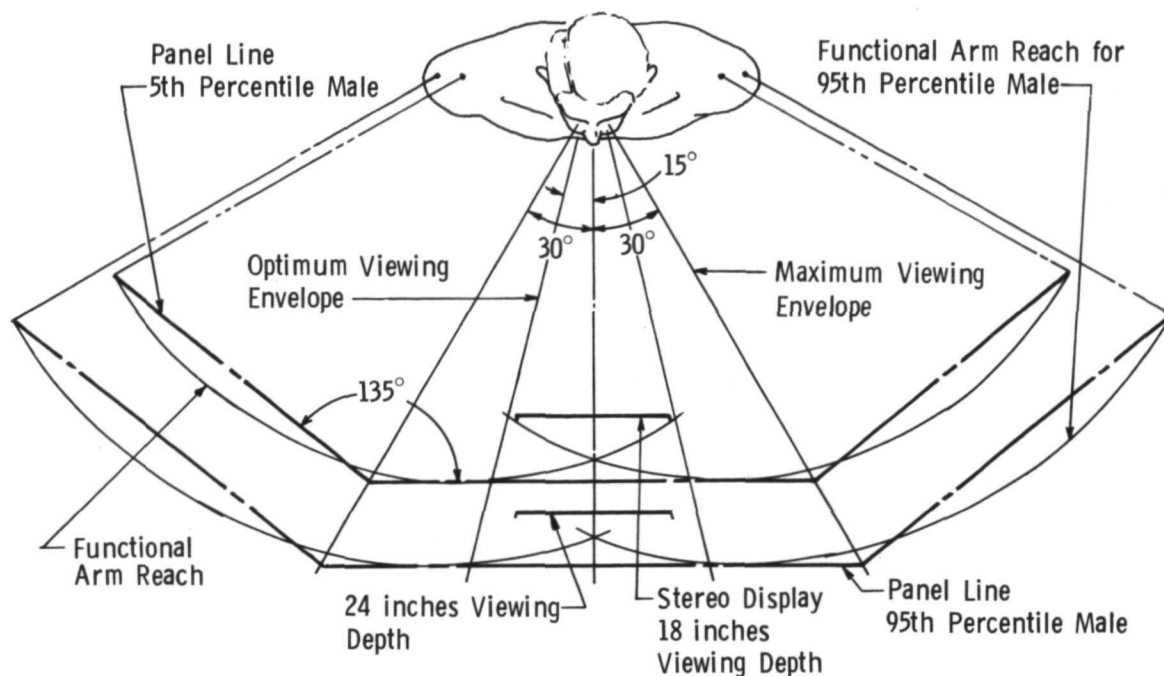


Fig. IX-1 Top View, Horizontal Console Section, At Display Center

- a. Panel Depth - 22 inches measured along the sight centerline perpendicular from the panel surface to the eyes.
- b. Panel Width - Maximum - 28 inches
Optimum - 13 inches
- c. Panel Height - Maximum - 22 inches
Optimum - 14 inches
- d. Functional Arm Reach - 25 inches, measured along the arm from the shoulder pivot point
- e. Side Panel Dimensions - Dimensions used are variable and dependent on the center panel selected and the panel growth requirements.

f. Side Panel Angle - 135 degrees measured on the horizontal/plane from the center panel surface.

2. Side View Analysis

To show this view properly a number of layouts are shown indicating the different dimensional limits or envelopes in which specified areas of the console panels could be located. Figure IX-2 shows a side view of the depth envelope available for locating the center panel. The viewing distance of 45.6 to 61 cm (18 to 24 in) is used as a program requirement; and at present, data evaluated shows no problem of designing within this limit. The next layout, Fig. IX-3, shows the same vertical visual envelopes when tilting the head forward 15 degrees or backward 25 degrees. The forward tilt of 15 degrees simulates a normal line of sight because the normal comfort angle is 10 degrees below the standard line of sight, however, for a seated operator the downward angle is closer to 15 degrees. To simulate the head tilted backward a 25 degree angle is used which simulates a maximum head to shoulder angle that can be made without straining the neck or eye muscles. Both of these angles are measured from the vertical body axis to the head axis from the neck pivot point. As shown in Figure IX-4 and IX-5 two options have been laid out showing the longitudinal console depth outline for a console concept with arm rest and one without arm rest. The concept without arm rest allows a greater freedom for selecting a manipulator control system. Both of the concepts assume a fixed eye position in the vertical axis, the head tilted forward 15 degrees, a fresnel screen located over a mono-screen and a perpendicular line of sight 56 cm (22 inches in depth) from the eye to the fresnel stereo screen center. The rationale for locating the two videodisplays vertically, one above the other is the correlation with the location of the camera mounts on the FFTO. The top display is the primary display, fixed

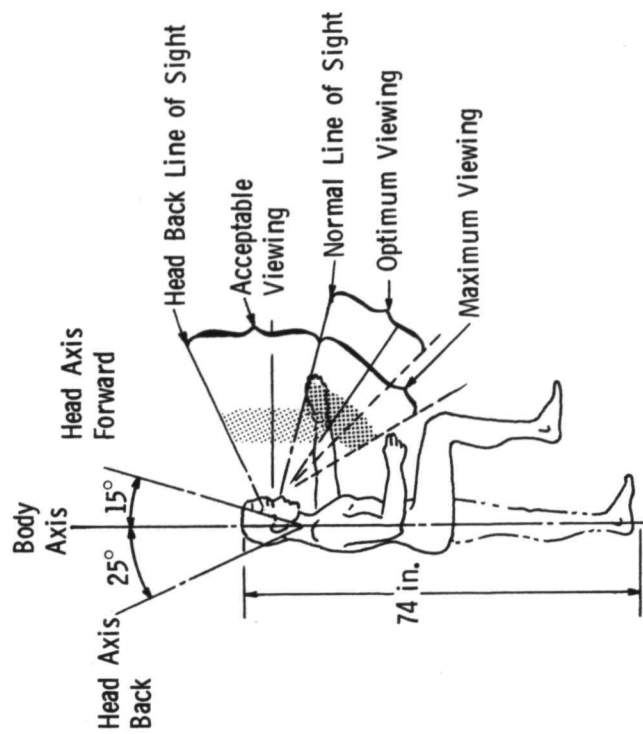
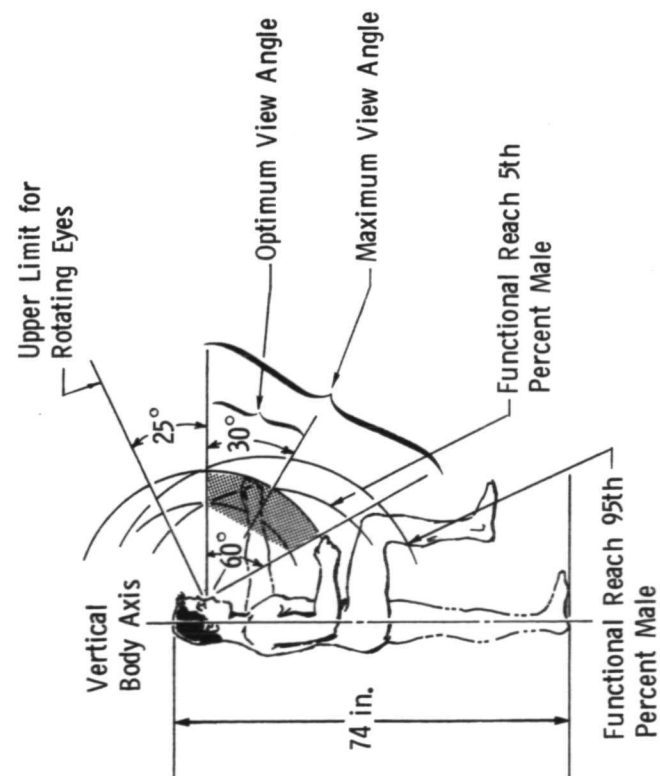


Fig. IX-2 Viewing Envelope for Locating Center Panel

Fig. IX-3 Viewing Envelopes When Tilting Head Back or Forward

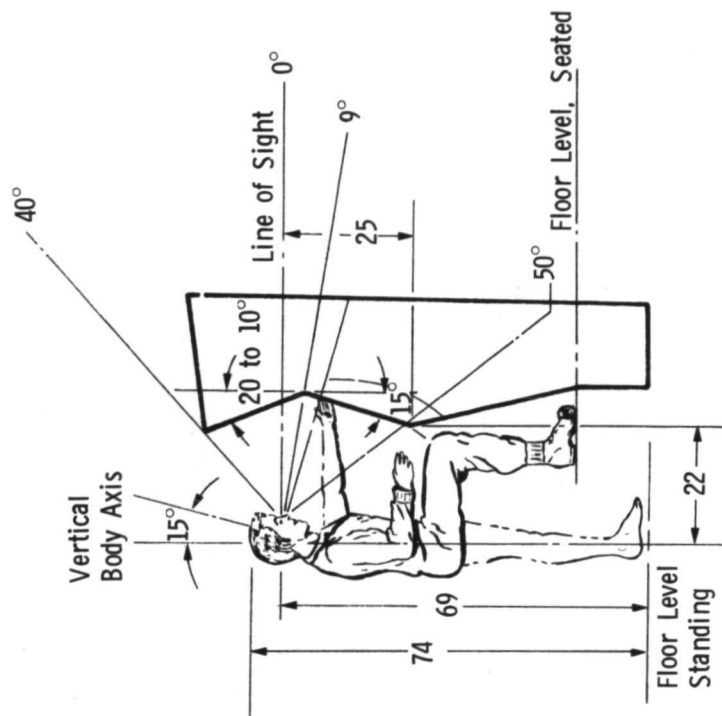


Fig. IX-5 Panel Configuration without Arm Rest Panel

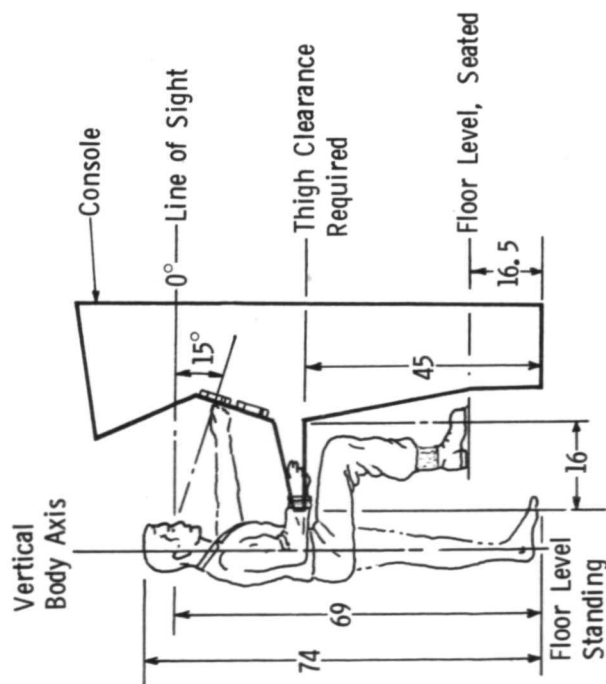


Fig. IX-4 Panel Configuration with Arm Rest Panel

to the moveable stereo mounted cameras. The lower display is driven by the fixed forward looking camera. The location of the FFTO cameras in the vertical plane is considered optimum to the horizontal plane. Thus, the FFTO camera/control station display relationship is maintained without scan-distance penalty. For additional information on this TV screen display configuration see Section VII. Both of the concepts shown in Fig. IX-4 and IX-5 assumes that the operator may be standing, seated or some position in between. When the operator is standing the eye location correlates to the 95th percentile male and requires a floor adjustment of 8 inches to accommodate the 5th percentile operator. A foot and waist restraint system is required to hold the operator in the desired location.

The seat concept selected is adjustable 10.2 cm (4 in) in the vertical direction and adjustable in the horizontal plane to form a sitting position. A lap belt and foot bar is used to restrain the operator in the chair. Based on the fixed eye-height, operator size range, video displays and hand manipulator controls, and the maximum permissible reach of 63.5 cm (25 in) a TV display distance of 56 cm (22 in) was defined.

3. Recommended Dimensional Configuration

The two basic configurations evolving from the analysis are shown in Fig. IX-6 and IX-7. The major difference between the two options is a lap panel vs no lap panel. With this variation, a considerable freedom is available for the selection of a manipulator controller. Figures IX-8 and IX-9 shows the applicable control and display element mounting location classifications for both concepts.

The surface area available in Fig. IX-8 for mounting the control and display elements requiring a classification of I or II is

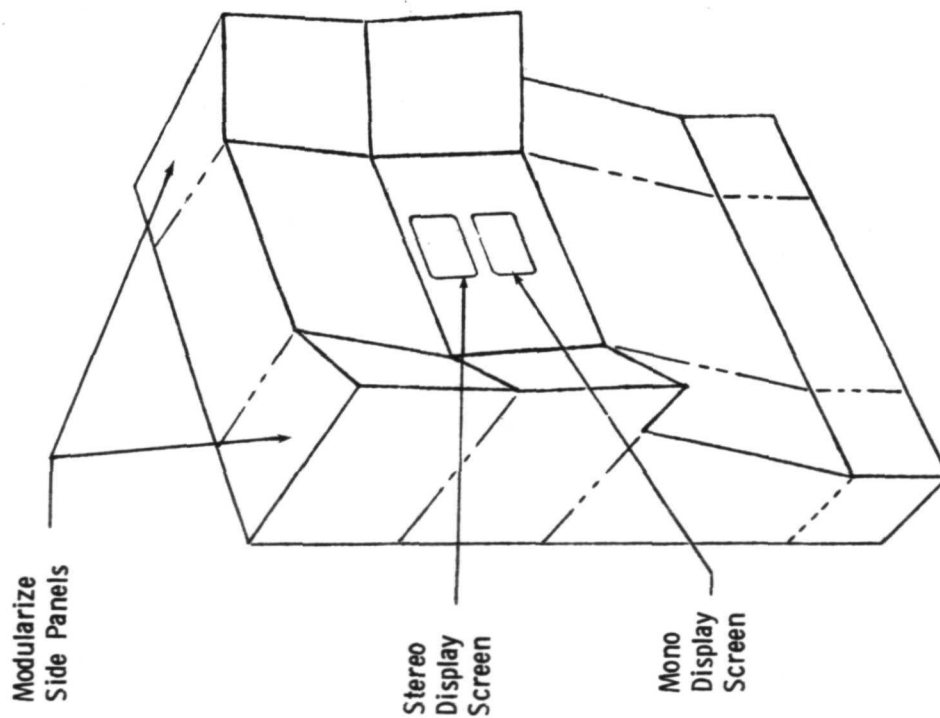


Fig. IX-6 CDS Concept

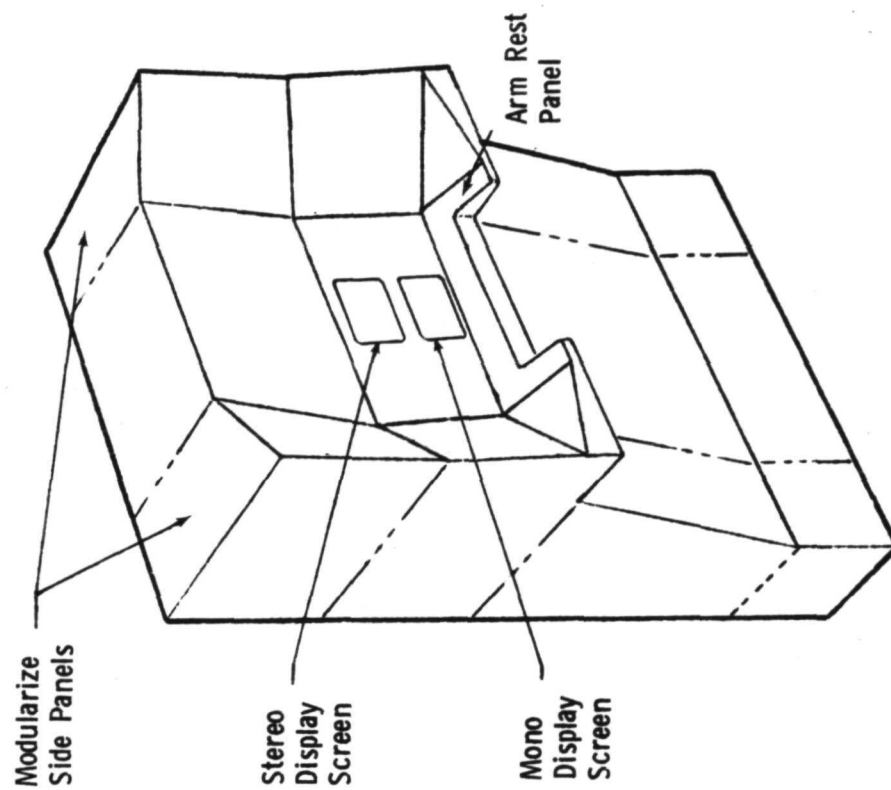


Fig. IX-7 CDS Concept with Arm Panels

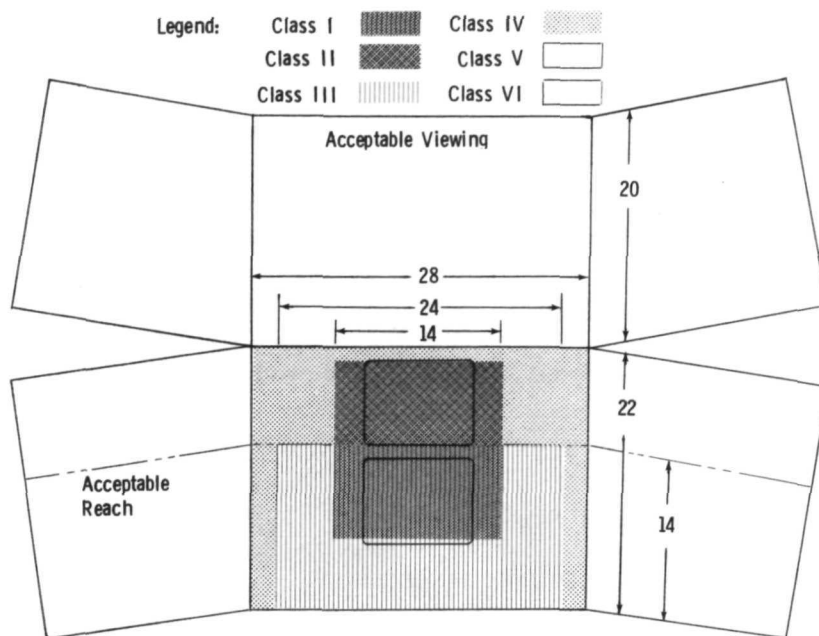


Fig. IX-8 CDS Panel Mounting Classification

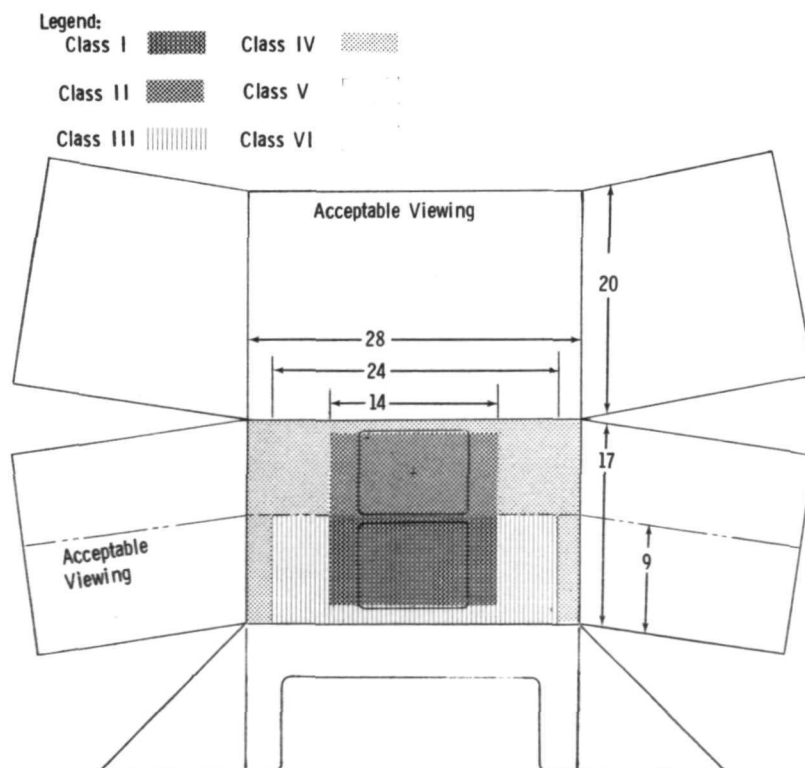


Fig. IX-9 CDS Panel Mounting Classification with Arm Rest Panel

1265 sq. cm (196 sq. in). This area is used for mounting the two TV display screens. The peripheral or remaining surface mounting area as to classification breakdown is as follows:

Class III has 1450 sq. cm (224 sq. in) of panel surface available

Class IV has 1265 sq cm (196 sq in) of panel surface available

Class V has approx. 3100 sq cm (480 sq in) of panel surface available

Class VI has approx. 9550 sq cm (1480 sq in) of panel surface available

For the second concept, as shown in Fig. IX-9, the surface area classifications are broken down as follows:

Class I & II has 1265 sq cm (196 sq in) of panel surface available

Class III has 670 sq cm (104 sq in) of panel surface available

Class IV has 1135 sq cm (176 sq in) of panel surface available

Class V has approx. 2100 sq cm (325 sq in) of panel surface available

Class VI has approx. 9550 sq cm (1480 sq in) of panel surface available

When considering the second concept of using an arm panel as shown in Figure IX-7 the panel surface available is increased by approximately 1935 sq cm (300 sq in). However, the open volume between the console and the console operator is reduced.

D. CONTROL AND DISPLAY STATION SYSTEM REQUIREMENTS

The primary purpose of this section is to determine the optimum console/panel surface area required and panel locations for the visual system controls and displays. An initial layout prepared during Phase I, has the visual system controls and displays only.

This layout is not too useful when one considers the interaction that control and display elements from other systems have on their relative location importance. The integration of the controls and displays required to operate a FFTO into one, results in a Control and Display Console layout that is completely different from the initial layout. Therefore, an attempt is made to feasibly interfold the visual system controls and displays into a total FFTO Control and Display Station. This requires the identification of systems other than the visual that are required to operate the FFTO. The FFTO can be separated into a number of prime systems; visual, propulsion, guidance/navigation, command communication, docking device and manipulator. Many vehicle system concepts applicable to the Free-Flying Teleoperator have been studied during the past decade. Each study has resulted in a final system design which included most of the above mentioned systems tailored to the particular mission/system requirements. Since this study did not cover the FFTO systems other than the visual system, the approach taken required a preliminary system integrated FFTO definition and related man-machine interfaces. In order to define an integrated FFTO Control and Display Station the type of subsystem and components must be known. A review of some of the FFTO studies done to date (Ref. 10,11, & 12) resulted in a preliminary system configuration definition with a number of the more feasible subsystem components assumed. The assumptions made are gross with the realization that considerable future effort is required in matching mission requirements with system capabilities. A brief description of these subsystems, and their control and display modes are given in the following paragraphs.

1. Visual

The visual system selected is an indirect viewing technique which utilizes two movable TV cameras mounted as an assembly on the FFTO.

A second camera uses a fixed mounting on the FFTO. The cameras are mounted to provide one stereoscopic image and one monoscopic image on the display screens at the CDS. This system also requires a number of additional subsystems as described in Section VIII. The main man-machine interface considerations for this system are the viewing requirements associated with the two display screens (one mono, one stereo fresnel), and display controls and the reach requirements associated with the three monitor controls, the three camera adjustments, the camera positioning and camera selection for viewing preference at the Control and Display Console. The prime viewing requirement for the fresnel display screen is the restriction it places on the operators head movement. The optical design of the system defines an exit pupil volume of approximately the following dimensions:

Horizontal Head Movement; ± 3.3 cm (± 1.3 inches)(defined by
Human Interpupillary Distance)

Vertical Head Movement; ± 7.6 cm (± 3.0 inches)

Forward Head Movement; ± 15.7 cm (± 6.0 inches)

By limiting the head movement so that the eyes are positioned within the required volume, establishes the fixed eye position and the standard line of sight dimensional length to the center of and perpendicular to the fresnel display screen. This in turn establishes the fresnel display screen as the most critical display element in defining the man-machine/Control and Display Console configuration. With the fresnel display screen mounting location fixed on the CD console, all other control and display elements and their locations become relative to the operators use interaction with the stereo image display. An activity analysis to assign relative importance of control and display elements for peripheral panel mounting locations has been prepared and is described in Section IX.E.

Camera positioning has the following control capability: The monoscopic camera is on a fixed mounting and can be positioned only with the attitude control system. The stereoscopic camera assembly is mounted on a deployable boom. The boom has the capability to pan 359 degrees and a capability to tilt 180 degrees from the primary hinge point. The camera mounting platform is also capable of ± 90 degrees tilt.

2. Propulsion

The propulsion system used on the FFTO is assumed to have the same general control and display elements and hardware for a number of different propellant types. The basic equipment include fuel tanks, gas pressurization, thrusters, and associated valves such as fill/drain, fuel isolation, liquid vent etc. Control is required from the CDS to activate and deactivate valves by both automatic and manual means. For display purposes fuel remaining, gas pressure, temperatures and valve position status lamps are required.

3. Electrical Power

The power supply system is assumed to be a storage battery system with a recharge capability. A main circuit breaker is used to switch from Shuttle to FFTO power and from one battery bank to another battery bank. Displays for this system include status lamps, voltage and amperage readout, and battery select temperature readout.

4. Guidance Navigation and Control (GNC)

The Guidance Navigation and Control system provides the FFTO with an attitude and translation control center. The system is most likely a partially active three-axis control system having active error sensing (rate) and active control torquing about all three axis. The assumed components located on the FFTO that make up

this system are the computer that inputs the thrust selection logic to the propulsion subsystem, the rate gyro, the control moment gyros (CMG), the range/range rate sensor, and the associated electronics. Controls required from the C&D station include; attitude controller with an attitude mode selection, translation controller with a translation mode selection, gyro controls; optional thruster firing selection (computer input) and system command telemetry. Displays required for these components include range/range rate indication, status lamps and digital clock readouts.

5. Docking Mechanism

The probe and latching drogue concept is assumed for docking. The probe is passive and mates with a drogue cone which incorporates the latching device. The probe is FFTO mounted and the drogue and latch is target or satellite mounted. Controls for this unit include main power and unlatching. Displays include TV image, docking status lamps and interfacing guidance, navigation and control aids.

6. Manipulator

A modularizing approach for this manipulator/grappler system has been assumed due to the number of different mission task categories. This requires a FFTO structure design that can accommodate a number of different manipulator concepts through the use of a common interface. This in turn requires a common interface for the man-machine interface functions. The operator control hardware required for this function is still open. However, the operators control functions are about the same and are identified as: hand controller with seven degrees of freedom and attached switches to activate such items as zoom lens, ALC, auto program select, camera auto track and end-effector actuation. The associated displays include TV image, status lamps, contact indication, applied loads

readout and a location reference indicator.

E. OPERATOR ACTIVITY ANALYSIS

The activity analysis as prepared for this program, studies the activities carried out by the FFTO operator doing his assigned work. This work assignment includes the control and monitoring of the FFTO task operation. However, a number of different tasks have been envisioned for the FFTO. One of the more difficult mission tasks would be one of conducting maintenance on a free flying experiment. As a preliminary basis the following functions were included: FFTO mission preparation, FFTO checkout, deploy from Shuttle docking, FFTO maneuvering (checkout) to target, inspect target, dock to target, perform maintenance task, undock from target, return to Shuttle and stow FFTO. With these functions as a starting point a preliminary selection of control/display type hardware concepts were identified. The identification was made by considering the the following human factors:

1. Control Requirement and Evaluation Criteria

A listing of the control requirements was developed for the subsystems necessary to operate a FFTO. The integrated FFTO system assumed was the one defined in Section D. The following evaluation criteria was used in the analysis.

a. Physical Activity Required by the Operator - The ground rule was assumed that all manned control inputs would be accomplished with the hand and lower arm movements of either left or right arm.

b. Task Period when Activity Required - This item was considered similar to a use/frequency analysis where the control activity defined was assigned one of the following: activate at start and end of mission, intermittent observation, intermittent control, continual observation, continual control and uncontrolled frequency.

c. Time Required to Accomplish Activity - Time in minutes or seconds to do a specific activity.

d. Pre or Post Activity Required - This was an attempt to show a link analysis where the number of use-times a control or display element is followed by the same use of other control-display elements. This helps in establishing a console location as to operating sequence.

e. Classification - A classification rating has been applied to the different control and display elements to aid in laying out the console panels. These classification levels have been defined as follows:

Class I - Control and display elements, requiring optimum viewing and reach locations.

Class II - Control and display elements requiring optimum viewing

Class III - Control and display elements requiring optimum reach locations.

Class IV - Control and display elements requiring maximum viewing without rotating head.

Class V - Control and display elements requiring acceptable reach and viewing

Class VI - Display elements requiring acceptable viewing only

f. Relative Importance - A second rating or priority list was developed to further establish the relative panel locations within each classification. This was more of a subsystem rating which included a number of the above items such as frequency of use, right or left hand operations, sequence of use and importance to mission success.

2. Activity Summary

A summary of the activity analysis is shown in Table IX-1. It can be seen that this type of information is also particularly useful for judging the relative importance of various operator activities and the demands they make on the operators time and effort.

The limitation of any activity analysis is that it cannot direct attention to the fact that activities that occur only rarely might still occur simultaneously. Also a low percent of total time does not necessarily mean that conflicts could not occur.

F. VISUAL DISPLAY ANALYSIS

1. CDS Hardware Considerations

The Control and Display Station hardware selection included the following considerations:

- . The work load distribution for each limb and whether the same limb might be required to do two or more functions at the same time.
 - . The matching of proper control action to each assigned task.
 - . The use of guards where controls may be accidentally activated or incorrectly operated.
 - . Similarity of controls for ease of operation.
 - . Selection of controls and displays that have been verified as spacecraft common hardware.
 - . Selection of hardware for simplicity of operation.
- The hardware selected and rationale has been separated into the control and display elements.

Table IX-1 FFTO Control & Display Station Operators Activity Analysis

FFTO Mission Functional Task	Control Requirements	Potential Control Hardware	Activity Required of Operator	Task Period Required for Activity	Time Required To Accom. Activity	Prior or Post Activity Required	Class-ification	Rel. Import.	Remarks
A. FFTO Mission Preparation	1. Power to GND Console	Circuit Breaker	Lever Action	Mission Start & End			V		Status Lamp
	2. Activate FFTO	Guarded Toggle Switch	Lift and Pull	Mission Start & End		Mon. Panel Fuel Ind.			Service Station (Optional)
	3. Load Fuel Tanks	Guarded Toggle Switch	Lift and Pull	Post Mission		Mon. Panel Press Ind.			
	4. Pressurize Sys.	Guarded Toggle Switch	Lift and Pull	Post Mission		Mon. Bat. Charge Ind.			
	5. Battery Charge	Guarded Toggle Switch	Lift and Pull	Post Mission		Perform with FFTO Activated and Deactivated	V		
B. FFTO Control and Display Station Check-out (ELECT.)	1. Elect. Circuit Breaker	Toggle Switch	Lever Action	Post Mission/as Req.			V		
	2. Fuel System Isolation and Emergency Ctr. Check-out	Toggle Switch	Lever Action	Post Mission/as Req.		FFTO Prep and GND Check-out Complete	V		
C. FFTO Deploy from Shuttle	1. Shuttle Can Fallot	Shuttle Function	Lever Action	Mission Start & End			III		Switches QNDW Communication from the Shuttle to FFTO
	2. Fuel Sys Com Link with FFTO Manifold	Toggle Switch	Lever Action	During Free Flight			V		
D. FFTO Systems Check-out, Prep. & Guidance	1. FFTO External	Circuit Breaker	Lever Action				III		On-Off Status Lamps, Data Readout
	2. Manifold Isolation	Toggle Switch	Lever Action			Fuel, Press & Temp Indication	III		Status Lamps, Control Moment Gyro, 3 CHDs with Single Control, 6 Status Displays
	3. Valve Actuation	Toggle Switch	Lever Action				III		Safe Arm Indication
	4. Radar Gyro Act.	Toggle Switch	Lever Action				III		Selection Between Manifold A, B and ADB is normally automatic.
	5. Thruster Safing	Toggle Switch	Lever Action				III		Manual Override Prev. for Emergency
Visual	6. Thruster Arming	Toggle Switch	Lever Action			Thruster Safe Arm	III		
	7. Control Dynamics	Push-button	Push Action						
	8. Actuation of Auto Range	Push-button	Push Action						
	9. Cameras Activated	Toggle Switch	Lever Action	Mission Start & End			V	3-L	
	10. Telecommunications	Push-button	Push; Selection	Intermittent			V		
	11. Camera Monitor Adj.	Toggle Switch (On Panel)	Lever Action				V	2-L	(1) Home Camera and (2) Stereo Cameras
	a. Brightness	Rotary Pot	Turn Action				V		(2) Display Screens; Option of Camera, Select on Either Screen, Stereo Display on Top Screen Only
	b. Contrast	Rotary Pot	Turn Action				V		
	c. Vertical	Rotary Pot	Turn Action				V		
	d. Horizontal	Rotary Pot	Turn Action				V		
	12. Ground Glass Screen	Push-button	Lever Action	Target Inspection		Monitor Screen Act. and Adjusted	III	2-R or L	(3) Two Position On-Off (2) Two Position On-Off (2) Two Position On-Off (2) Two Position On-Off
	13. IRIS	Toggle Switch	Push Hold			Camera Power Act.	III		(3) Two Position On-Off (2) Two Position On-Off (2) Two Position On-Off (2) Two Position On-Off
	b. Zoom	Toggle Switch	Push Hold				III		(1) Stereo, Location Ind.
	c. ALC	Toggle Switch	Push Hold				III		(1) Two Position Select; Manual-Auto
	d. Focus	Toggle Switch	Push, Pull & Rotate			Look onto Man. Act.	III		Three Position; Manual-Off-Jato Preg.
Manipulator	e. Pan/Tilt	Control Stick	Push, Pull & Rotate				III		
	f. Deploy	Control Stick	Lever Action	Maintenance Task		Light Power Act. Camera Track Act. Mon. End Eff. Cont. & Load Status	III	1-R	
	14. Camera Track	Toggle Switch	Lever Action						
	a. Manual	Same as D.13, ed							
	b. Auto	Light Status							
	15. Manipulator Actuation	Toggle Switch	Lever Action						
	a. Joy Stick	Six Degree Freedom	Lower Arm & Wrist						
	b. Camera Position	Rocking Switch	Push Action						
	c. End Effector	Rocking Switch (2)	Push Action						
	d. Actuation	(Self Cent. Rocker)	Push Hold						

Table IX-1 FFTO Control & Display Station Operators Activity Analysis (Cont'd)

FFTO Mission Functional Task	Control Requirements	Control Hardware	Activity Required of Operator	Task Period Required for Activity	Time Required To Accom. Activity	Prior or Post Activity Required	Classification	Rel. Import.	Remarks
E. FFTO Maneuvering to Target	1. Same as D.1 thru 8		Lever or Push Action	At Start of Maneuver		Mon. Man. Iso Valve	III	1-R	Apollo or Skylab Type Unit
	2. Angular Control in 0, 90, 180, 270	Type 3 Axis Angular Controller	Hand & Wrist Action	Continual During Maneuvering Task		Spin Up, Fuel Level & Battery Charge			Angular Displacement Information in 0, 90 and 180 provided by stereo or Two Mono Displays
	3. Attitude Control Mode Select: Level	Push-Button	Push-On, Push-Off	Continual During Maneuvering Task		Mon. Stereo TV	III	2-R	
	4. Attitude Control Mode Select: Roll	Push-Button	Push-On, Push-Off	Continual During Maneuvering Task		Power Actuation			
	5. Attitude Control Mode Select: Pitch	Toggle Switch	Lever Action	Intermittent, Manual		Auto Range Active	III	1-L	Two Position, Auto-Manual Apollo or Skylab Type Unit
	6. Translation Control Mode Select: Manual	Push-Button	Push-On, Push-Off	Intermittent, Manual		Power Actuation	III	2-L	Linear Displacement Information in X, Y and Z provided by Stereo TV Monitor or Two Mono TV Monitors
	7. Translation Control Mode Select: Auto	Push-Button	Push-On, Push-Off	Intermittent, Manual		Power Actuation	III	R or L	Digital Display, Two Clocks, Reset Cap.
	8. Translation Control Mode Select: Manual	Toggle Switch	Lever Action	Intermittent, Manual		Power Actuation	III		Computer Supplies Thruster Logic with Inputs. CMG, Alt & Tra Sel. Modes, etc.
	9. Translation Control Mode Select: Auto	Toggle Switch	Lever Action	Intermittent, Manual		Power Actuation	V	1-R	CMGs Actuated, CMGs at Correct Speed, Light Status (Y) CMGs, Single Control, 6 Status Displays
	10. CMG Control Act.	Toggle Switch	Lever Action	Intermittent, Manual		Power Actuation	III	2-L	Two Position; Manual-Auto Track Pan/Tilt Only, No Display on Auto Track, Follows End Effector
F. Inspect Target	1. Manual Track	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect	III	2-R	Two Position; Manual-Auto Track
	2. Linear Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			On Auto Track, Follows End Effector
	3. Camera Positioning	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			This Control Req. Takes Full Attent. while Viewing TV screens Until An Attitude Hold is Made, Manual or Auto Track
	4. Camera AdJ. & Cont.	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			Contact Status Light, Latching At Docking is Automatic & Latch Status
	5. Attitude Hold	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			Unlatching at Undocking Req. A Manual Input
	6. Linear Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			Display Required for Status; Light for Target Contact
	7. Camera Positioning	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			Loads; Clamping & Retrieval
	8. Camera AdJ. & Cont.	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			1) Stow 2) 3) 4)
	9. Attitude Hold	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	10. Linear Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
G. Dock to Target	1. Attitude Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	2. Linear Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	3. Camera Positioning	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	4. Camera AdJ. & Cont.	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	5. Attitude Hold	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	6. Linear Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	7. Camera Positioning	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	8. Camera AdJ. & Cont.	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	9. Attitude Hold	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
	10. Linear Control	Toggle Switch with Light	Lever Action	Intermittent, Manual		Find & Inspect			
H. Perform Maintenance Task	1. Manipulator Activation	Push-Button	Push Action	Intermittent, Manual		Manipulator Active	III		
	2. End Effector Cont.	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	3. Auto Program	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	4. Checkout Seq.	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	5. Undock	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	6. Maneuvering & Guidance/Nav & Control	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	7. Return to Shuttle	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	8. Stow FFTO into Shuttle	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	9. Deactivate FFTO	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			
	10. FFTO Undock	Push-Button	Push Action	Intermittent, Manual		Manipulator Active			

a. Control Hardware - The type of hardware selected for control purposes is listed in Table IX-2, which also includes the control requirement and general rationale for hardware selection. A number of hardware alternatives are available for many of the different functions.

Most of the control hardware items selected can be found that are partially or fully flight qualified. Many of the control units are common spacecraft hardware, however, the inconsistent dial designs and scales requires a modification to be compatible with the FFTO CDS.

b. Display Hardware - The type of hardware selected for display purposes is listed in Table IX-3, which also includes the display requirement and general rationale for hardware selection. A number of hardware alternatives are available for many of the display functions. Except for the TV monitor and display screens most other items can be found that are partially flight qualified. Many of these displays are available, however, when comparing the information of the dial designs and scales require modification to be compatible with the integrated FFTO CDS.

2. Augmented Display Considerations

The availability of on-board computer and TV monitors presents the interesting possibility of incorporating these units to compute and display information helpful in performing FFTO mission tasks. A list of possible computer generated displays for some selected FFTO mission tasks is presented in Table IX-4. The list identifies only the tasks where computer support may be applicable. However, the feasibility depends on available hardware, cost, operation complexity and weight, volume and power requirements. This equipment to be of maximum use would provide computer display of graphic and alpha-numeric data. The information given in Ref. 11

Table IX-2 Control Type Hardware and Rationale

Control Requirement	Type Selected	Rationale
Camera Controls Positioning (Boom) (Camera mount)	Main Power; Toggle Switches Pan/Tilt; Pencil Stick Control Tilt, Self-centering-Rocker Switch Iris; Self-centering-rocker switch Zoom; Self-centering,-rocker switch	Spacecraft common hardware Permits control motion analogous to camera motion Permits control motion analogous to camera motion Permits device motion analogous to common spacecraft design Provides compact unit with position indication
Monitor Adjustment	Auto Light Cont (ALC); toggle switch Focus; Self-centering rocker switch Main Power; toggle switch Camera Select; toggle switch Brightness; rotary pot Contract; rotary pot Vertical; rotary pot Horizontal; rotary pot Main Power; toggle switch Toggle switch & push button matrix Rotary pot	Provides two position switch for two levels of lighting Same as Iris Spacecraft common hardware Same as above Common monitor control hardware Same as above Same as above Same as above Same as above Spacecraft common hardware
Illumination Telecommunications Range Reticule Translational Attitude Control	Honeywell Apollo Type Translation and Attitude Controllers	These controllers are suitable 3-axis controllers which are space qualified.

Table IX-2 Control Type Hardware and Rationale (Cont'd)

Control Requirement	Type Selected	Rationale
Docking/Undocking Arming Control	Guarded Toggle Switch	Guarded to prevent inadvertent actuation. Provide status information through toggle position.
Docking/Undocking Latch Control	Guarded push button	Guarded to prevent inadvertent actuation.
Automatic Clutch Activation	Push-button matrices with status lights	Provides compact functional groupings. Simple way to provide a large number of combinations.
Control Dynamics Selection	Guarded toggle switches	Guarded to avoid inadvertent activation or deactivation.
Power Controls for FFTO & CD Console	Guarded toggle switches	Same as above
Manifold Isolation Valve and Safing Sel.	Toggle switches	Provides a visual status information and a monitor function with the status lamps.
Gyro Actuation and Cage Controls	Dual thumb wheels with detents	Provides compact unit with minimum volume requirements/
Lenticular Faceplate adjustment	Toggle switch, time indication	Same as above.
Video Tape Record	Panel switches, rotary pots	Same as above.
Circuit Breaker Panel	Push button matrix	This unit is suitable with slight modifications and the basic unit is space qualified.
Thrust Logic Computer	Main power toggle switch	Spacecraft common hardware
Manipulator Control	Mode select; push button matrix	Provides compact functional groupings
	Ratio reset; toggle switch	Spacecraft common hardware
	Grasp; toggle switch	Same as above.

Table IX-3 FFTO Display Hardware Selection and Rationale

Display Requirement	Hardware	Rationale
Translation and attitude information for maneuvering	Two 12-in diagonal measure black & white displays. One with a Fresnel screen.	One stereo display is essential to provide information in 3 axes of freedom. One mono display is provided to act as backup in case of failure to one of the stereo cameras two mono views are essential to provide information in 3 axis of freedom. <u>Size of Monitor:</u> The 10 to 12 inch diagonal measure for the monitors were selected on a weight and volume tradeoffs. For the operators capability to perform tasks, lab simulations have shown little difference in operator performance when using a 12 in. diagonal or slightly larger monitor.
	Moving tape, range and range rate display.	1. Ease of comparative readout 2. High density of data presentation 3. Displays direction of motion analogue to the monitor condition 4. Space qualified hardware available
	Digital Event-Timer and clock	1. Ease of readout 2. Space qualified hardware available
Camera Positioning; Stereo Cameras	Circular scale around hand control stick; pan/tilt, left, right, tilt; up, down	The selection of a control stick provides dual control with one controller and provides control analogous to camera motion.
	Tilt; up, down, toggle switch	Boom position is provided with servo motor drive to joints giving a pan/tilt and tilt cap.
	Auto track, push-button with integrated light	Quick reference to camera position status 1. Optimum for weight & surface area.

Table IX-3 FFTO Display Hardware Selection and Rationale (Cont'd)

Display Requirement	Hardware	Rationale
Stereo Cameras (Cont'd)		2. Integration of controls with displays 3. Provides for simplicity of installation and maintenance No additional requirement (NAR)
TV image for cameras and monitors	Image on monitor then adjust camera.	
Docking/undocking latch arming	Status light with switch position	NAR
Docking/undocking unlatch	Status light with switch position	NAR
RTCM status information	Hardware not defined	
CMG Status & rate information	Activation switch position status lights	Spacecraft precedent
Attitude & translation control mode selection	Push-button matrices with integrated status lights	Control selection of push-buttons 1. Optimum weight and surface areas 2. Integration of controls with displays 3. Simplicity of installation and maintenance
Main power (on-off) and subsystems power	Switch position & status lights	No other practical alternative
Guidance/Navigation & Camera Links	Toggle or Push-button matrices with static lights.	Same as attitude & translation
Propulsion System Status		
. Manifold select.	Toggle switch & status light	No other practical alternative
. Isolation valves		
. Thrust safing status		
. Fuel remaining	Linear display	Spacecraft precedent
. Gas pressure	Gage, direct readout	Spacecraft precedent
Manipulator status	Push-button matrix with integ. station lights	Same as attitude & translation
End-Effector Loads	Strain gages	

Table IX-4 Potential Computer Supported Displays

Phase/Task	Display	Computer Support
<u>Checkout Phase</u>	Checkout sequence list and	Bookkeeping function
<u>Rendezvous Phase</u>	Checkoff locator	with additional call-ups
Command Closing Rate Translation	Attitude angle and rates ΔV required ΔV applied ΔV actual	Generation of ΔV and attitude angles required, applied and actual
Visual surveillance of attitude	. Attitude angles & rates . FFTO, Shuttle, target & Reference (sun or stars)	Generation of graphic displays
Monitor Range and Rates	. Range and rates	Generation and display
Maintain Communication envelope attitudes & alignment	. Communication envelope . Body geometry	Generation of envelope Geometry display
Inspection	. Road map with new call-up list	Bookkeeping function for inspection sequence and result action
Target track	. Distance from FFTO to target	Distance of distance from reticle input
Propulsion System Status	. Fuel, Temp. Press & operating modes	Generation or relay of status
Align docking axes	. Docking aids	Generation of graphic displays
Measure satellite	. Rates	Generation rotation, nutation
Sensor Positions	. Reference	Generation and display of FFTO/Sensor axes relation
<u>Dock and Latch Phase</u>		
Operate manipulators/ end-effectors	. Arm position and rate feedback	Generation & display of arm orientation
Synchronize rates	. Rate display of arm	Generation syn. rate and display
Disengage	. Decision output display	Computation of force

Table IX-4 Potential Computer Supported Displays (Cont'd)

Phase/Task	Display	Computer Support
<u>Maintenance Phase</u>		
Maintenance	. Operating sequence display	Bookkeeping function
<u>Recovery Phase</u>		
Maneuver Procedures	. Same as rendezvous	
Position Orientation	. Shuttle system aid	Shuttle data display
Monitor system status	. computer display	Computer interpretation checkout data

was used in compiling the information listed below and in

Table IX-4. In general the computer generated graphics include:

Generation of FFTO, shuttle, target, sun or star geometry display

Generation of range and range rate envelopes

Generation of FFTO and target dynamic conditions

Generation of sensor and manipulator arms position display

Generation of references axes orientation

Generation of mission tasks sequence and task in process

Generation of troubles shooting aids and decision trees

Generation of reticles to serve as docking, alignment or distance determination aids.

The computer generated numerics include:

Generation of attitude and translational rates and angles; required, applied and actual

Generation of commodity (fuel, gas & electrical) amounts used or remaining for leakage determination and projected mission time availability

Generation of system status information

Where specific computer programs, displays and display formats must be developed, a simplified coding system for quick callup is required. A separate TV monitor is provided for computer display of both graphic and alpha-numeric data. However, the capability is also provided to display the computer generated data onto or overlaying the video image from either sensor assembly.

G. PRELIMINARY INTEGRATED FFTO CDS LAYOUT

1. Panel Layout Methodology

The work effort and sequence used to arrive at integrating the visual system and subsystem controls and displays into a total FFTO Control and Display Station Concept is summarized in Figure IX-10. Each of the major task is represented by a block in the flow diagram.

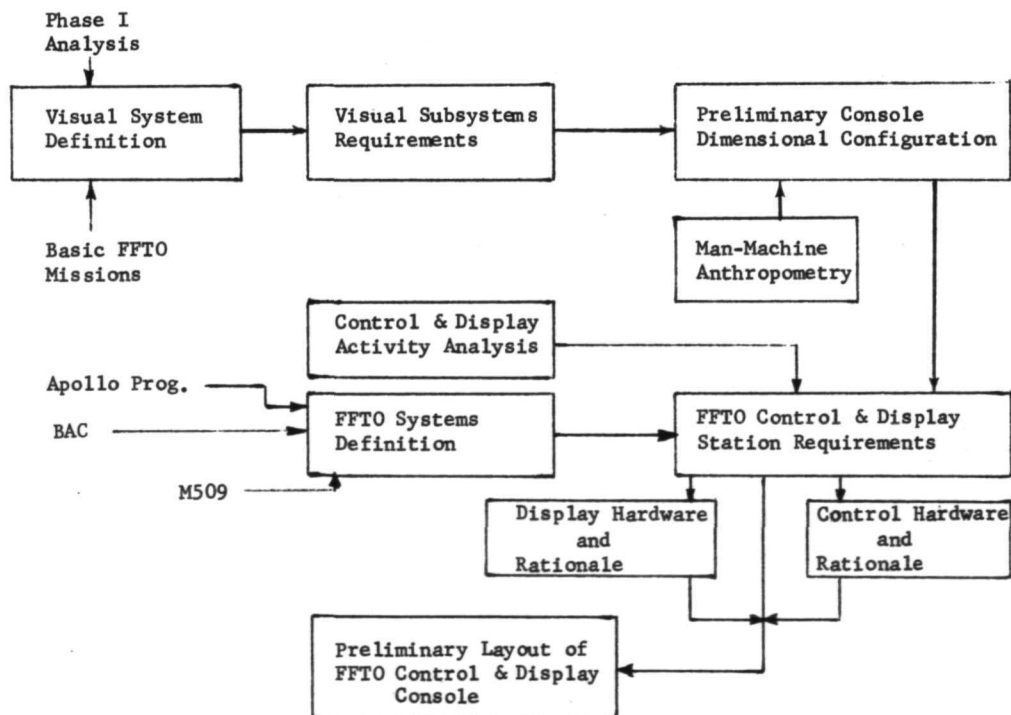


Figure IX-10 Control and Display Station Layout Methodology

2. FFTO C&D Panel Layout

A preliminary layout at an integrated FFTO CDS is shown in Fig. IX-11. A summary of some layout considerations is discussed in the following paragraphs:

The two video displays are considered the basic elements in establishing C&D panel configuration. As discussed in section D-1 the over-under concept is assumed with the stereo-fresnel screen being the top display. The location of the displays in the vertical plan is considered superior to the horizontal for two prime reasons; one is the display correspondence to camera mounting locations on the FFTO and the other is the capability to have most of the display viewing areas located within the operators optimum viewing envelope. The display locations relate directly back to the fixed eye - height and distance (x,y, & z) reference point.

All other controls and displays that are included in the panel layout are mounted in functional groupings. The functional grouping as shown in Fig. IX-11 are mounted in an arrangement that is peripheral to the two display screens. The location within this peripheral arrangement is determined by the activity analysis classification and relative importance as defined in Table I. Some of the rationale used in evaluating potential mounting locations is given in the following paragraphs.

At the lower right of the mono display is an Apollo type pistol-grip attitude controller assembly and a mode selection push-button matrix used to control the FFTO attitude changes with the right hand.

In the same area on the opposite side of the display is an Apollo type T-handle thrust/translation control assembly and a translational mode selection push-button matrix used to translate with the left hand.

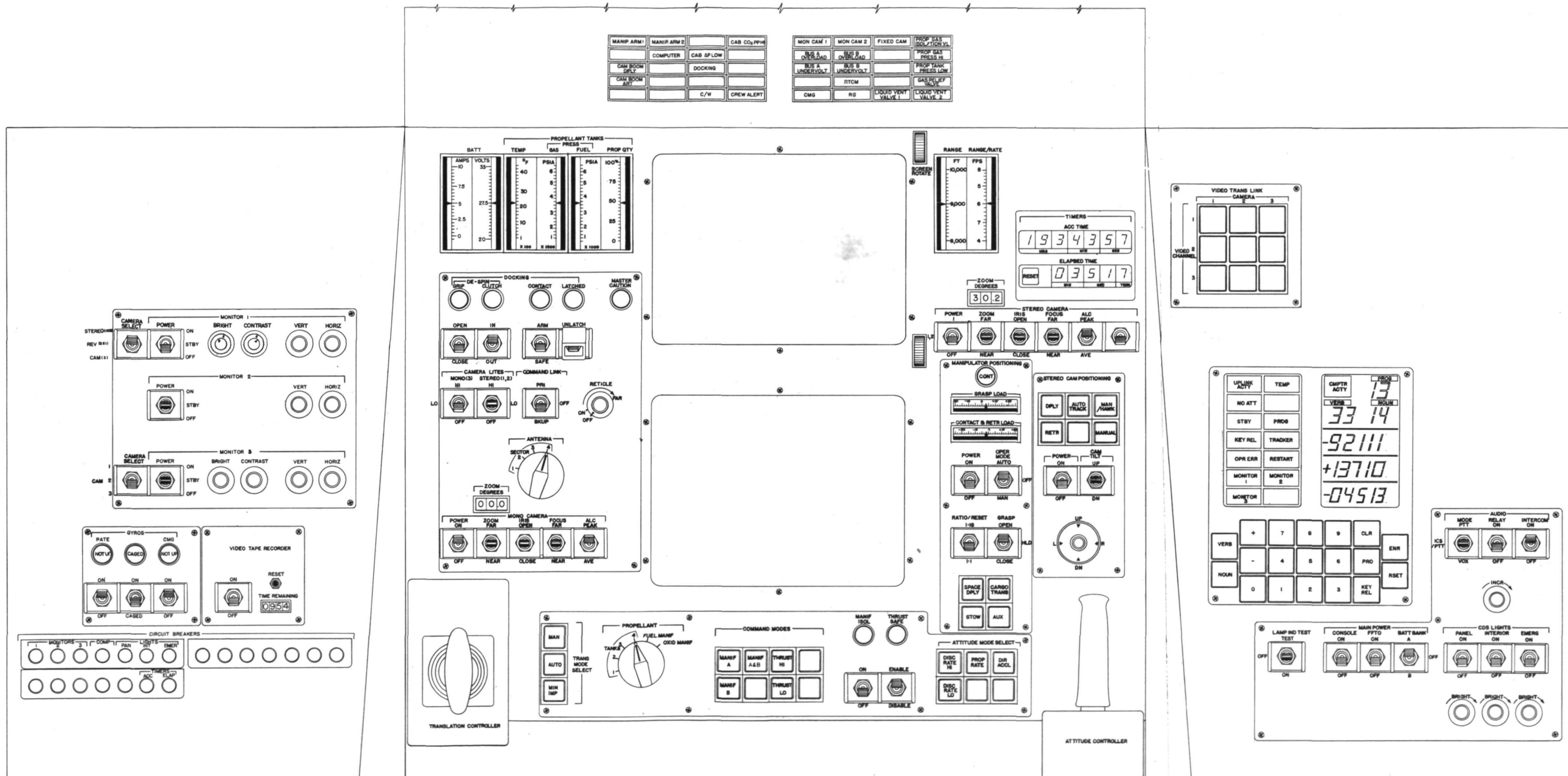


Fig. IX-11 Preliminary Integrated FFTO CDS Panel Layout

Any attitude command has priority over a translation command. These controllers are located in the specified areas as per Apollo convention.

Range and range rate data are regarded as primary flight parameters. However, the importance of the information to the FFTO operator is unknown, the same information would be provided from the shuttle system. An initial layout of these displays places them to the right of, and as close as possible to the stereo-display. The two digital clock readouts are located immediately below which provides backup range rate information. The propulsion system status; fuel, pressure and temperature is displayed to the left of the stereo-display. These require regular monitoring. This location close to the stereo display enhances the monitoring task with minimum disturbance to primary control functions. The main power switches, the camera lighting switches, the gyro switches and the undocking controls and the despin control group are located below these indicators. These controls require initial adjustment and are generally left in their preflight status during FFTO flight.

The mono-camera controls and the reticle adjustment switch requires adjustment during flight and are therefore located on the left panel close to the TV display. These controls have been placed on the left panel with left hand control on the assumption that the translation control is not a full time function.

The camera positioning controls are used generally in either the docking mode or close-in inspection mode. This requires that the controls be located relative to other right and left hand activity functions. Monitor controls are located on the left side panels because they require initial adjustment during preflight and only limited or no adjustment during FFTO flights.

The maneuvering controls are located between the Apollo translation and attitude controllers. Their central location allows either left or right hand operation.

The FFTO computer control center is located on the right side panel within easy reach of the right hand. The option to display the computer output onto the TV monitors is considered feasible in aiding the FFTO operator (see IX-12). The other controls and displays mounted on the side panels include the circuit breaker panel, the electrical power system status, the internal lights and emergency panel lights, and areas available for growth.

The top panels over the two video displays are used as a general annunciator panel which provides fault isolation and caution/warning/emergency indication. A master caution light is provided on the main panel located centrally within the operators optimum viewing envelope. Any activation of this light draws the operators attention to the top panels.

The CDS panel display arrangement is shown in Fig. IX-12. This is a "Fome-Cor" mockup of the panel configuration concept and will be used to verify dimensional interfaces of the man-machine human engineering design considerations.

The work presented in this section is intended as a preliminary design concept of an integrated typical free-flyer control and display station. The reason for including the information in this report is to show the preliminary impact that the selected visual system has on designing a FFTO CDS and the applicable man-machine interface. Many of the assumptions made are very gross in nature with the realization that a considerable future integrated effort is required as additional FFTO mission requirements are finalized and the selection of FFTO subsystem designs approved.

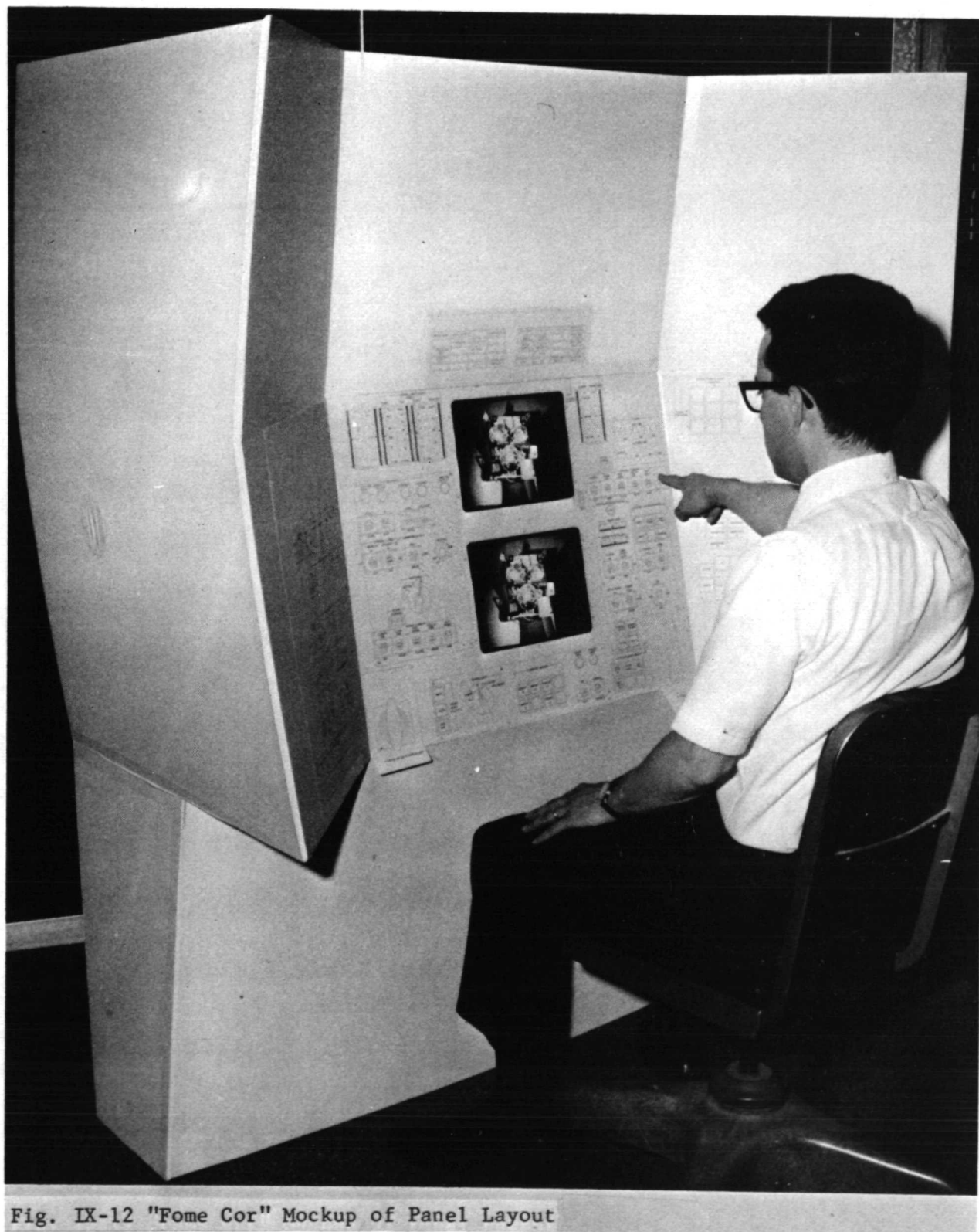


Fig. IX-12 "Fome Cor" Mockup of Panel Layout

X. CONCLUSIONS AND RECOMMENDATIONS

The "Conceptual Design Study for a Teleoperator Visual System" resulted in a hybrid monoscopic-stereoscopic TV system. This system, inherently simple, provides considerable operational flexibility and visual coverage adequate to accomplish all of the anticipated FFTO type activities. The major hardware elements required by the system are all typical of similar hardware used in previous space applications and at most require slight modification to meet the visual system specifications. The one area where limited development is required is the TV monitor display required for the monoscopic application as no space qualified versions of the size required were found to exist. Also, if any system component optimization is desired, e.g., miniature "low weight and power - high sensitivity and resolution" TV cameras, these will become developmental items. A strong interface with the Shuttle Program is recommended to identify this program's planned developmental activities and where components similar to those required by the FFTO are found to exist, specification compatibility may be provided prior to the developmental period at essentially no cost but changes or modifications at a later date could become a significant cost item.

While a preliminary design concept of this visual system has been provided, the subsystem elements must be integrated as a system and further simulations and detail evaluations conducted. At the spacecraft end of the system, the sensors, illumination, and the articulation device must be evaluated as an integral unit. At the control station, reduced bandwidth techniques, both 15 frame/sec operation and single channel multiplexed stereo must be further analyzed through man-in-the-loop simulations.

The activities conducted during this study also indicated that the visual system is strongly influenced by the other FFTO subsystems

which unfortunately have not been defined in adequate detail. These areas include FFTO visual guidance and control requirements, docking device and manipulator definition, and specific FFTO tasks and work sites, all of which must be assembled at the system level to assure inter-system compatibility (e.g. the capabilities of each system are "matched" and "play together").

For example, if a visual guidance technique not requiring simultaneous "fore" and "aft" viewing is implemented, the fixed monoscopic sensor could be eliminated. Conversely, if additional work site coverage is necessary, this sensor may require articulation and be moved to a location on the lower portion of the FFTO. This example illustrates the type of inter-system compatibility analysis required.

However, in some areas the visual system may remain unchanged. With reference to the above example, if the fixed monoscopic sensor were deleted, the monoscopic monitor at the controls and display station would still be recommended for it provides the following: (1) a non-restrictive stereoscopic-to-monoscopic view (2) backup and redundancy (3) multi-operator views, and (4) display of FFTO operational instructions and alphanumeric data.

In summary, the visual system must be assembled and evaluated further. Integration with the other FFTO systems must follow and simulations conducted to verify the overall design concept. Where impacts exist, trade-off studies will establish which subsystem(s) are least affected and the recommended changes will be incorporated into the FFTO concept design.

XI. REFERENCES

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APPENDIX: SURVEY OF MOTOR USAGE IN SPACE

In December, 1971, MMA completed a survey of motor usage in space. This survey established that space qualified motors and components exist and, unless the requirements are extremely specialized or a completely new design is required, are not "long-lead" development items. A condensed summary from this referenced document is provided to indicate the information it contains.

Reference - Survey, Electrical Motors Used in Space, Technical Report T-71-48890-004, Martin Marietta Aerospace, Denver, Colorado, December, 1971.

Summary - This document, an almost complete history of all types of motors used in space, contains almost 300 entries. In all cases it defines the type of motor, manufacturer, its specific application and in the majority of instances, performance information is included together with details of any in-flight failures or shortcomings. Often in instances where detail is lacking, the manufacturer's model number is provided; information can then be obtained by reference to the manufacturer. Care should be exercised in using this information in that the performance specified against a specific motor only reflects the duty it is called upon to perform in the spacecraft. In many instances, the stated stepping rate, operating speed and duty, etc., may be greatly exceeded; however, the motor specialist when reviewing the data, knows within reasonable bounds, what to expect from a certain size and type of motor.

The main facility which the listing is intended to provide is to offer the space engineer a selection of space proven motors. Primarily, it is an economy measure to avoid unnecessary development and qualification expense. In addition, it provides an insight into the types of motors and the type of application in which they

have given satisfactory service.

Time did not permit the complete correlation of data for many of the entries, particularly operational life and environment. However, in regard to life, the type of application will be a guide; for instance, deployment functions such as for booms, antennae, solar panels and delatching mechanisms are usually one shot devices wherein high speed brush type gearhead motors are quite satisfactory. For continuous operation such as on momentum wheels and optical instruments, whether hermetically sealed or not, the brushless types, either hysteresis synchronous, induction, stepper or brushless DC, predominate. Brush type DC torquers have not proven satisfactory for momentum wheel operation (ref. ITOS & NOAA). For servo control, the brush type DC torquer is most frequently used in preference to 2-phase AC induction type servomotors. For accurate speed control, such as in tape recorders, the hysteresis synchronous motor has been almost exclusively used; however, a recent trend toward the use of brushless DC is observable. The brushless DC motor is also replacing the induction motor on momentum wheels. In regard to brushless DC Motors, the motor supplier often supplies only the motor, sometimes in a frameless configuration, leaving the spacecraft manufacturer to provide the associated electronics.

In regard to environment, the majority of earth satellites have reasonably benign ambient temperature requirements ranging from -20°F to $+150^{\circ}\text{F}$ which permits the use of wet lubricants. Optical contaminations is often a deterrent to the use of wet lubrication; however, the survey shows that with shaft seals and prudent selection and application, the contamination problem is minimized to acceptable levels. Dry film lubrication is suitable for only a minimal life capability which is limited in the case of gearing by the number of tooth engagements; consequently, motor speeds

should be held to a minimum, consistent with life requirements.

It is pointed out that while some motor applications on classified satellites have been encountered, no attempt to probe this classification has been made. It is also known that the Skylab and ATM listings are by no means complete, but these were given least priority since they have not as yet experienced any flight time.

Motor manufacturers represented in the survey include: Abrams, Aeroflex, AiResearch Mfg. Corp., American Electronics Corp (Incorporating Gayload Rives), *Barnes Engineering Co., *Bendix Navigation & Controls Div., Brailsford & Company, **Cedar Engineering, Clifton, Division of Litton Industries, Computer Devices, *Eastern Industries, TA Edison Instruments Div., McGraw Edison Co., Inland Motors Corporation; Giannini Controls, Harowe Servo Controls, Hydroaire, IMC Magnetics Corp., *Kinetics Corporation, **Killsman Instruments, Nash Controls, Inc., Lundy Electronics and Systems, Inc., Macbar Mechanisms, Inc., G & R Monaco Corporation, Reflectone, HC Rotor, Schaeffer Magnetics (Division of USM Corporation), Servonetics, Sigma Instruments, Singer Kearfott, Sperry Electronics Components Plant, Globe Industries, Div. of TRW, *University of Colorado, and **Whittaker Corp. (now superceded by Schaffer Magnetics).

The motor survey sheets indicate the following distribution of motor types:

<u>Type of Motor</u>	<u>%</u>
Hysteresis Synchronous	25.5
Permanent Magnet Stepper	18.2
PMDC or Wound Field, Brush Type	17.4
DC torquer, Brush Type	12.0
Induction	11.3
Brushless Torquer, PMDC	8.0
Variable Reluctance Stepper	4.0
Latching Stepper	2.9
DC Start, AC Run	0.7

*These corporations manufacture motors for their own product lines.

**These corporations have either discontinued motor production altogether or no longer cater to the Aerospace industry.

This distribution may also be analyzed as follows:

<u>Type of Motor</u>	<u>%</u>
AC	37.5
DC	37.4
Stepper	25.1

In summary, the following satellites and the number of different motor/applications appearing on the space qualified motor survey sheets are identified below:

<u>Satellite</u>	<u>No. of Motors</u>
AGENA	—
APOLLO	
Service Module	6
Command Module	8
LEM	13
Science Experiments	2
Lunar Rover	5
APOLLO TELESCOPE MOUNT	24
ATMOSPHERIC EXPLORER	3
ATS	12
DEFENSE AND CLASSIFIED	16
FOREIGN AND INTERNATIONAL	6
GEMINI	8
INTELSAT	4
LES	5
MARINER	10
MISCELLANEOUS	6
NIMBUS AND ERTS	32
OAQ	13
OGO & POGO	8
ORBITER	3
OSO	22
OV	5
PIONEER	2
RAE	3
SAS	6
SESP	7
SKYLAB	8
SMS	3
SURVEYOR	11
TIROS, ITOS & NDAA	6
VELA	14
VIKING	
Lander	15
Orbiter	4
TOTAL	290