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INFRARED SIMULATION SYSTEM (IRSS)

Phase I Final Report

R. J. Buessler
H. Popper

General Electric Company

Re-entry and Environmental Systems Division

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Final reptos

U.S. Army Missile Command

Redstone Arsenal, Alabama 35809

Contract DAAH01-71-C-0571

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JULY 1971

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ABSTRACT

This report documents the analytical and design efforts performed by the
General Electric Company in synthesizing an Infrared Simulation System (IRSS).
This design meets or exceeds the requirements of MICOM Technical Require-
ment No. 1276, can be implemented in a reasonable interval, and will operate
reliably, safely and with minimum alignments thereafter.

The Infrared Simulation System will be used for the development and evaluation
of advanced infrared missile guidance components, subsystems and systems
as a part of MICOM's Advanced Concepts Development Facility (ACDF) now
under construction.

This report covers, in addition to the detailed description of the design
approach, selected rationales leading to important choices, results of analyses
and trade-offs made, a consideration of interfaces among key subsystems and
with the Hybrid Computation Laboratory, and planned potential for future
growth in both capability and application.

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1.0 INTRODUCTION

1.1 SUMMARY

This Final Report summarizes and records the work done under Phase I (Design) of IRSS by General Electric's Re-entry and Environmental Systems Division under contract DAAH01-71-C-0571. It is organized into the following major subsections:

- Technical Requirements and Design Goals
- Description and Technical Approach
- Discussion of Key Performance Parameters
- Detailed Descriptions of Various Subsystems and Interfaces
- Provisions for Modular Growth

Figure 1-1 shows the layout of the IRSS. It consists of four major subsystems which are discussed in detail in the remainder of this report. These are: the Guidance Unit Mount, the Display, the Projection, and the Control Console/Computer Interface subsystems. The layout of the IRSS Laboratory itself is shown in Figure 1-2, and a dimensioned overall layout in GE Dwg. No. SK-56205-537 in Appendix C.

1.2 PURPOSE AND USE

1.2.1 GENERAL

The effort reported herein leads to providing the Advanced Sensors Laboratory, R&ED, USAMICOM, with an Infrared Simulation System (IRSS) to be used in the development and evaluation of advanced infrared guidance systems. This IRSS will be a part of the Advanced Concepts Development Facility (ACDF) currently under construction as an addition to McMorrow Laboratories, Bldg. 5400, Redstone Arsenal, Alabama.

1.2.2 PURPOSE OF THE ACDF

The Advanced Concept Development Facility is an RDT&E tool which will facilitate improved effectiveness in the development of Army missile systems. This will be accomplished by providing the resources and capabilities necessary for developing and evaluating missile systems, subsystems, and components throughout the RDT&E development cycle. One of the major resources of the ACDF will be the Electro-Optical/Infrared (EO/IR) Simulation Laboratory. This laboratory will provide the facilities necessary for simulation of the target/missile/environment interaction for a wide variety of electro-optical and infrared guidance concepts. A hybrid computer laboratory containing large scale analog and digital computers will be an integral part of the ACDF. The EO/IR Simulation Laboratory will have access to these computers for the simulation of missile and target motion, generation of driving functions for the physical simulation equipment, experiment control, and data

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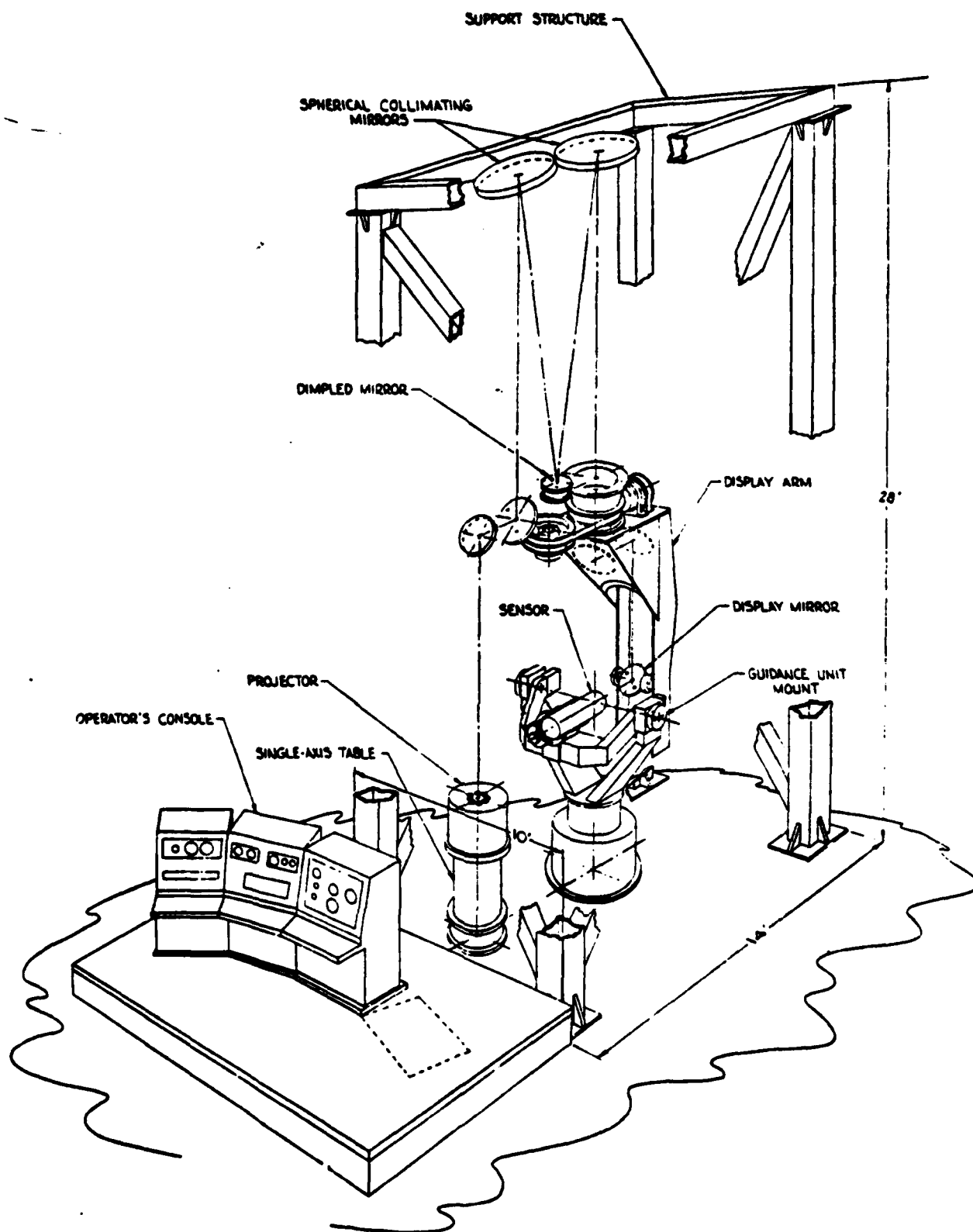
Figure 1-1. Infrared Simulation System

2
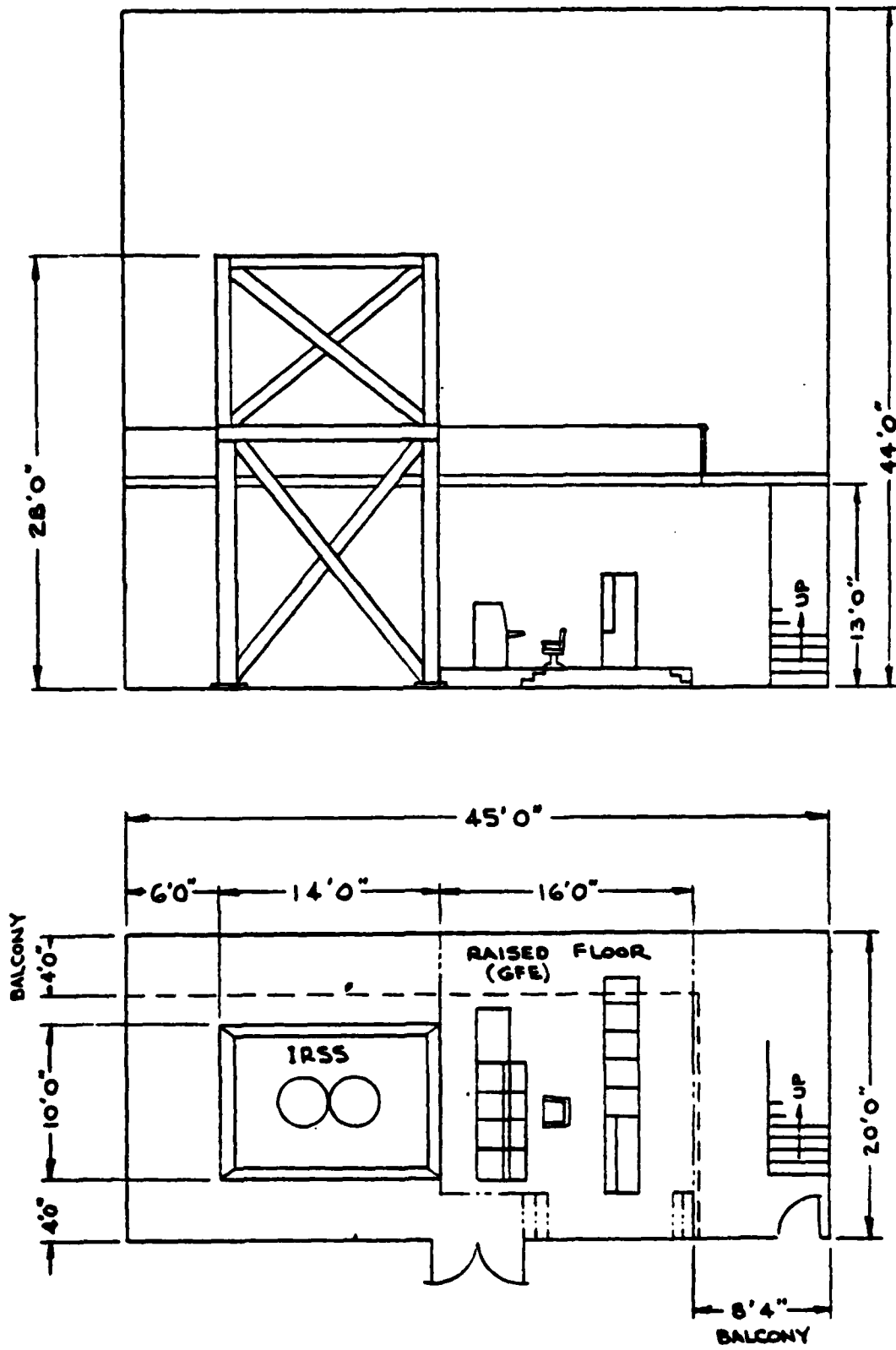
Figure 1-2. Placement of Apparatus in ACDF Room 102

recording. This combination of laboratories will allow full scale closed-loop simulation of missile behavior from launch to intercept.

1.2.3 PURPOSE OF THE IRSS

The IRSS will be a part of the EO/IR simulatory and as such will be one of the vital elements in the overall system development process in that it will allow rapid and repeatable testing of guidance components, subsystems, and systems under realistic but controlled conditions. As a design tool, this system will be used to: (1) evaluate breadboard and brass board hardware performance; (2) evaluate design modification to existing hardware; (3) establish component parameters for optimum performance; (4) perform post flight analyses; (5) establish miss distance statistics; and other related studies. In addition to these uses, studies of passive and active infrared countermeasure effectiveness will be conducted.

Although the primary utilization of the IRSS will be in the development and evaluation of infrared homing guidance systems for surface-to-air missiles, the basic facility will possess sufficient flexibility such that, with modifications or additions, other types of guidance systems, such as command-to-line-of-sight or laser semi-active, can be accommodated.

1.2.4 INTENDED USE OF THE IRSS

The IRSS is to be a general laboratory simulation tool adaptable to a variety of uses throughout the guidance system development cycle. In this respect, it is intended that the IRSS provide a capability for accomplishing those functions which are typically performed on several different equipments. Three levels of simulation can be identified within this context:

1.2.4.1 System Simulation

At this level, all essential features of a real-time engagement, to include target, background, and missile must be simulated. Real hardware will be used for the guidance system. Provision must be made for presenting a target to the system, moving the target according to the apparent relative motion, and moving the system to simulate missile maneuver. The spectral and spatial characteristics of the targets and background presented to the system must be indistinguishable from the real world as perceived by the system. A full range engagement, from launch to intercept, will be flown. The purpose of this level of simulation is to determine the response of the system to real world situation, establish miss-distance statistics, and to ascertain the limits of its performance as a function of many variables. Closed loop operation using analog/digital computers is required.

1.2.4.2 Subsystem Evaluation

At this level, the IRSS will function essentially as a rate table, with single or multiple sources wherein a guidance system is presented with radiometric and dynamic stimuli

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and its response to these stimuli measured. Routine target tracking tests, multiple target discrimination tests, and passive and active countermeasure tests are typical of the evaluations which will be done at this level.

1.2.4.3 Component Evaluation

At this level, components of the basic guidance system will be under test. Inasmuch as their behavior when made a part of the guidance system is of primary interest, tests similar to 1.2.4.2 will be performed. Thus, the simulation characteristics described there apply.

1.3 HISTORY

Work under this contract commenced on 31 December 1970 and was completed (with the exception of this report) on 28 May 1971. This report was completed on 30 June 1971 in draft form, for submission to MICOM within thirty days thereafter (per Item A003 of DD1423).

The first milestone was the finalization of the design concept contained in General Electric's IRSS Proposal N-71957 of 28 September 1970, including subsequent amplifications submitted to MICOM on 23 November 1970. This effort was completed and presented to MICOM at the first technical and administrative contract review meeting held at Redstone Arsenal on 18 January 1971. Approval of this finalized conceptual design, including the modifications made at the referenced review meeting, was issued by MICOM on 2 February 1971.

The next major milestone was the translation of the appropriate requirements of TR-1276 and the design goals also provided by MICOM on 2 February 1971 into a firm, two-level technical specification (No. A-4110) for a Guidance Unit Mount, which will represent by far the largest material subcontract under IRSS. Procurement documents based on this specification were sent to four vendors on 5 March 1971 and returned by two on 29 March 1971 as described in much more detail in Section 5.1 of this Final Report. After subsequent fact-finding, a Source Selection Board met formally on 21 May 1971 and recommended that award of this subcontract in Phase II be made to Fecker Systems Division of Owens-Illinois Corporation.

On 6 April 1971, a mid-term contract review meeting was held at MICOM, and on 7 April 1971, a presentation of IRSS status, capabilities, and potential given to MICOM management personnel.

Another important area of concern not only to the proper design of the IRSS as such, but to its functioning as a viable part of the ACDF, was the definition of its interface with the Hybrid Computing Facility at MICOM. In addition to the design effort reported herein, two interface meetings were held at MICOM, attended also by personnel of B&K Dynamics, Inc., who is the contractor responsible for developing operational plans in this area (19 March and 7 April 1971).

Efforts to arrive at Phase II (fabrication and installation) implementation costs and schedules commenced on 26 April 1971 and were completed on 21 May 1971.

1.4 DESIGN PHILOSOPHY

The IRSS was conceived, and will be implemented, in keeping with a firmly established design philosophy, since experience has shown time and again that the ultimate utility of a system can be maximized only if this is done at the start and maintained unswerv-ingly throughout the preliminary and final design periods. The principal elements of General Electric's approach to IRSS are stated below in relation to specific objectives they are intended to achieve:

TABLE 1-1. IRSS DESIGN OBJECTIVES AND REALIZATION

Objectives	Philosophy Elements
Accuracy	Mechanical Stiffness Electro-magnetic Interference Control
Reliability	Off-shelf/commercial Components Proven Design Techniques Redundancy
Maintainability	Continuous Cooling Gas Flow Ease of Alignment Commonality of Components
Flexibility	Compound Projection Modular Design
Growth Capability	Reflective Optics Data Management Approach MICOM Guidelines Considered
Safety	Personnel Equipment

The implementation of this approach, and the achievement of these objectives, are discussed in detail in the remainder of this report.

2.0 REQUIREMENTS

2.1 INTRODUCTION

MICOM, in TR-1276 dated 30 January 1970 (revised 28 August 1970), laid down the basic requirements which the IRSS had to meet. These are given below.

In addition, in order to provide guidelines which GE-RESD could apply to the Army's advantage whenever possible, a set of supplementary specifications was transmitted by MICOM to GE on 2 February 1971. These were most helpful to GE in preparing subsequent specifications, especially that for the Guidance Unit Mount (see Section 5.1), and were incorporated in the Phase I (design) effort to the largest extent practicable. They are reproduced in this report as Table 5-2.

2.2 TARGET GENERATION SYSTEM

The Target Generation System consists of an assembly of equipment and components, not necessarily a self-contained unit, which provides for generation of simulated aircraft targets, backgrounds, and countermeasures. The purpose of this assembly is to present to the guidance unit under test suitable radiation sources to simulate the physical, radiometric, and dynamic characteristics of targets, backgrounds, and countermeasures. These characteristics must be designed so as to be manually or automatically controlled. Manual control will be effected with instrumentation co-located with the IRSS. Automatic, programmed control will be accomplished with the computers in the Computer Laboratory. Position readout signals with accuracies commensurate with requirements of Table 2-1 will be provided for azimuth, elevation, and range. Rate readout signals for azimuth and elevation with 1% linearity will also be provided.

2.2.1 TARGETS

A source array suitable for simulation of a wide variety of tactical aircraft will be provided. Target size, shape, radiant intensity, and relative motion must be simulated. The sources must be configured to simulate the radiation signature of aircraft in all of the following spectral bands: UV (.3 - .4 microns), visible (.4 - .7 microns), near IR (1 - 3 microns), Mid-IR (3 - 5 microns). Table 2-2 gives the aircraft characteristics which are to be simulated. Multiple, independent infrared targets are required for purposes of simulating multi-aircraft formations or multi-engine aircraft. Simultaneous presentation of single targets in any two bands (e.g., UV - mid-IR or near-IR - Mid-IR or UV - VIS, etc.) will be required for testing multi-band guidance concepts. Multiple interchangeable source assemblies may be provided to cover the full range of targets. The characteristics of the targets must be continuously variable and programmable over the range of values shown in Table 2-2 to permit proper simulation as a function of range and aspect angle. Target motion, which also must be variable and programmable, will be provided to simulate target/missile relative motion during an engagement. Table 2-1 gives the requirements for target motion.

TABLE 2-1. TARGET MOTION REQUIREMENTS

1. **Azimuth**

    Total Angle   -   ±90 degrees

    Angular Rate   -   0 to 100 deg/sec

    Angular Accel. -   0 - 400 deg/sec^2

2. **Elevation**

    Total Angle   -   ±30 degrees

    Angular Rate   -   0 to 100 deg/sec

    Angular Accel. -   0 to 400 deg/sec^2

3. **Range**

    (Simulated by variation in target size)

    Maximum launch range(*)   -   5000 meters

    Minimum range(**)   -   50 meters

    Maximum closure rate   -   1500 meters/sec

4. **Position Accuracy**

    ±1 milliradian in azimuth and elevation (target center)

    ±5% of range for ranges up to 1500 meters

5. **Repeatability**

    ±0.5 milliradian in azimuth and elevation

    ±1% of range for ranges up to 1500 meters

(*)Actual variation of target size should be commensurate with the resolution of the guidance unit.

(**)This is the range at which the problem will be considered terminated for purposes of target growth simulation. Extrapolation to true range at intercept will be made analytically.

TABLE 2-2. AIRCRAFT TARGET CHARACTERISTICS

Item	Target	Shape	Size*	Intensity*	Quantity
1.	**Infrared**				
a.	Tailpipe	Circular	0.15 – 1 meter, variable with range 50 m – 5 km.	1 – 1000 watts/steradian in 1-3 and 3-5 micron bands, distributed continuously over the spectral bands.	Four (4) independently maneuverable. Separation 0-30 meters between locations (center to center), variable with range and aspect angle. Each source should be usable in each band.
b.	Plume	Triangular	1 x 1 meter – 1 x 5 meter (base x height) variable with range and aspect angle.	1 – 500 watts/steradian in 3-5 micron band, distributed continuously over the spectral band, uniformly distributed over the radiating area.	One – simultaneously presentable with one of the targets in 1.(a).
2.	**Ultraviolet/Visible**				
	Fuselage	Rectangular	1 x 1 meter – 3 x 20 meter. Variable with aspect angle.	Contrast ratio – -0.1 to -0.9 adjacent background variable over range 10^{-4} to 10^{-6} watts/cm²/ster in each band.	One – simultaneously presentable with any combination of one 1. (a) and 1. (b) targets.

*These values referenced to zero range, i.e., at the target. They must be variable so that proper range dependence of apparent size and received flux may be simulated. Range will vary from 50 – 5000 meters.

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2.2.2 BACKGROUNDS

For the system level simulation, it is desired that background simulations be provided. This simulation should present to the guidance unit under test a source array which reproduces in all essential features the radiant intensity distribution of typical background features such as clear sky, scattered small clouds, partial overcast, etc. These features can be included in a single presentation. Both infrared and ultraviolet backgrounds are required and must be simultaneously presentable. Multiple hardware is acceptable for this purpose.

2.2.3 COUNTERMEASURES

It is desired that the system be capable of simulating various types of infrared and optical countermeasures such as flares and jammers. At this time, however, only flare characteristics are defined well enough to be specified. Table 2-3 gives the flare characteristics to be simulated. Sufficient flexibility must be provided to introduce jammer simulations or actual jammer hardware at some time in the future.

2.3 GUIDANCE UNIT MOUNT

This element will be a dynamic mount providing three axes of motion (pitch, yaw, and roll) on which the guidance unit under test will be mounted. The dynamic motion requirements of the mount are given in Table 5-1. Certain types of guidance units require continuous roll motion at rates up to 20 revolutions per second. This motion may be provided by either the main mount or by an additional, removable fixture. This roll motion is required for guidance units up to five (5) inches in diameter. If a removable fixture is provided, the mount must meet the dynamic motion requirement with the

TABLE 2-3. SIMULATED FLARE CHARACTERISTICS

1.	Size	- 0.1 - 1 meter, variable
2.	Shape	- Circular
3.	Radiant Intensity	- up to 10 times any target, with spectral distribution approximating 2000°K blackbody.
4.	Separation Velocity	- up to 30 meters per second.
5.	Separation Direction	- any direction with respect to target.
6.	Ejection Rate	- up to one per second for 15 seconds.

NOTE: All dimensional quantities are given relative to zero range, i.e., at the target.

additional weight of the fixture included in the load. Power input (including possible use of thermoelectric cooler, see Table 2-4) and signal take-off apparatus required to operate, control, and monitor the guidance unit under test will be provided at the mount. This apparatus will consist of a multi-channel terminal for interconnecting to the control console and such cabling and connectors (may be slip rings) as are required to connect this terminal to the mount and the guidance unit without interfering with proper operation of the mount. The motion of the mount will simulate missile motion during flight and must be controllable by the computers through the control console. The IRSS will be used for evaluation of a wide variety of guidance systems at all levels of development from breadboard to production. Table 2-4 gives the general characteristics of guidance systems with which the IRSS will be used. The design of the system must be such as to accommodate any unit having characteristics within the limits given. This may be accomplished, if desired, by providing interchangeable hardware. The continuous roll gimbal design must provide the capability for transferring cryogenic coolant from an external supply to the test item mounted on the roll gimbal. Operating conditions are given in Table 2-4. Position readout signals with accuracies commensurate with requirements of Table 5-1 will be provided. Rate readout signals with 1% linearity will also be provided.

2.4 CONTROL CONSOLE AND COMPUTER INTERFACE

A multi-functional control and operational console will be provided in the IRSS room. The purpose of this console is to provide autonomous operation, control, and monitoring of the IRSS and guidance units under test during subsystem and component evaluations and to provide an interface connection to the Computer Laboratory, via the EO/IR Control Room during system simulations. The console will provide a capability for: (1) manual or programmed control of the IRSS; (2) monitoring and recording of signals from the IRSS; (3) interfacing the IRSS with the EO/IR Control Room; and (4) inter-communication with the EO/IR Control Room. The programmable control functions are not to be such as would require general purpose computer equipment as part of the console. All general purpose computer (analog or digital) facilities will be external to the physical simulation systems.

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TABLE 2-4. GUIDANCE SYSTEM CHARACTERISTICS

1. **Physical Characteristics:**

   a. Length — up to 25 inches

   b. Diameter — 2.75 inches to 10 inches

   c. Weight — up to 25 lbs.

2. **Optical Characteristics:**

   a. Type Optics — relative, refractive, or catadioptric

   b. Entrance Aperture — up to 5 inches

   c. Spectral Coverage — selected intervals in the overall range of .3 to 15 micro meters.

   d. Field-of-View — up to 6 degrees

   e. Gimbal Angle — up to ±50 degrees

   f. Resolution — up to 1.0 milliradian

3. **Dynamic Characteristics:**

   a. Tracking rate — up to 30 deg/sec in any plane

   b. Slew Rate (when caged) — up to 30 deg/sec

   c. Roll Motion — up to 20 revolutions/sec continuous (for missiles up to 5 inches in diameter.)

4. **Mechanical:**

   Detector Cooling

   Cryogenic — open or closed cycle - working pressures up to 6000 lbs per square inch - laminar flow rates up to 20 liters per minute-operating temperatures down to 77 degrees Kelvin.

   Thermoelectric — operating temperature down to 195°K requiring currents of up to 20 amps at voltages 0.1 - 5 volts.

NOTE: Provision of cooling equipment is not a requirement of this TR, however, allowance must be made for the presence of tubing, cables, etc., required by any such equipment.

3.0 TECHNICAL APPROACH

3.1 SYSTEM CONCEPT

3.1.1 GENERAL

Functionally, the Infrared Simulation System is divisible into four major entities: The guidance unit mount, the target generation system, the computer interface, and the control console. The general relations among them are illustrated in Figure 3-1. These four entities are functional groups, not necessarily discrete pieces of hardware. At the option of the designer, they may be integrated into a lesser number of physical assemblies or further subdivided into a greater number.

The first fundamental decision facing the designer was whether to move toward integration or dispersal of function. For example, an integrated system in which the guidance unit mount and target generation system are hung together on a simple multi-axis gimbal system has an attractive advantage in alignment stability, but it has disadvantages also. Once built, it will be difficult to expand. It will probably be heavy and expensive to build, and the more functions are incorporated in the assembly the less likely is the use of off-the-shelf hardware. On the other hand, resolving the system into further subassemblies means a greater possibility of using off-the-shelf equipment, generally a smaller and lighter system, and greater flexibility and room for expansion. On the negative side, dispersal of function introduces a major interface problem and the need for more frequent alignment. In summary, then, if the interface and alignment problem can be solved satisfactorily and if flexibility, growth potential, and maximum use of shelf hardware are important values, dispersal is usually the better way to go.

On the basis of these general considerations and our experience with other physical mission simulators of the same general type, we have opted for dispersal. Specifically, we have elected: (1) to keep the guidance unit mount physically separate from the target generation system, (2) to further divide the target generation system into target projection and display subsystems, configuring the display to serve as an alignment-insensitive interface between target projection subsystem and guidance unit mount, and (3) to package the computer interface and control console as a single unit for convenience. This general approach is illustrated in Figure 3-2 for an open-loop configuration.

It is convenient to resolve the target generation system into two distinct subsystems: The display subsystem and the target projection subsystem. The target projection subsystem generates the target group, supplies the necessary radiance, and controls size, aspect, and local motion in the field. The display subsystem mixes the images, generates the major motion of the field, holds the window before the sensor, and fills the pupil of the sensor uniformly with radiation from each element of the target.
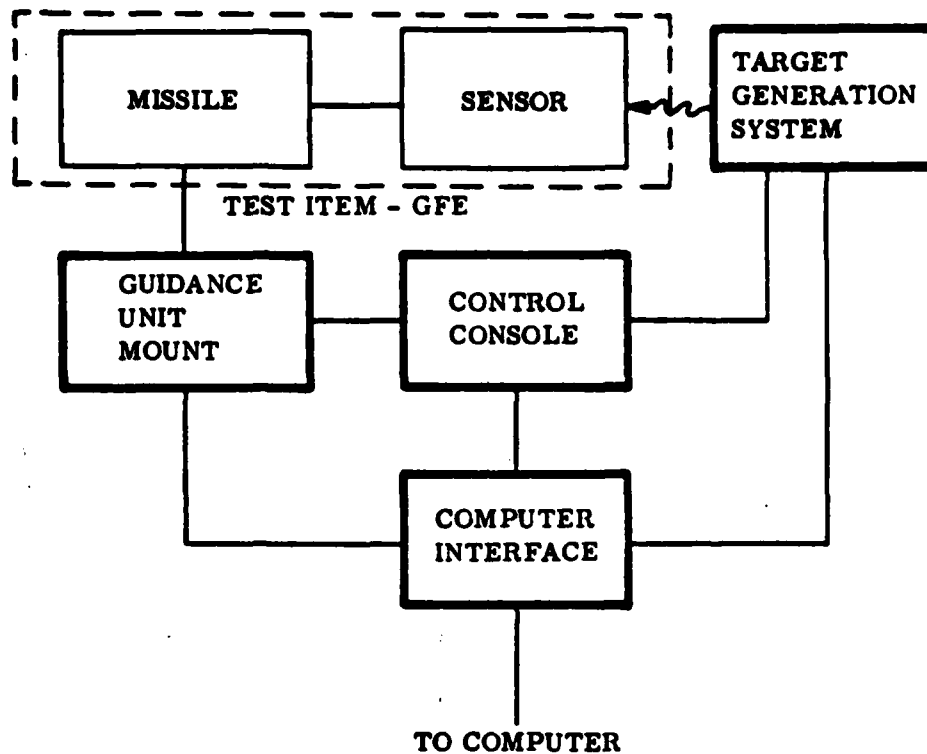
Figure 3-1. Functional Entities in the Infrared Simulation System
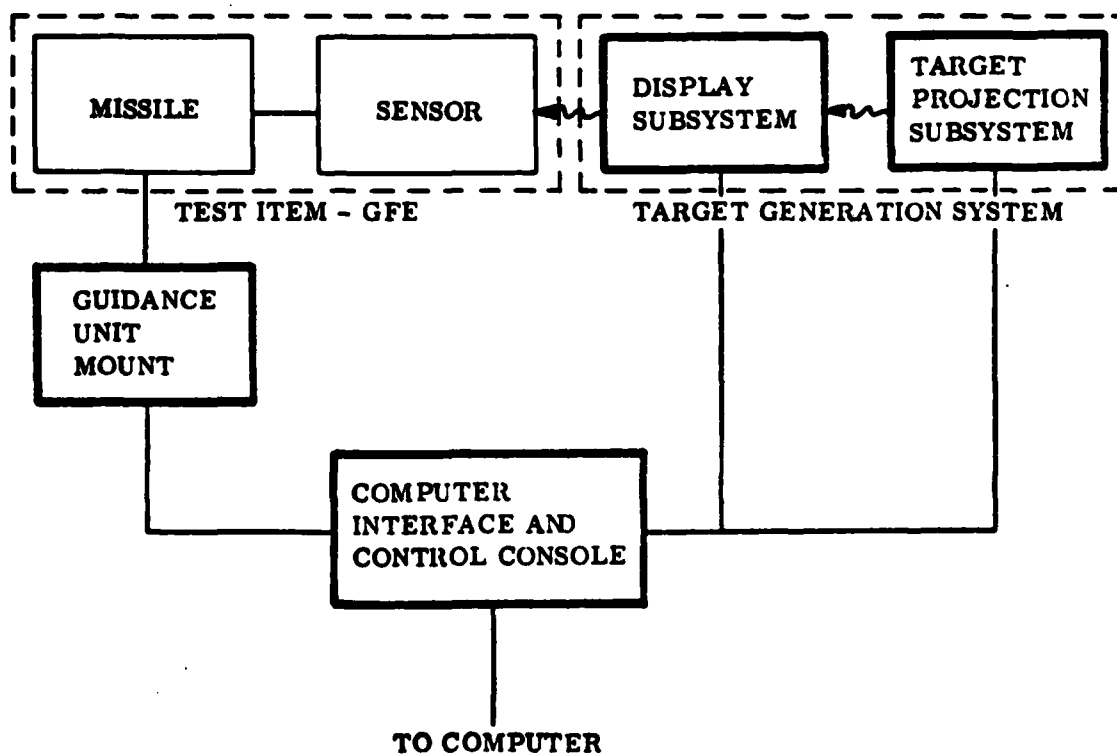
Figure 3-2. Principal Subassemblies in the Infrared Simulation System

3.1.2 OPERATIONAL

At launch, the missile guidance unit will be locked onto the target. The target will be in the sensor field of view and presumably will signal that fact to the gunner through some acquisition signal such as a light or an audible tone. Before launch and before uncaging, it is the gunner's responsibility to maintain the target in the field. After uncaging, he needs only to keep the missile body within 50 degrees of the target and the sensor, moving in its own gimbal, will follow the target. After release, the sensor will track the target and will command the missile to follow according to whatever guidance rule is being employed.

The functions of the target generation system are: (1) to maintain before the sensor a window into target space at all times the sensor is tracking; (2) to generate a spatially and spectrally complex target system whose geometry and radiation characteristics appear to the sensor substantially as they would in the real world, to full scale, and in real time; (3) to display to the sensor the generated target system in its true inertial position in real time, and (4) to cause the radiation from each target or target element to fill the sensor aperture fully and uniformly as long as the sensor is tracking.

The principle of operation of the IRSS can be understood by reference to Figure 3-3. An assembly of eight independent projectors (one being a dual-purpose one) (1) focussed at infinity projects as many as seven scene elements plus two spectral backgrounds into the spherical collimator, (2), which forms a composite, inregister image of the complex scene on a special dimpled spherical mirror (3). The dimpling expands the solid angle of radiation from each projector to ensure filling the sensor aperture from each scene element. The spherical collimator then forms a virtual image at infinity of this composite scene. The sensor (4) in the guidance unit mount (5) observes this scene through the window held before it by the display arm (6) and mirror (7) whose servos track the sensor in azimuth and elevation. The target projection subsystem is mounted on a single-axis pedestal, (8), which controls apparent scene rotation. Fine positioning of the targets within the display window is done by small gimballed mirrors in the projection assembly.

The merit of this design concept derives chiefly from four key design decisions:

(a) to separate physically the guidance unit mount from the target projection subsystem, coupling the two optically through an afocal display subsystem inherently insensitive to alignment errors;

(b) to employ the principle of compound projection whereby imagery from eight independent modular projectors is compounded in the display, a special dimpled mirror operating to fill the sensor aperture from each projector. This scheme allows simultaneous projection of up to seven target elements and two structured backgrounds each displayed in either the 0.3 to 0.7 or the 1 to 5 micron range, at the user's option;

SUPPORT STRUCTURE

(2) SPHERICAL
COLLIMATING
MIRRORS

PRINCIPAL SUBSYSTEMS

- TARGET PROJECTION S/S
  (1) & (8)
- DISPLAY S/S
  (2), (3), (6), & (7)
- GUIDANCE UNIT MOUNT
  (5)
- COMPUTER INTERFACE &
  CONTROL CONSOLE
  (9)
- SENSOR (GFE)
  (4)

(3) DIMPLED
MIRROR

(6) DISPLAY
ARM

(7) DISPLAY
MIRROR

(4) SENSOR

(1) PROJECTOR
ASSEMBLY

(5) GUIDANCE
UNIT
MOUNT

(9) OPERATOR'S
CONSOLE

(8) SINGLE-AXIS
TABLE
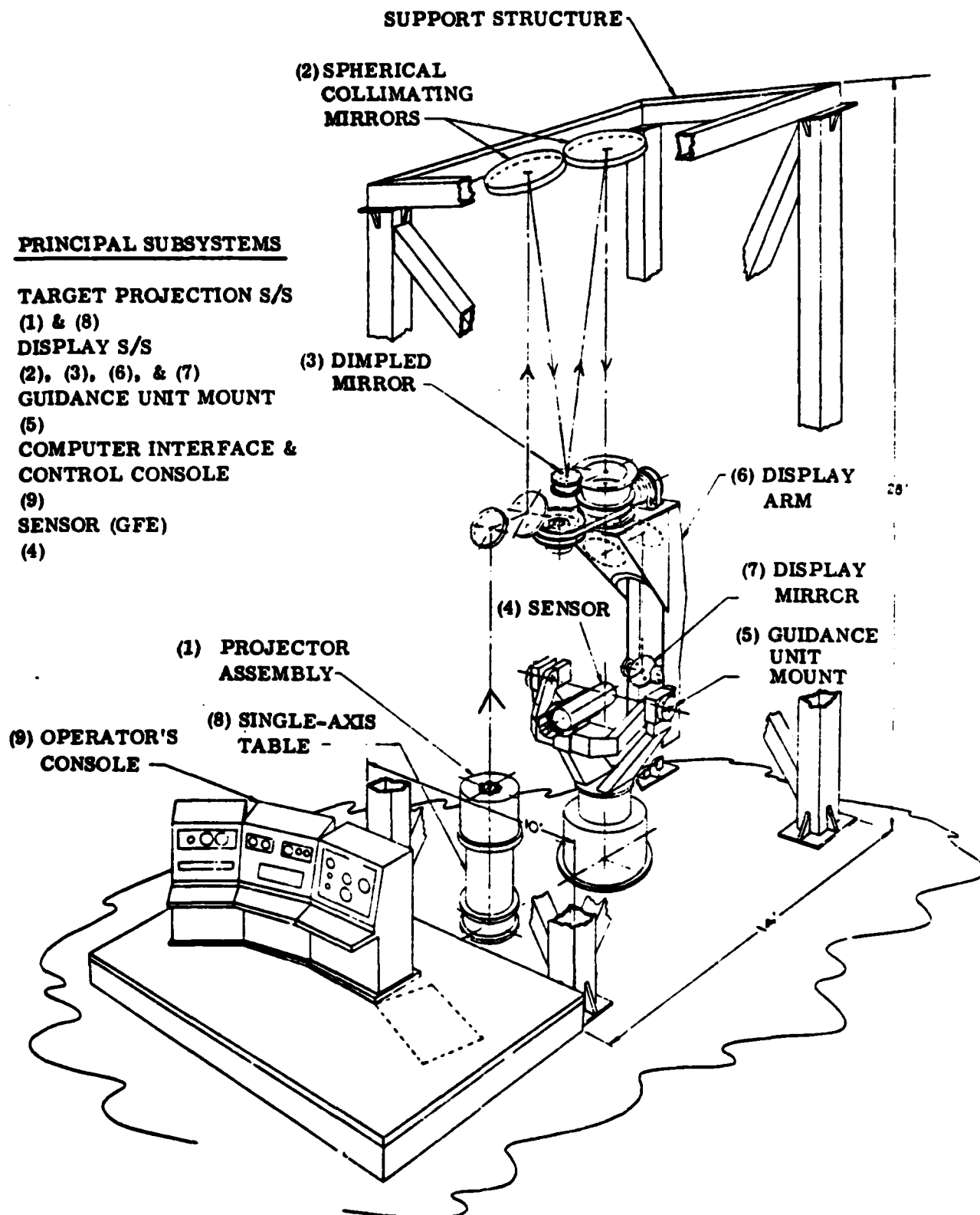
Figure 3-3. Infrared Simulation System Functional Elements

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(c) to provide only a 7-degree display window, slaved to the sensor within the missile. This minimizes the size, weight, and cost of the display optics and control apparatus; and

(d) to employ two-stage target positioning, performing coarse positioning (± 1/2 deg.) with the high-inertia display window and fine positioning (± 0.5 mr) with the low-inertia projector assembly. This approach allows precise positioning with low-cost hardware.

In our design concept, we have elected to base the target generation system on the technique of compound projection. This means that (1) the scene is resolved into spectrally and spatially distinct elements, (2) a separate projector is provided for each element, (3) these distinct scene elements are superposed, in register, in a mixing projector which also expands the pupil of each projector to a size adequate to ensure filling the sensor pupil. The basic principle of compound projection is illustrated in Figure 3-4, for a refractive system. Essentially, the axes of the several projectors are all aligned and each is focussed to project its target element image at infinity. If a collimator is now brought up before the projector array and its axis made parallel to the projector axes, an in-register composite image is formed at the focus of the collimator. If next a diffusor or other means of pupil expansion is placed at this image plane, it can be arranged that a downstream projection lens or collimator is fully illuminated by light from each separate image element. That downstream lens will then be unable to distinguish the compound image so produced from one that might have been produced by a single projector of (impractically)
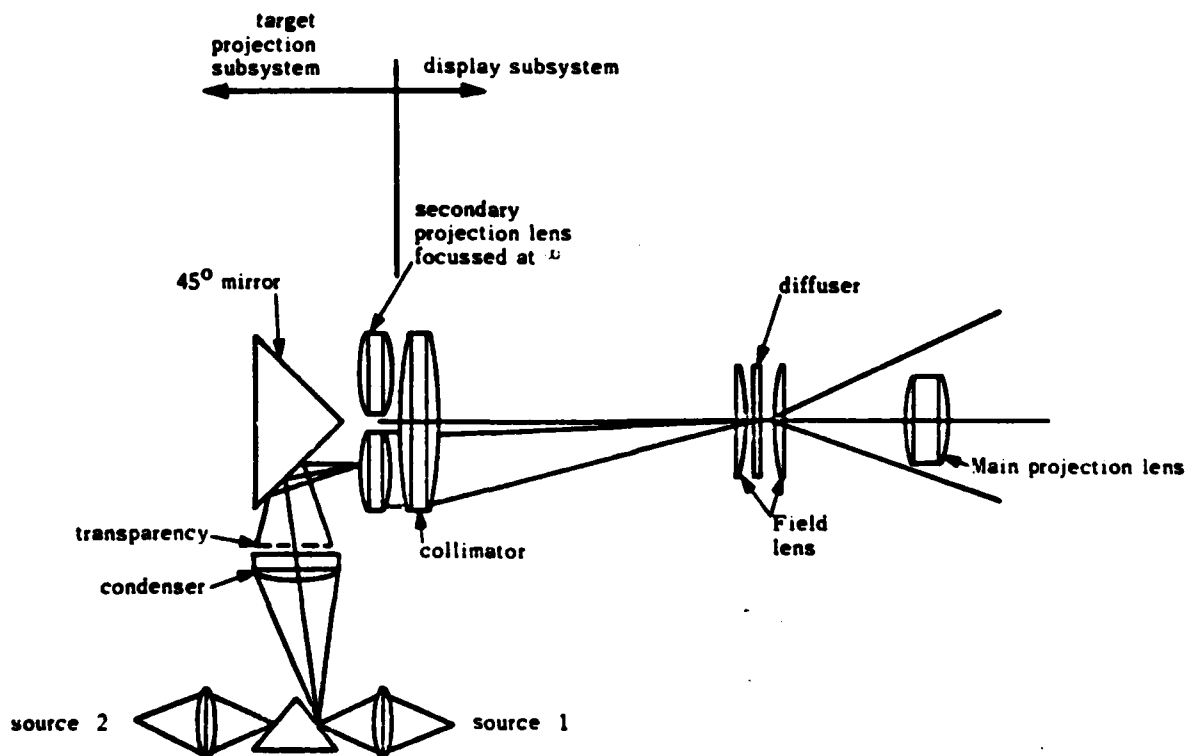
Figure 3-4. Working Principle of Compound Projector

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greater complexity except for a reduced apparent brightness traceable to pupil expansion. Figure 3-4 also illustrates how the source for each of the several projectors can itself be a composite of several sources, thereby allowing the practical synthesis of complex spectra if desired.

3.2 FUNCTIONAL DESCRIPTION OF MAJOR SUBSYSTEMS

Each of the four major subsystems are described here as to their function and principle of operation. Additionally, certain major trade-offs and design decisions that have determined their basic form are also discussed. The detailed design of each subsystem appears in Section 5.

3.2.1 GUIDANCE UNIT MOUNT

It is required to supply a three-axis flight simulator able to support the missile under test, or any subsystem thereof, and to move it within a specified envelope at specified rates and accelerations. The guidance unit mount will be used to produce all of the airframe rotational motions encountered in an actual intercept. Additionally, electrical, high pressure gas, and liquid nitrogen interfaces must be provided for the test item.

An examination of Figure 3-5 shows that the missile movement envelope covers nearly a hemisphere. The target generation system must be mounted in such a way relative to the guidance unit mount that the rotational axes of both are homocentric.

The only unobstructed access to that center is along the azimuthal axis. Therefore, this axis must be the base for both systems. Since both ends are open, we have elected to mount the guidance unit to the floor via the lower azimuthal axis and bring the target generation system in from above via the upper azimuthal axis. To minimize both clearance problems and size, the basic configuration of the guidance unit mount should be an azimuthal yoke carrying a lower-half elevation gimbal which, in turn, carries a roll gimbal, the whole arranged so that obstructions above the missile body proper are either non-existent or minimal as shown in Figure 3-6.

It is intended that this subsystem be designed to GE-RESD specifications and procured as an entity. Section 5-1 discusses this process, and its implementation, in some detail.

3.2.2 DISPLAY SUBSYSTEM

3.2.2.1 General Approaches to Display

Before discussing the chosen solution of the display problem, it is of value to consider first the general problem and the alternatives available for implementation.

18
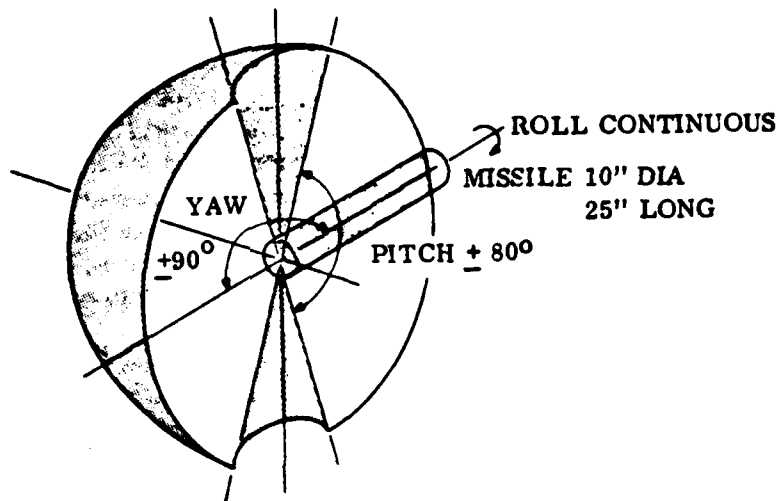
PITCH: P → ± 80°[SETTING ACCURACY ± 0.2 MR, REPEATABILITY ± 0.1 MR]

YAW: Y → ± 90° [SETTING ACCURACY ± 0.25 MR, REPEATABILITY ± 0.25 MR]

ROLL: R → CONTINUOUS [SETTING ACCURACY ± 0.25 MR, REPEATABILITY ± 0.1 MR]

Figure 3-5.   *Missile Motion Envelope*
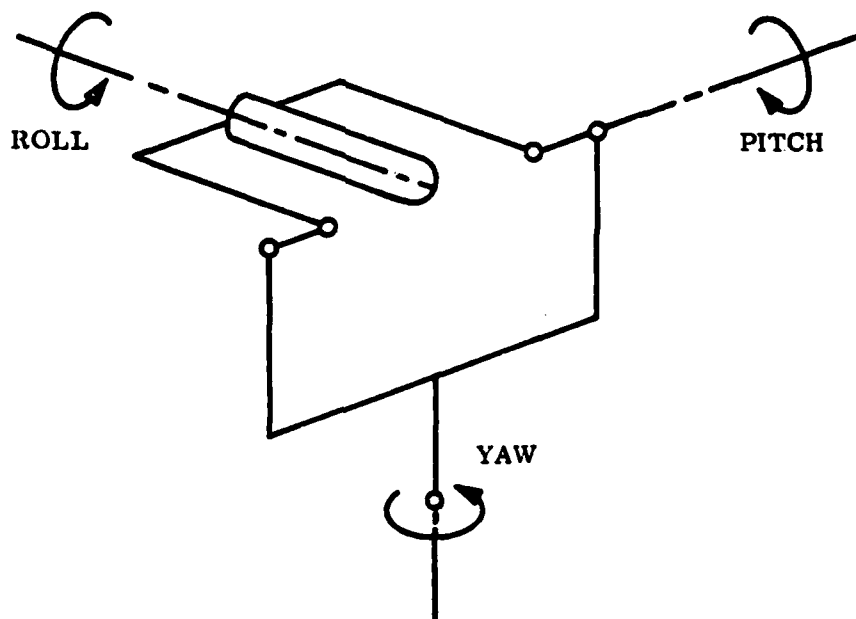
Figure 3-6.   Guidance Unit Mount Gimbal Configuration

19

The basic factors to be considered are illustrated and defined in Figure 3-7. In general there will always be: (1) a large display field within which targets may at some time be seen, (2) a relatively small sensor field able to observe only a part of this display field at any instant, (3) a display window through which the sensor can look into the display field to see the target, (4) a background which must be seen simultaneously with the target, and (5) the target itself, which can appear anywhere in the display field.

Given these several elements, the designer has only one he can control, the display window, and only three things he can logically do with it. He can elect to (1) fix the window to the ground (or the inertial frame), (2) fix the window to the target, or (3) fix the window to the sensor. These possibilities are illustrated in Figure 3-8. The first approach requires that the window be as large as the full display field which, in the present case, is very large indeed. The second requires that the window be twice the size of the sensor field, if background is to be visible whenever the target is anywhere in the sensor field. The third elective requires that the window be at least as large as the sensor field, but in addition it also requires what the other two approaches do not, namely, that information be provided with respect to the sensor's orientation within the missile.

3.2.2.2 Selected Approach

Generally speaking, volume, weight, and cost all vary directly with the size of the display window. We have, therefore, elected to follow the third option of slaving the window to the sensor, since it requires the smallest window. This approach is illustrated more fully in Figure 3-9, along with a block diagram showing the required method of control. Note that it is not necessary to track the sensor precisely, but only to overlap the sensor field with the window. A 7-degree window allows a full 1/2-degree error in tracking without affecting what the sensor sees. Tracking errors are not reflected in target position. The accuracy of target positioning is dependent only on the precision with which the window position can be measured and not on the window tracking error. The choice of option three, slaving the window to the sensor, has several important design consequences. First of all, it is not necessary to provide as large a physical apparatus as might otherwise be necessary and it, therefore, becomes practical to design something that can fit into the limited space available. It is only necessary, as a minimum, to hold up before the sensor a lens or mirror certainly somewhat larger than the 5-inch sensor pupil but still on that scale. A smaller apparatus also means greater ease in meeting dynamic requirements and a lower overall cost.

3.2.2.3 Optical Configuration

As shown earlier in Figure 3-4, the display subsystem is afocal, consisting essentially of two collimators back to back with a diffusor or other pupil expansion element located at the common focal plane. The display subsystem must accept inputs from multiple projectors focused at infinity at one port, combine these images, and expand

20
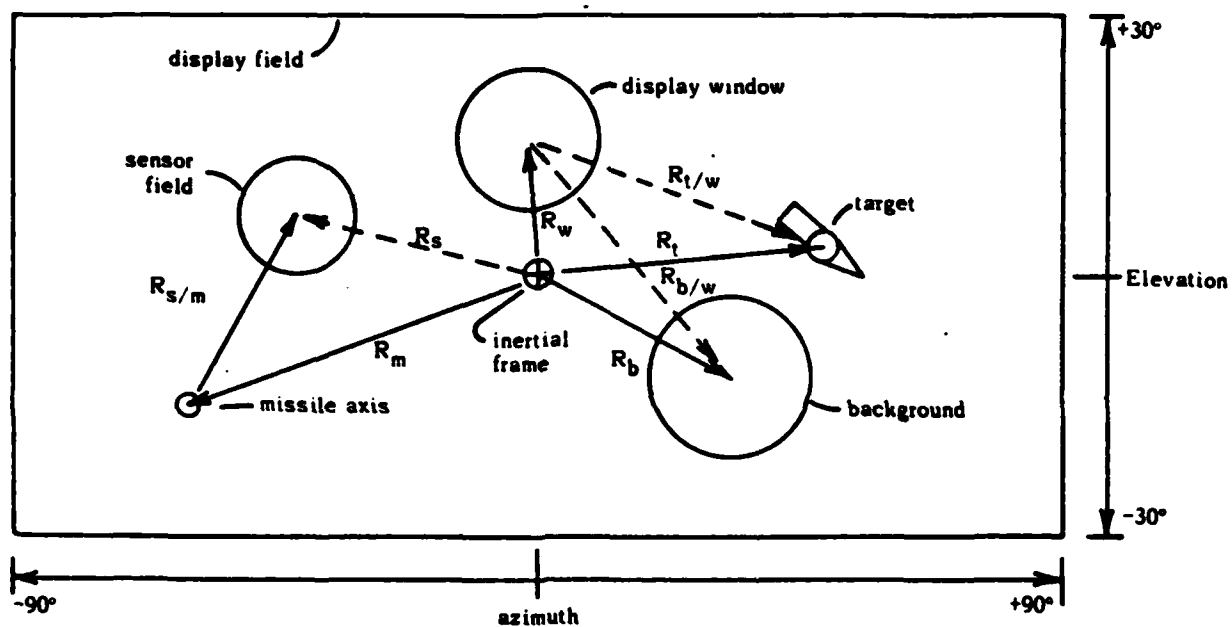
R_m = missile axis direction, from guidance unit mount encoders

$R_{s/m}$ = sensor axis direction relative to missile axis, from sensor gimbal pickoffs

R_s = sensor axis direction, inferred from $R_s = R_m + R_{s/m}$

R_w = display window direction, as commanded

R_t = target direction, from control computer

$R_{t/w}$ = target direction relative to display window, from $R_{t/w} = R_t - R_w$

R_b = background center direction, as commanded

$R_{b/w}$ = background center direction relative to display window, from $R_{b/w}$ $R_b - R_w$

Figure 3-7. Basic Factors in Target Display

21
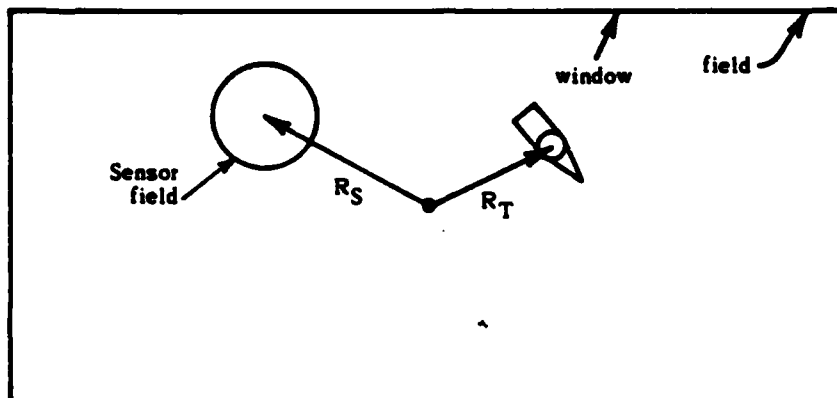
Option 1: Display window $\div$ display field
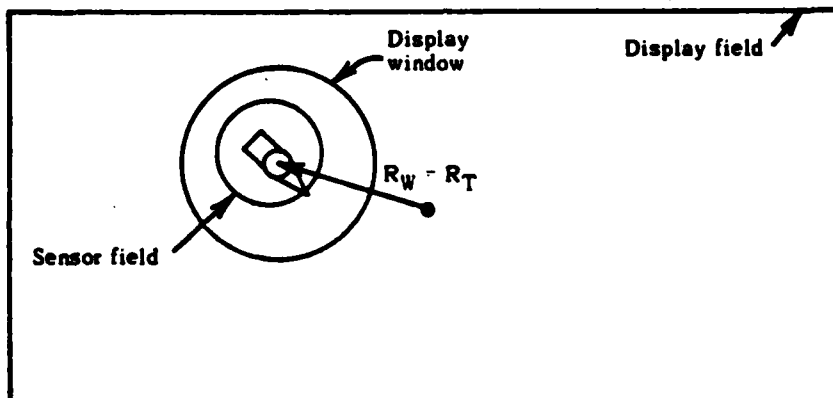
Option 2: Display window slaved to target
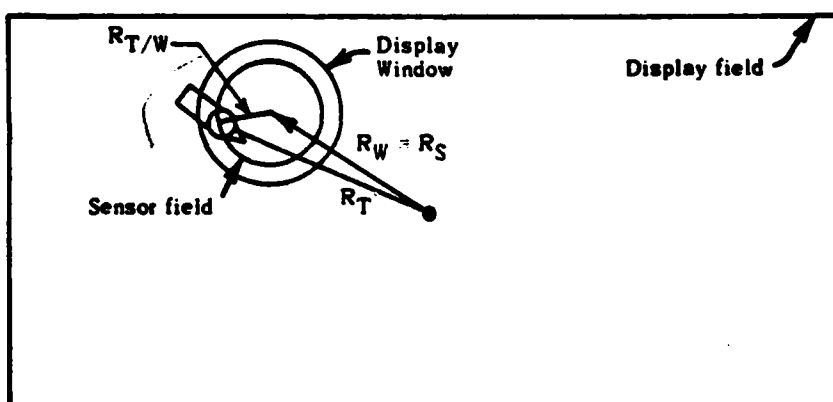
Option 3: Display window slaved to sensor

Figure 3-8. Design Options in Control of Display Window

22
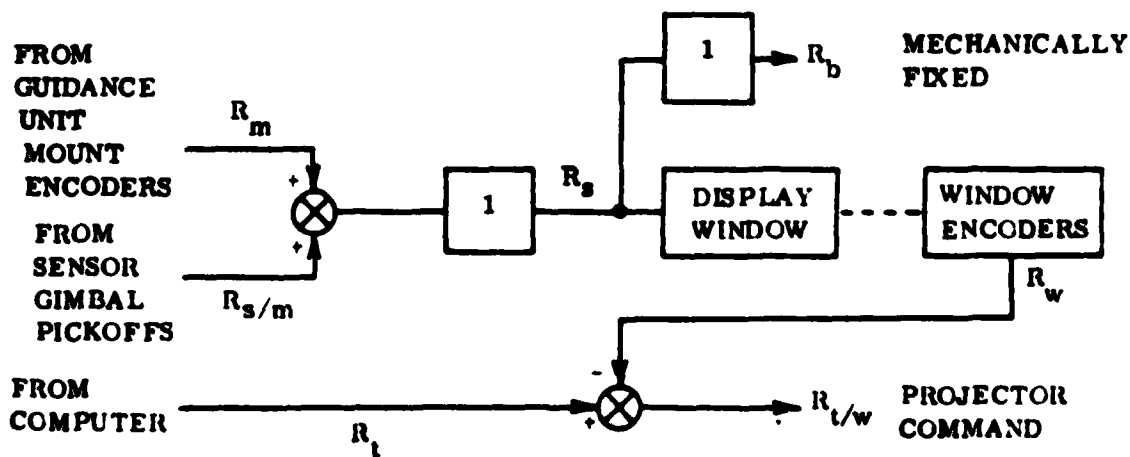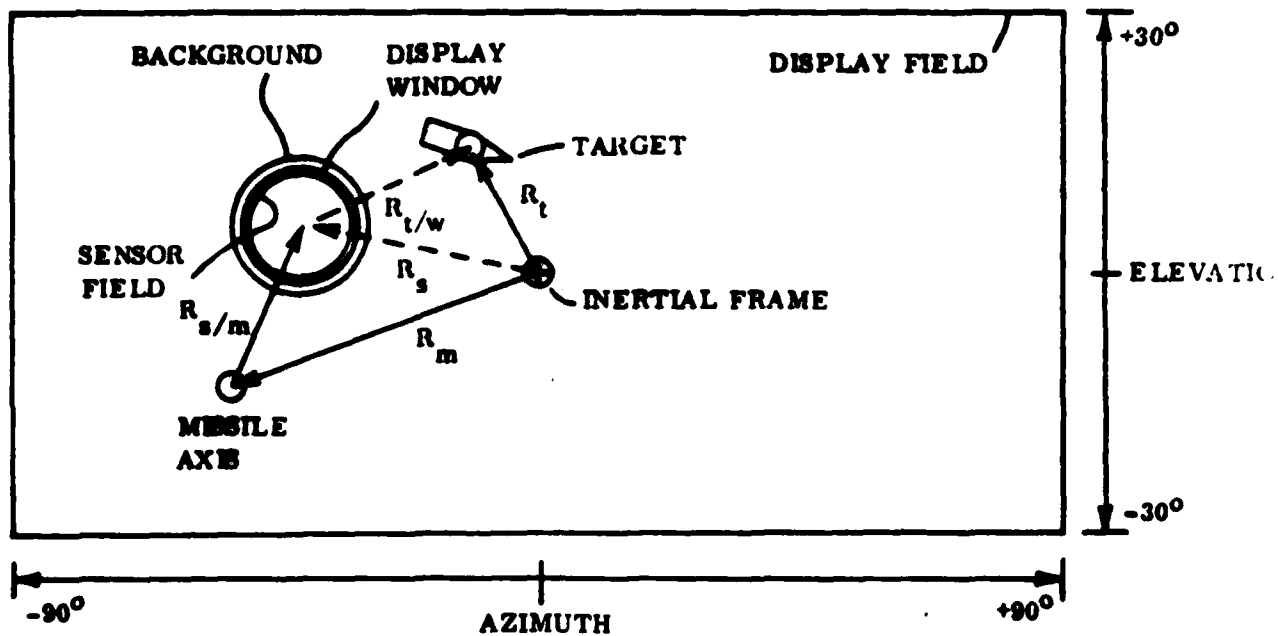
Figure 3-9. Proposed Scheme of Display

the light tube from each projector without degrading the imagery or diminishing the scene radiance by an unmanageable amount, and then reproject the component image to infinity through a light tube at least 5 inches in diameter at the sensor.

The first factor to consider is that all the separate projectors pass imagery through the display. Since these projectors will be working at various spectral intervals from 0.3 to 5 microns, the display subsystem must be achromatic over this range. There is really only one practical choice for a system of decent resolution which is achromatic over such a range: It must be reflective, and both entrance and exit ports must face collimating mirrors. The logical and natural form for such a reflective system is the two-mirror concentric relay shown in Figure 3-10. Only the general form is shown; folding, mounting, and articulation will be discussed later.

The main mirror serves as both input and output collimator. The secondary expands the light tube - or enlarges the exit pupil - corresponding to each of the input projectors. How this pupil expansion is to be performed is an important consideration. The secondary could be an ordinary diffuser of some kind. It could, for example, be a convex spherical surface of ground glass, etched to round the irregularities and thereby limit the angular width of the diffusion lobe, then aluminized. This would be a simple, cheap, and highly effective approach. It has one drawback, however, which further study may show to be serious: The illumination across the lobe will exhibit a Gaussian profile and consequently the illumination over the newly enlarged pupil will not be uniform. The sensor under test will therefore be subjected to
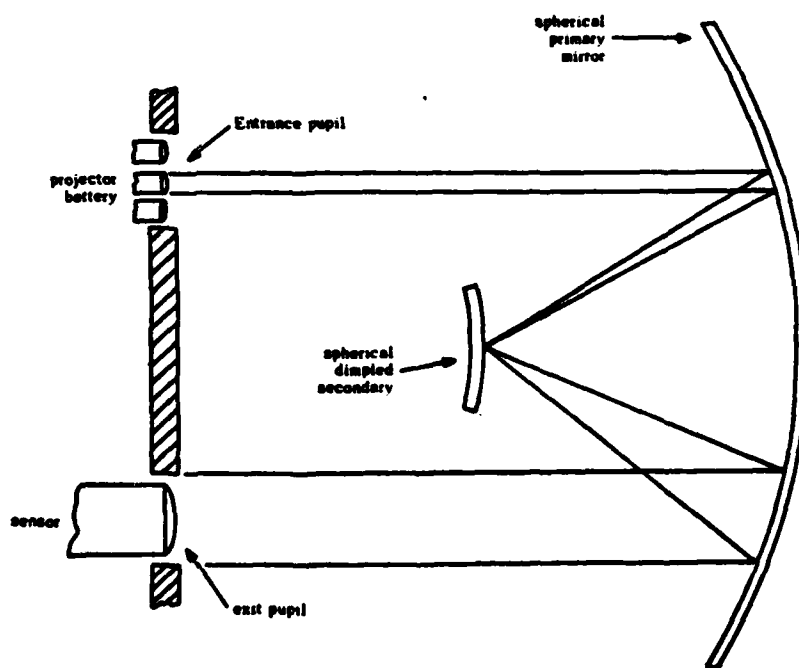
Figure 3-10. General Form of Display Optics

something less than a realistic situation. Since vignetting of the aperture is forbidden for this very reason, and since non-uniform illumination is tantamount to vignetting, this approach is unacceptable.

Pupil expansion accompanied by highly uniform illumination over the pupil can be produced by dimpling instead of grinding the mirror. The dimples required will be very small (less than 1 mm), shallow, concave depressions covering the surface of the mirror in a regular array. They are easily produced in a metal mirror by striking the surface with a special dimpling tool. The action of the dimpling in expanding the pupil can be understood by reference to Figure 3-11. If the dimples are significantly smaller than the blur circle at the secondary, they have the effect of dissecting the blur circle and producing at the primary overlapping point projections of those dimples covered by the blur circle. The apparent size of the blur is unchanged but the new exit pupil is a much enlarged projection of a dimple, sharp in outline and uniformly illuminated. Even if the blur circle spans only two dimples, a significant evening-out of illumination is produced.

3.2.2.4 Mechanical Configuration

Having chosen to configure the display subsystem after the general scheme of Figure 3-10, the final step is the choice of technique for moving the display window over the 180 degree by 60 degree display field. The basic question is whether the principal optical elements themselves are to be movable or whether they are to be fixed and only their images moved through some system of articulation. Three possibilities are shown in Figure 3-12. In the first option, a large fixed primary is used in combination with a movable secondary. In the second, both primary and secondary are movable. In the third, both primary and secondary are fixed, window movement being provided by an articulated display arm. Although the third option requires the addition of three more optical elements into the system (i.e., flat relay mirrors), there are several other factors overwhelmingly in its favor. Option 1 requires an extremely large primary, $186° \times 66°$, which would be prohibitively expensive. Option 2 would require a perhaps even more expensive 2-axis gimbal to move the heavy primary mirror. Clearly, option three must be the choice since it requires motion of only three relatively small mirrors and the primary is the minimum possible size.

3.2.3 TARGET PROJECTION SUBSYSTEM

Our system concept is based on the principle of compound projection, in which a spatially and spectrally complex target is resolved into simple elements, each of which is projected independently by one unit in a multiple-projector array.

The target projection subsystem (as shown in Figure 3-13) consists of (1) a single axis table, on which is mounted (2) the assembly core containing (3) the several element projectors and (4) the directional control assembly.

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ENTRANCE PUPIL

EXIT PUPIL

DIMPLED MIRROR

$$D \approx \frac{F}{f} \, \delta$$

SUPERPOSED, ENLARGED
POINT PROJECTIONS OF
BLUR SEGMENTS PRODUCE
SMOOTHING OF PUPIL
ILLUMINATION

IMAGE BLUR
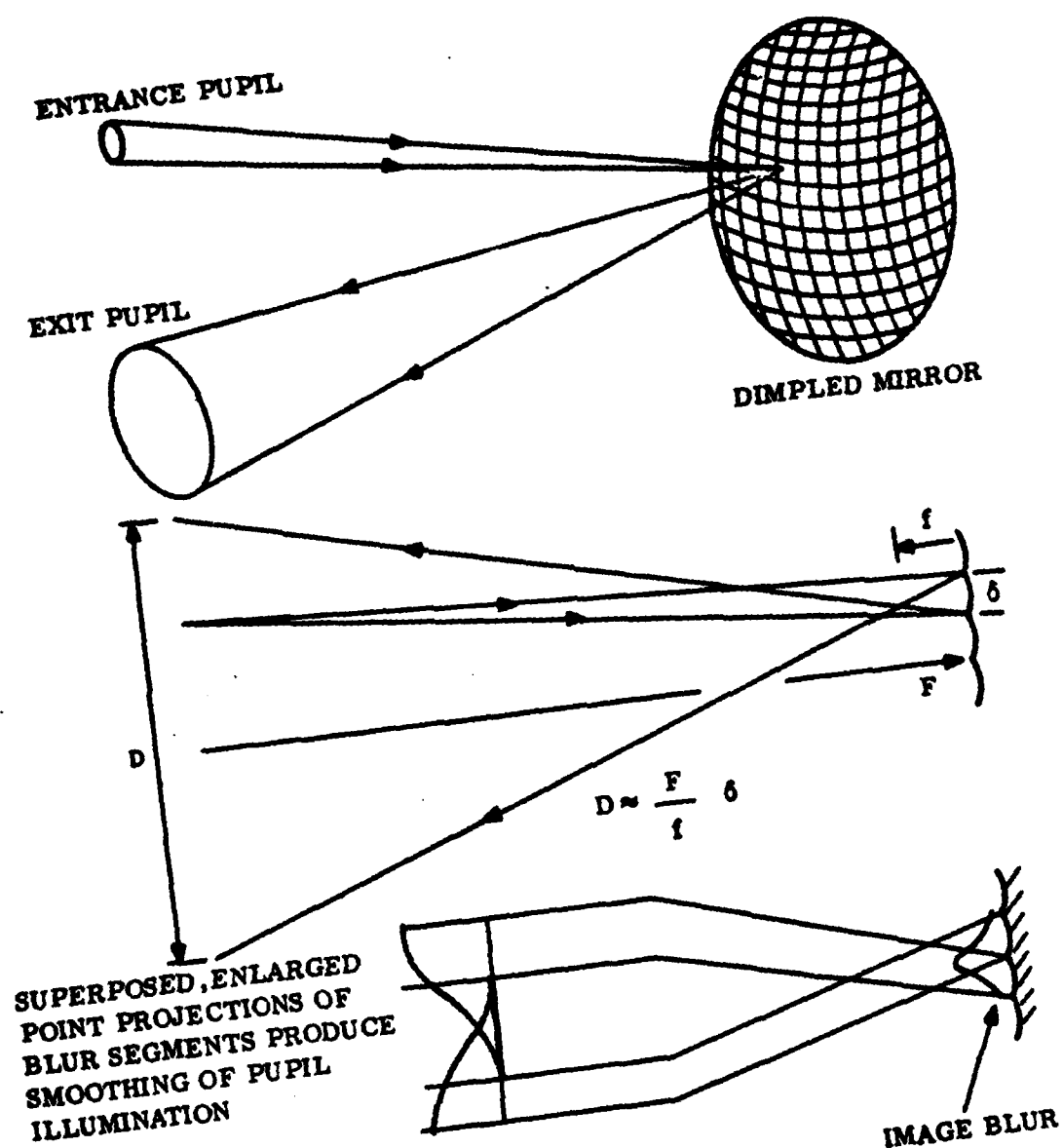
Figure 3-11. Behavior of Display Secondary Mirror
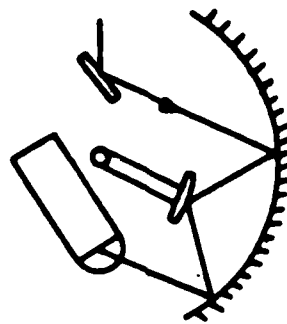
Option 1 — Fixed primary,
movable secondary
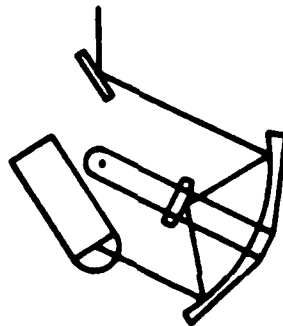
Option 2 — Movable primary,
movable secondary
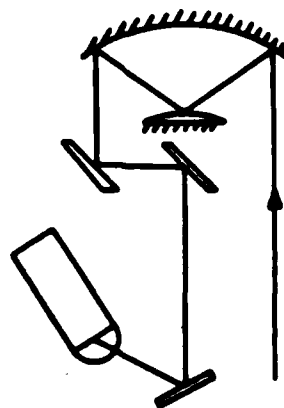
Option 3 — Fixed primary,
fixed secondary,
movable leg

Figure 3-12. Display Mounting Options

A

A

(4) DIRECTIONAL CONTROL ASSEMBLY

(3) SINGLE ELEMENT PROJECTOR

VIEW A-A

(2) ASSEMBLY CORE

(1) SINGLE AXIS TABLE
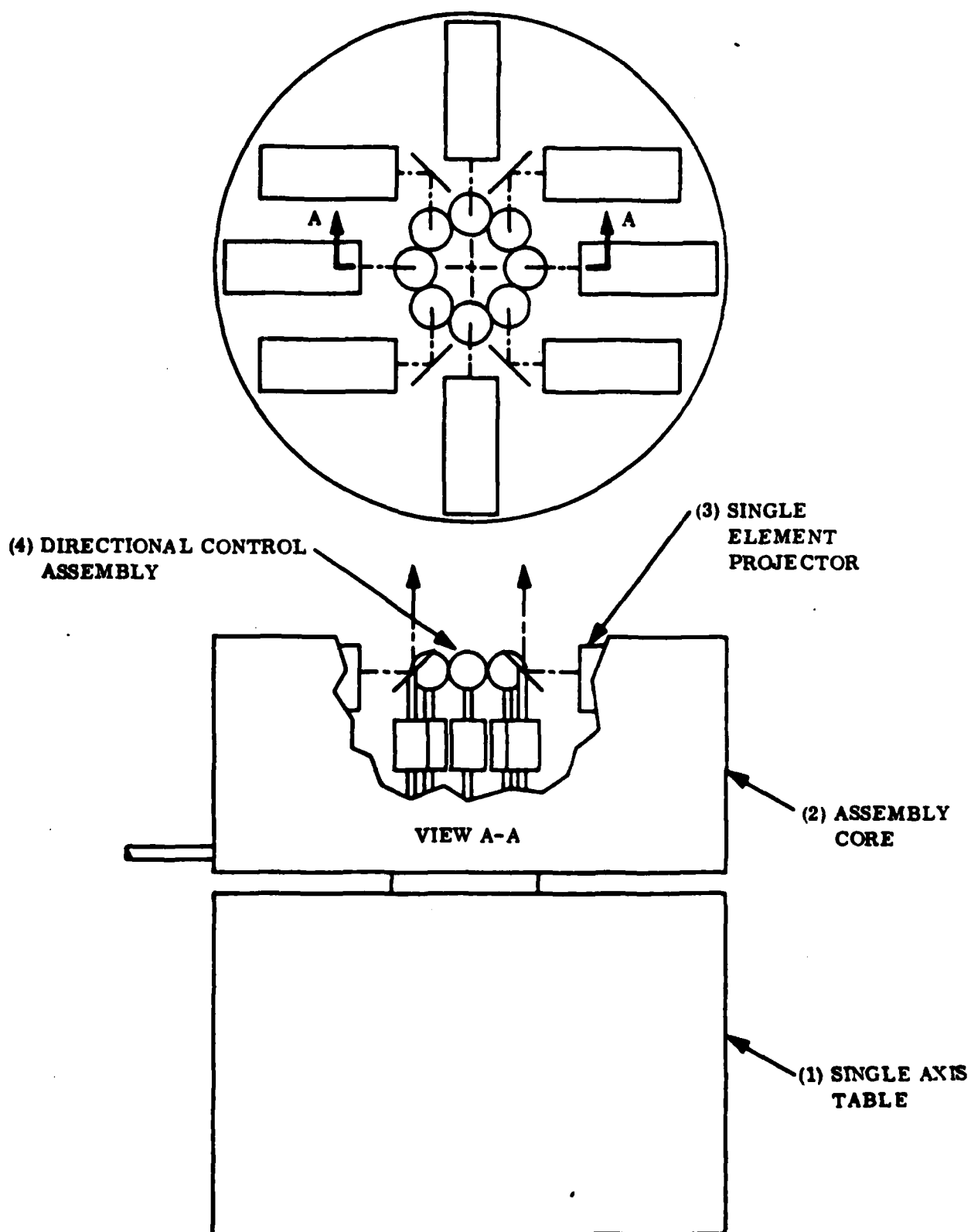
Figure 3-8. Target Projection Subsystem

The projector azimuth table is used to remove display field rotation introduced by azimuth rotation of the display arm while the directional control assembly provides precise target position control $(R_t/_w)$ within the display window.

Two general types of element projector are required. The first, shown in Figure 3-14, is suitable for projecting a pure background or a single target element that must be produced at maximum intensity. The second, shown in Figure 3-15, is designed to project a target and a background simultaneously with various degrees of contrast. Since the (fuselage)/(U.V. - Visible background) contrast ratio must be less than one, this type of projector is essential to fuselage projection.

Each projector will operate over one spectral range, either 1 to 5 or 0.3 to 0.7 microns, and with the exception of the fuselage one will produce only one scene element. Examination of Figure 3-16 shows that seven projectors will suffice to project the most complex target group required and still provide some reserve capacity. However, symmetry considerations make it easy to add an additional projector to bring the total to eight and further increase the capacity. Such capacity is especially needed for countermeasures simulation. With high flare ejection rates, two or three flares may be in the field at once. Super-radiant flares may be simulated by superposing images from two or more flare projectors.

These eight projectors are of modular design and, insofar as possible, will use identical components. The objective is to provide the greatest possible operational flexibility by permitting changes in spectral range to be accomplished merely by substitution of optics, and changes in projected target shape by an equally simple change of transparency mechanism.

3.2.4 CONTROL CONSOLE AND COMPUTER INTERFACE SUBSYSTEM

The control console and computer interface subsystem provides all of the electronic equipment necessary for both open-and closed-loop operation. In the closed-loop mode, both analog and digital interfaces will be provided for linking the IRSS to the MICOM Hybrid Computers where all command generation and data recording takes place. In the open-loop configuration, command generation and data recording will take place in the control console. The principal components of this subsystem are:

(a) Control Electronics, which include all of the servo and control loop electronic equipment necessary for operation of the 8-channel projector and display arm.

(b) Command and Data Management, which includes the analog and digital equipment necessary for interfacing of command and performance data with the remote MICOM hybrid computer facility and the various IRSS subsystems, and provides the means to conduct open loop testing by generation of precision function programs. The focal point of this section is a GE-PAC 30 process controller which enables wide flexibility in system usage through the various software routines planned for the IRSS.

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XENON ARC LAMP

SPECTRAL AND NEUTRAL DENSITY FILTERS

CONDENSING LENSES

PHOTODETECTOR

SCENE TRANSPARENCY

FIELD LENS REQUIRED FOR PLUME AND BACK-GROUND ONLY

PHOTODETECTOR

PROJECTION LENS

MOTORIZED IRIS

TO DISPLAY S/S

PHOTODETECTOR

IRIS TRANSMISSION
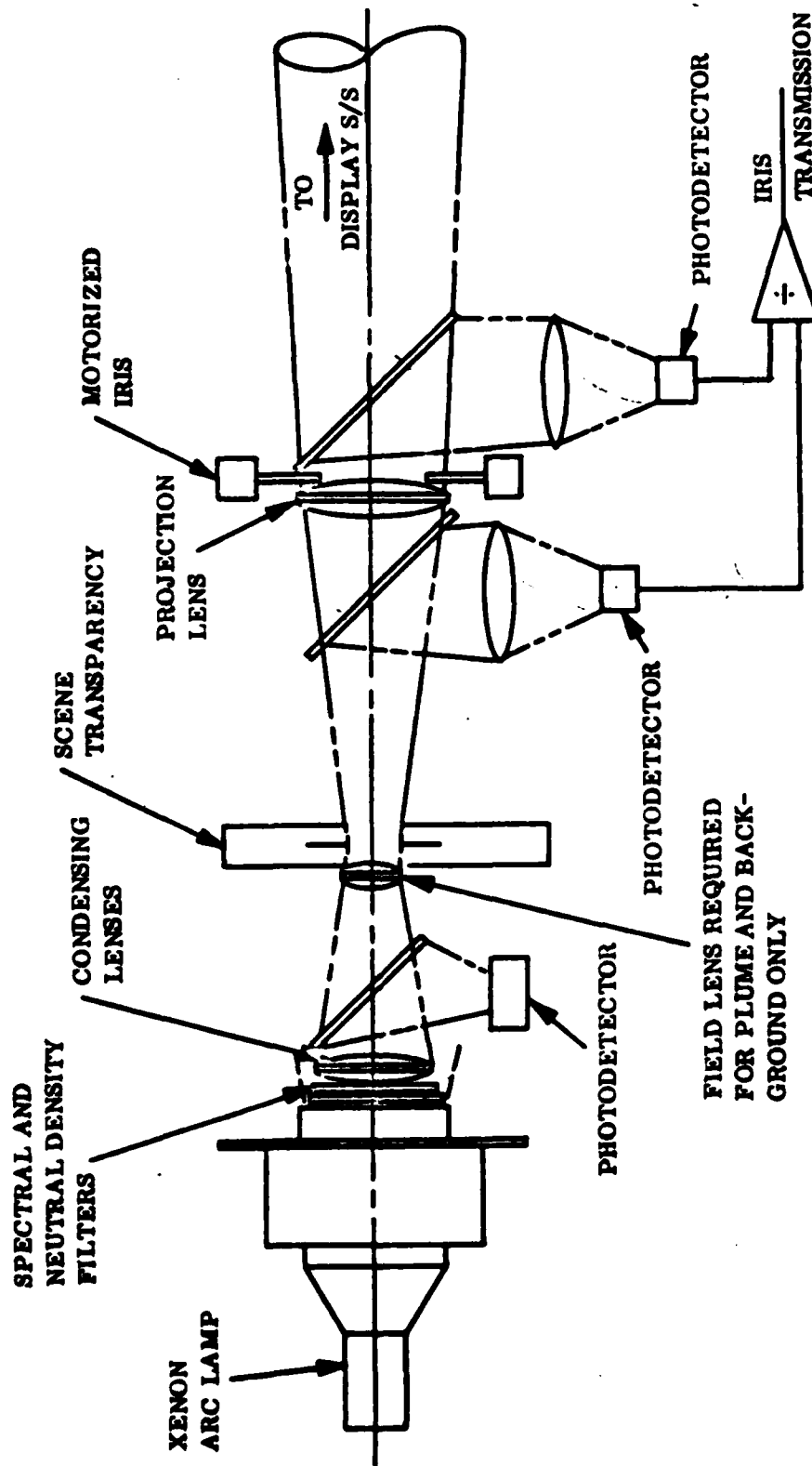
Figure 3-14. Single-Purpose Projector

FIELD LENS

BACKGROUND RADIANCE
CONTROL FILTER PRO-
VIDES REALIZABLE OUT-
PUT OF 10^{-6} TO 10^{-4}
WATTS/CM^2/SR IN EACH
OF THE BANDS
$0.3 - 0.4\mu$ AND $0.4 - 0.7\mu$

XENON ARC LAMP

SPECTRAL ADJUSTMENT FILTER

CONDENSING LENS

PHOTODETECTOR

CLOUD
WHEEL

PROJECTION
LENS

TRANSPARENCY
ASSEMBLY

DISPLAY STAGING PLANE

TARGET RADIANCE CONTROL
FILTER PROVIDES 1/10 TO 9/10
OF THE RADIANCE AVAILABLE
IN THE BACKGROUND SCENE

IRIS ASSEMBLY

TO
DISPLAY S/S

PROJECTION LENS
(DOUBLET WITH
LITHIUM FLUORIDE
AND QUARTZ
ELEMENTS)

Figure 3-15. Dual Purpose Projector

31

	PROJECTOR REQUIREMENTS	SPECTRUM (μ)
1	IR BACKGROUND	
1	TAILPIPE	1-5
1	FUSELAGE AND UV-VISIBLE BACKGROUND	0.3-0.7
1	PLUME	1-5
3	FLARES OR OTHER	1-5
7		

SINGLE ENGINE AIRCRAFT

1	IR BACKGROUND	1-5
4	TAILPIPES	1-5
2	FLARES OR OTHER	1-5
7		

MULTI-ENGINE AIRCRAFT

1	IR BACKGROUND	1-5
4	TAILPIPES	1-5
2	FLARES OR OTHER	1-5
7		

MULTI-AIRCRAFT FORMATION

Figure 3-16. Target Group Requirements

(c) <u>Operator Controls and Displays</u>, which provide the means to operate and monitor the IRSS. The operator console will include the following:

1. System Power Control and Lock

2. Display Arm Controls

3. Projector Controls

4. Guidance Unit Mount Control Panel

5. Emergency Shutdown

6. Operational Mode Selection

7. Manual (locking 10-turn potentiometer) input to each control loop

8. External (patching) input to each control loop

9. System Status Display

10. Data Monitor Jack Panel

11. System Test Equipment including:

    Dual Beam Storage Oscilloscope

    Function Generator

    Digital Voltmeter

12. Teletype & Tape Reader/Punch Console (Terminet)

(d) <u>Analog Computation Equipment</u> includes an EAI 680 Analog Computer (GFE) which will be required to do coordinate transformations on a real-time basis.

4.0 SYSTEM PERFORMANCE CONSIDERATIONS

4.1 INTRODUCTION

To carry the IRSS (or any other system of similar complexity) to a successful conclusion requires that attention be given during the design phase not only to specific hardware performance requirements (stated in Section 2 and realized in Section 5), but to those "software" efforts which comprise good systems engineering. These include error analyses and establishment of error budgets (a naturally iterative process); cost-effectiveness and risk assessments at component, subsystem, and system impact levels; and such design variables as maintainability, electromagnetic compatibility, and reliability.

While this report devotes separate Sections to the first two of these last three criteria (5.5.7 and 5.5.8, respectively), reliability is not treated in the same manner but covered throughout the design reported herein. The reason for this treatment is our awareness of its many facets, and how to achieve them: component derating, component life, vendor control, use of selected parts, redundancy, choice of materials, use of government-approved manufacturing techniques, and application of precision bearing technology.

4.2 ERROR BUDGETS

4.2.1 SUMMARY

The areas of interest are:

  (1) target position accuracy

  (2) optical resolution

  (3) image brightness

  (4) range accuracy

These budgets are presented here rather than at the end of Section 5 so that the significance of each source can be noted and kept in mind as the details of component performance are discussed in that Section.

4.2.2 TARGET POSITION ACCURACY

Target position error budgets for both elevation and azimuth are included as Tables 4-1 and 4-2. Both totals are well below the required 1 mrad limit and represent realistic and obtainable values.

TABLE 4-1. TARGET AZIMUTH ERROR ANALYSIS

Systematic Errors at Maximum Acceleration		
Display Arm:		E (mrad)
Torsional Deflection		-.1
Drive Belt Deflection		.03
Directional Mirrors:		
Dynamic Lag Error		.45
Total Systematic Error		.38 mrad

Random Errors		
Alignment Errors:	E (mrad)	E^2
GUM	.1	.01
Projector	.1	.01
Display Arm	.1	.01
Display Arm:		
Encoder Output	.1	.01
Vertical Guide Rails	.06	.0036
Bearing Runout	.025	.0006
Projector Az. Table:		
Encoder Output	.05	.0025
Dynamic Lag Error	.1	.01
Directional Mirrors:		
Computational Error	.2	.04
Position Transducer (RVDT)	.25	.0625
	Total =	.1592

Therefore, E_{rss} = .40 mrad

Total Error = .78 mrad.

TABLE 4-2. TARGET ELEVATION ERROR ANALYSIS

Systematic Error at Maximum Acceleration		
Display Arm:	E (mrad)	
Bending	.01	
Directional Mirror:		
Dynamic Lag Error	.30	
Total Systematic Error =	.31 mrad	

Random Errors

Alignment Errors:	E (mrad)	E^2
GUM	.1	.01
Projector	.1	.01
Display Arm	.1	.01
Display Arm:		
Encoder Output	.05	.0025
Vertical Guide Rails	.06	.0036
Bearing Runout	.025	.0006
Projector Az. Table:		
Encoder Output	.05	.0025
Dynamic Lag Error	.1	.01
Directional Mirrors:		
Computational Error	.2	.04
Position Transducer (RVDT)	.25	.0625
	Total =	.1512
	Therefore, E_{rss} =	.39

Total Error = .70 mrad

4.2.3 OPTICAL RESOLUTION .

Angular blur of a point source object is due to the three sources shown in Table 4-3, and is well below the 1 mrad. limit.

TABLE 4-3. OPTICAL RESOLUTION

	β (mrad)
Display subsystem:	
Collimating Optics	.3
Display subsystem:	
Mirrors - Manufacturing Tolerances	.09
Projection Lens	.3
Total System Angular Blur	.69 mrad

4.2.4 IMAGE BRIGHTNESS

Image brightness depends primarily on system opacity and available source radiance. System opacity for the various types of projectors is tabulated in Table 4-4 and applied in Table 4-5 to determine available image radiance. The derivation of these values is discussed in Section 5.

4.2.5 RANGE ACCURACY

Range simulation is accomplished by varying target size and radiance using a servo controlled transparency and iris. The required simulation accuracy of 5% of commanded range is obtained by using precision mechanical and servo hardware and is described in detail in Sections 5.3.3.2 and 5.3.3.3.

4.3 SYSTEM ALIGNMENT

The principal concern in system design and assembly is that errors in apparent target position traceable to misalignment of system elements be much less than 1 milliradian through intelligent design and by proper alignment and adjustment procedures. IRSS follows a concept which is very insensitive to such sources of error and extremely simple to align.

There are two aspects of the alignment problem : the optical and the mechanical. We consider the optical first. The most important fact having a bearing on this problem is that the display optics are afocal; that is, the light both leaving and

TABLE 4-4. SYSTEM OPACITY FOR VARIOUS TARGETS

	Pupil Expansion	Reflection 9 Mirrors	Transmission	System Opacity
Tailpipe & Flare	1.75" dia. projection lens $$\varphi = \frac{(11.64)^2}{(1.75)^2} = 44.2$$	$\varphi_1 = \frac{1}{.98} = 1.02$ $\varphi = \varphi_1^9 = 1.12$	2 lenses @ 1.25 3 windows @ 1.11 $\varphi = (1.25)^2 \times (1.11)^3 = 2.14$	106.0
Plume & IR Background	1.4" dia. projection lens $$\varphi = \frac{(11.64)^2}{(1.4)^2} = 69.1$$	$\varphi_1 = \frac{1}{.98} = 1.02$ $\varphi = \varphi_1^9 = 1.12$	3 lenses @ 1.25 3 windows @ 1.11 $\varphi = (1.25)^3 \times (1.11)^2 = 2.67$	208.0
Fuselage & UV - Visible Background	.91" dia. projection lens $$\varphi = \frac{(11.64)^2}{(.91)^2} = 163.6$$	$\varphi_1 = \frac{1}{.86} = 1.163$ $\varphi = \varphi_1^9 = 3.88$	4 lenses @ 1.25 1 beamsplitter @ 2 2 beamsplitters @ 3.3 2 windows @ 1.11 $\varphi = (1.25)^4 \times (2) \times (3.3)^2 \times (1.11)^2 = 65.48$	4.16×10^3

TABLE 4-5. RADIANCE REQUIREMENTS AND THE VARIAN 150XBS LAMP

MERIDIONAL EXIT RAY ANGULAR ERROR (mrad)

$2\alpha_X = 0.290$ mrad

$\delta = 0.310$ mrad

BLUR CIRCLE

BLUR OFFSET – 0.755 mrad.

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

-0.3   -0.2   -0.1   0.1   0.2   0.3

TRANSVERSE EXIT RAY ANGULAR ERROR (mrad)
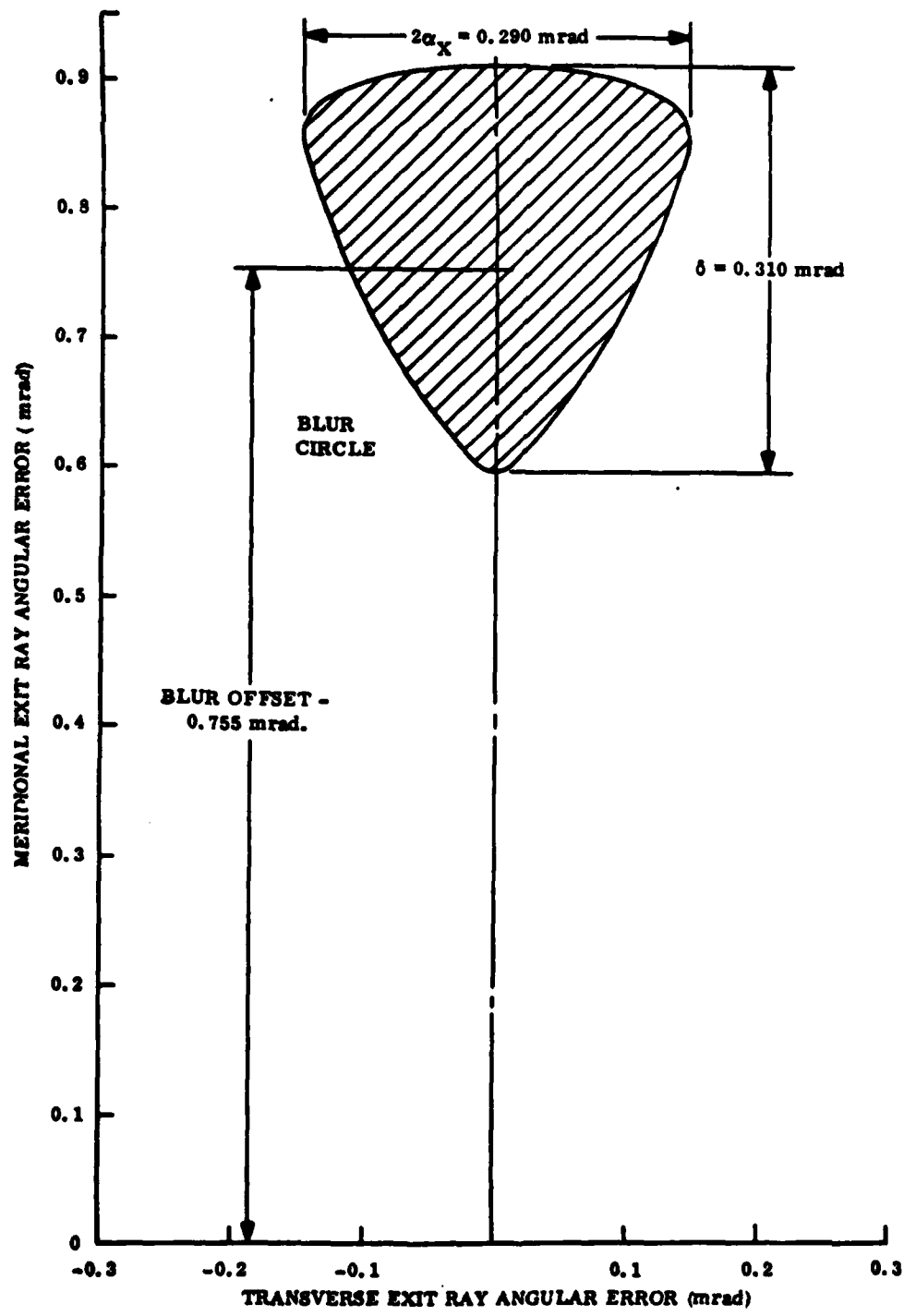
entering is collimated. In consequence it can be shown that the operation of the display optics is completely unaffected by minor linear or angular misalignments of the optics or by minor linear misalignments of the display arm or the projector assembly. Furthermore, the behavior of the display optics is relatively insensitive even to rather large relative displacements of the two mirrors themselves. This rather general insensitivity to misalignment is illustrated in the examples of Figure 4-1.

The decision to base system design on afocal compound projection enormously simplifies assembly and alignment. Mechanically, only three system elements need to be aligned: the guidance unit mount, the display arm, and the projector assembly. Since only angular misalignments can cause apparent shifts in target position, it is necessary to perform only angular alignment of these three elements. The most obvious and practical way to do this is to fix all three elements to a common base and then align all three to the common vertical with ordinary levels.

The general layout of the proposed system is shown in Figure 1-1. The steps in this alignment procedure and the implications for system design may be summarized as follows:

(1) First the guidance unit mount will be fixed to the base and its azimuth axis aligned to the vertical with 20 second levels, using adjustment screws

(2) Next, the structural mainframe will be erected on the same base, around the Guidance Unit Mount. The mainframe must have two holes: one for the projector assembly to look through and one through which the display arm will be dropped. The only real requirement on the mainframe is that it be very stiff, so that under the inertial loads applied by the moving display arm, angular deflections in the display arm mount will be well below 0.1 milliradian. The mainframe design is discussed in Section 5.4.

(3) Third, the display arm assembly is mounted through the hole mentioned earlier, so that the display azimuthal axis is approximately coaxial with the azimuthal axis of the guidance unit mount, then leveled with 20-second bubble levels. It is not necessary that the display and guidance mount azimuthal axes be collinear, only that they be parallel, since lateral misalignments do not affect the operation of the display in any way, provided the display window is significantly larger than the sensor field, which it is by design.

The initial alignment procedure for the display arm and its components is discussed in Section 5.2.4.4.

(4) Next, the projector assembly is fixed to the same base looking up through the second hole in the mainframe second level, positioned approximately according to the plan layout, then leveled to 20-second accuracy with bubble levels. Again, it is not necessary that the projector axis be placed exactly over the center of the entrance pupil, since lateral misalignments of this type have no effect on the angular position of the target.

41
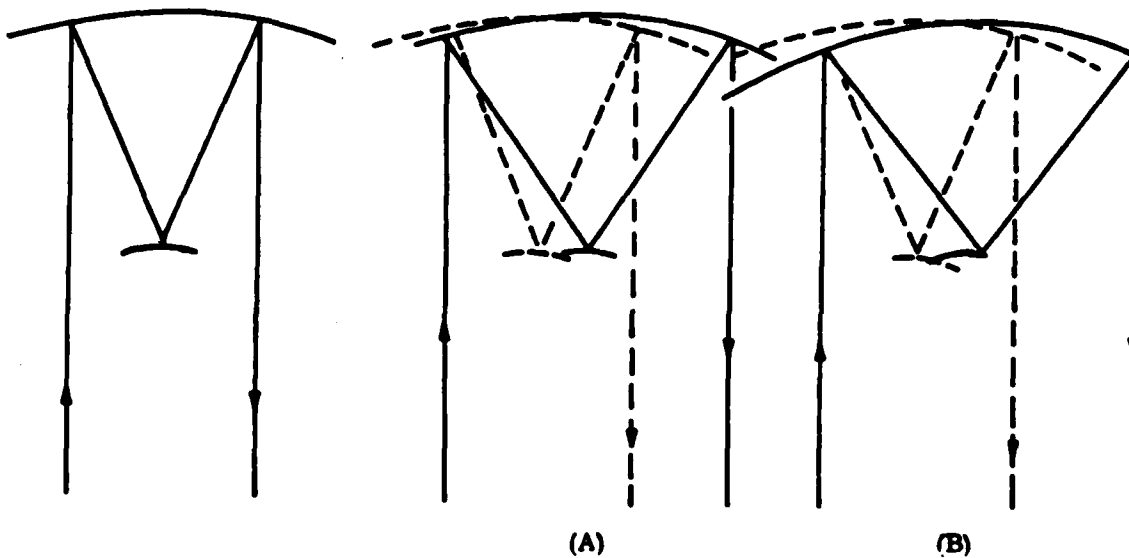
INSENSITIVITY OF TARGET DIRECTION TO (A) DISPLACEMENT
OR (B) TILT OF DISPLAY OPTICS
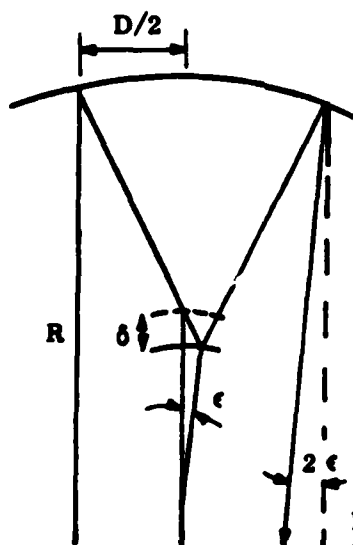
$$2\epsilon = K\delta$$

WHERE $K = 2.5$ m RAD/INCH
AND IS DERIVED FROM FIGURE 5-7

INSENSITIVITY OF TARGET DIRECTION TO
MISPOSITIONING OF DISPLAY OPTICS

Figure 4-1. Inherent Insensitivity of Display to Misalignment

(5) Finally, the collimating mirrors and the dimpled mirror are mounted on the structure so that the optical axis is centered approximately between the projector axis and display axis, and so that the main collimating mirrors are approximately at the correct height above the floor. The dimpled mirror is then adjusted for the proper separation between it and the collimating mirrors.

Once this is done, each of the transparencies is driven to its minimum opening and a quad-cell detector with an appropriate lens is mounted in the Guidance Unit Mount. The latter is then driven to the zero-zero-zero position. The display arm is driven to the zero-zero position, and the projector azimuth table is driven to the zero position. Taking each projector in turn, bias adjustments are made in the directional mirror control circuit until the quad cell output is nulled. This procedure eliminates the requirement for precise alignment of the projector components and the projector housing on its mounting plate, thus greatly simplifying the alignment procedure.

In summary, the employment of an afocal display subsystem makes design, assembly, and alignment of the entire system much simpler than it might otherwise be. No immense anvil is needed to maintain collinearity of the missile and display axes. No precision fabrication is required in the mainframe.

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5.0 DESIGN DEFINITION OF IRSS SUBSYSTEMS

5.1 GUIDANCE UNIT MOUNT

5.1.1 REQUIREMENTS

The basic characteristics of the guidance systems to be tested on IRSS were specified in Table 2-4. Table 5-1 contains the specifications for the Guidance Unit Mount laid down in MICOM's Technical Requirement No. 1276 (dated 30 January 1970 and revised 28 August 1970).

In order to provide as useful and flexible a system as possible, MICOM further agreed at the first contract review meeting held there on 18 January 1971, to provide supplementary design goals for the Guidance Unit Mount. This was done on 2 February 1971 (Table 5-2). These goals were then incorporated as an alternate performance level to be presented to potential vendors (see below).

5.1.2 SPECIFICATION

The above requirements and design goals were analyzed and supplemented by hardware-oriented considerations of reliability, freedom from effects of electro-magnetic interference (both self-generated and impinging), safety, and interface requirements with other IRSS subsystems. This effort resulted in the issuance of GE-RESD Specification No. A4110 on 26 February 1971. (See Appendix A).

With adequate procurement documents attached, this specification on 5 March 1971 was sent to four qualified vendors who in the preceding two months had indicated an interest in a response: Carco Electronics, Fecker Systems Division of Owens-Illinois Corporation, Aeroflex Laboratories, and Goerz Optical Company.

5.1.3 RESPONSES

On 29 March 1971, compliant proposals were received from the first two, addressing themselves to both the required and the desired performance levels (because the differences in both cost and implementation complexity between achieving these two performance levels were very small, it became obvious that procurement of the higher level performance unit only should be considered). Aeroflex requested numerous relaxations of the specifications before they would bid (this request was declined by RESD), and Goerz never replied in any form.

Inasmuch as Fecker's compliant response still left a number of questions unanswered to RESD's satisfaction, a fact-finding visit to their plant was made on 21 April 1971. Main items of concern were EMI testing, earlier completion, safety, and slipring experience and reliability. These were covered in an additional FSD document, F(1)-4106-004-022-1752, dated 30 April 1971.

TABLE 5-1. GUIDANCE UNIT MOUNT SPECIFICATIONS

Load size, typical - Cylinder, 3" dia., 10" long	

Load size, typical - Cylinder, 3" dia., 10" long
Load size, maximum - Cylinder, 10" dia., 25" long
Load weight, typical - 3 - 5 lbs
Load weight, maximum - 25 lbs
Orthogonality of Axes - 0.1 milliradian
Intersection of Axes - within 0.005 inches
Moments - assume load uniformly distributed with respect to
axes of rotation.

Specification	Pitch	Yaw	Roll (main mount)	Roll* (if applicable)
Displacement	$\pm 80°$	$\pm 90°$	Continuous	Continuous
Velocity @ Max. Load, exceeds	$\pm 100°/sec$	$\pm 100°/sec$	$\pm 1800°/sec$	$\pm 7200°/sec$
Acceleration @ Max. Load, exceeds	$1000°/sec^2$	$1000°/sec^2$	$3600°/sec^2$	$7200°/sec^2$
Position Accuracy	0.2 milliradian	0.25 mil	0.25 mil	N/A
Repeatability	0.1 mil	0.1 mil	0.1 mil	N/A

*This specification for velocity and acceleration applies to the roll axis of the main mount if no removable fixture is used.

In addition, Carco offered to supply RESD with an unsolicited proposal for what they expected to be a lower-cost solution than that originally requested. This was received by RESD on 29 April 1971.

5.1.4 EVALUATION

Careful evaluations of both technical and cost parameters of all three of these proposals were made. The technical evaluation of the compliant ones is summarized in Appendix B. Briefly, it was discovered that the solution offered by FSD was significantly superior from a performance point of view in two important areas: use of rotary joints (instead of storage bottles mounted on the inner gimbal) for continuous transfer of cooling gas to the test article, and higher bandwidth capabilities in all three axes. These helped account for a conservatively approximately 20% higher technical performance rating for FSD's version as compared to Carco's (379 vs. 323 points).

Financially, on the other hand, FSD's high-performance GUM (only version recommended) was less than 10% higher than Carco's ($257,419 vs. $239,516). Figure 5-1 shows a layout of this subsystem.

TABLE 5-2. SUPPLEMENTARY SPECIFICATIONS FOR INFRARED
SIMULATION SYSTEM

These specifications on the IRSS are supplementary to the specifications contained
in TR 1276. Since these specifications were not included in the TR at the time of
issuance, they are to be considered as design goals for the contract. The supple-
mentary specifications were arrived at by further consideration of the ultimate
requirements of the IRSS to perform the myriad of tasks for which it is intended.
As such, these specifications represent highly desired characteristics which the
contractor should strive to achieve.

SPECIFICATIONS

A. Guidance Unit Mount
1. Mode of Operation
The mount should be capable of operating in both position and rate mode
on all axes.
2. Ratio of Maximum to Minimum Rates
Position Mode: No less than 5×10^5 for all axes.
Rate Mode: No less than 1×10^4 for all axes.
3. Roll Rate Accuracy
Accuracy (in rate mode): Better than 5% of requested rate.
Ripple: No greater than $\pm 2\%$
Read-out Accuracy: Better than 1% (referenced to called-for rate).
Read-out Linearity: Better than 1% (referenced to called-for rate).
4. Bandwidth:
Position Mode: Using a 1 degree peak-to-peak sine wave input, with
maximum specified load and measuring bandwidth at the
frequency at which 90 degree phase lag between output
and input occurs, bandwidths for the three axes shall
be as shown below:

Pitch = 15 Hz
Yaw = 20 Hz
Roll = 25 Hz

Velocity Mode: Using a 20 degree per second peak-to-peak sine wave
input on pitch and yaw axes and 50 degree per second sine
wave input on roll axis, frequency bandwidth measured as
above shall be no less than 25 Hz on all axes.
5. Connections to Payload
The mount shall be capable of accepting a maximum of 15 outputs from the
test item for purposes of recording. Outputs and inputs required for activation or
other control purposes are not included in this number.

B. Target Generation System
1. Target Jitter
Extraneous inputs shall not cause the actual target position to vary more than
± 0.5 milliradian from the called-for position. This specification shall apply to both
position and rate inputs.
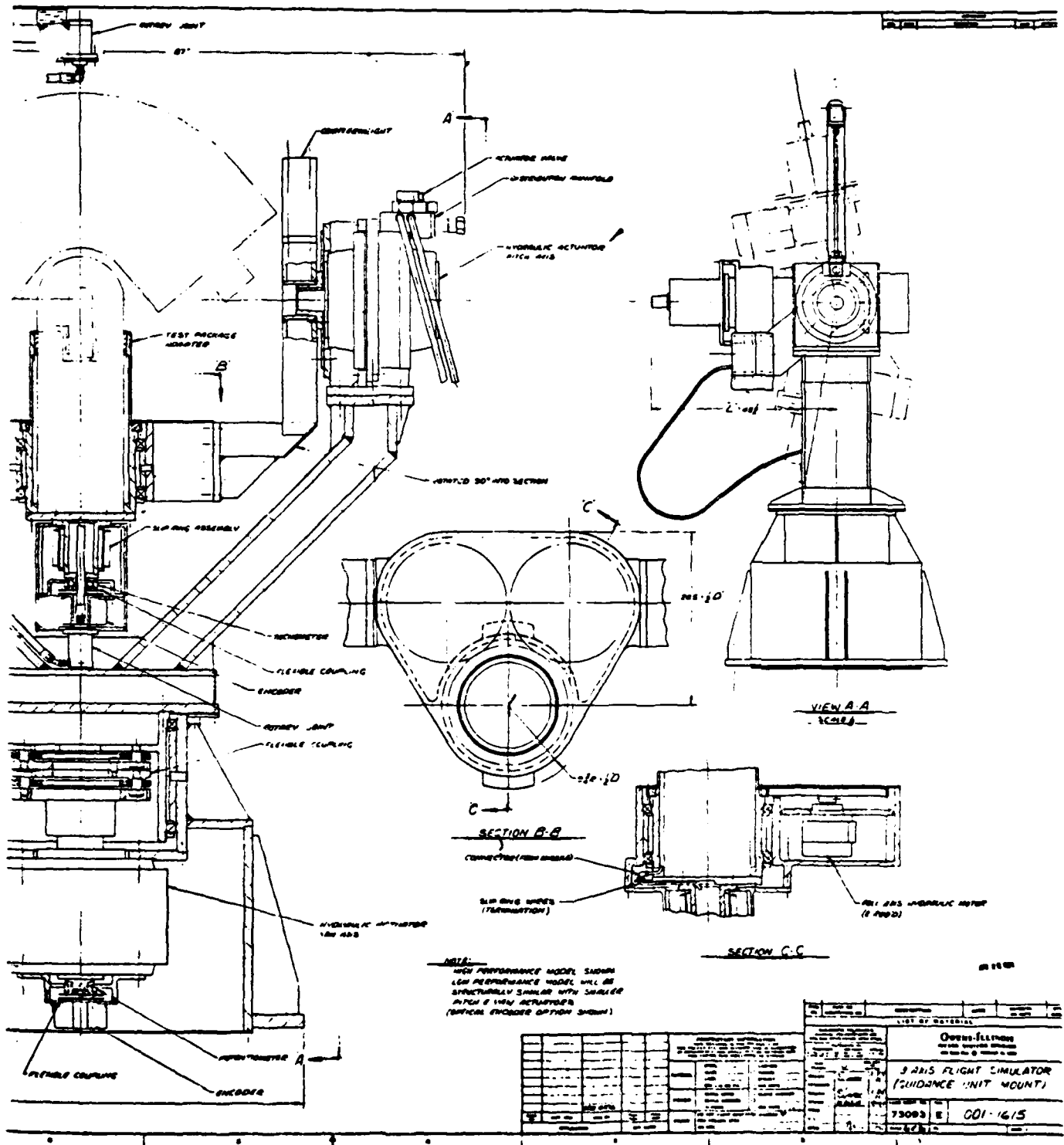
Figure 5-1. Three-Axis Flight
Simulator (Guidance Unit Mount)
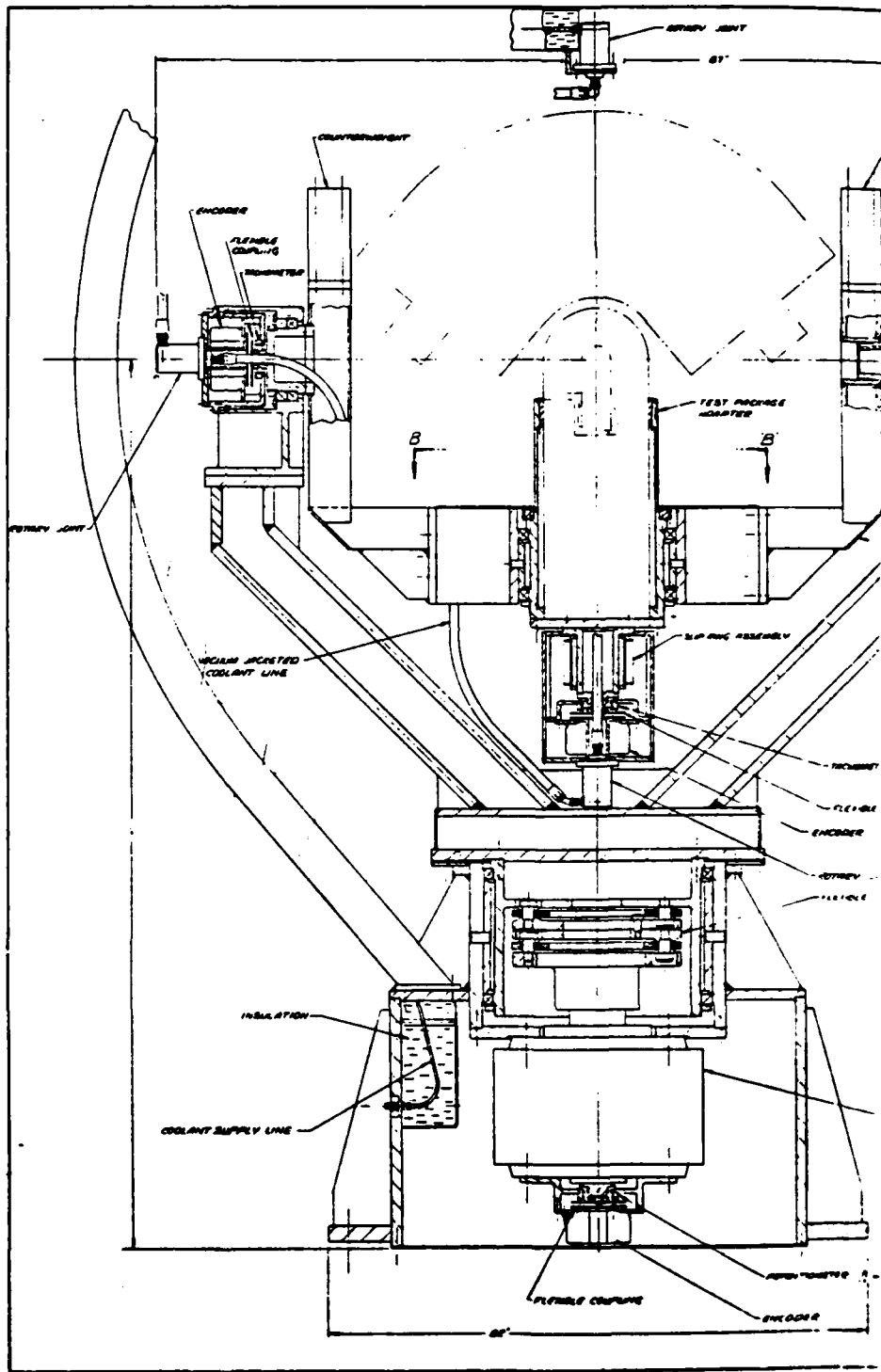
5.1.5 RECOMMENDATION

Since this subcontract procurement exceeds $100,000, a formal source selection
board proceeding was instituted by the Materiel Operation in consonance with RESD
policy and applicable ASPR's. The Board met on 25 May 1971 and concurred with
the recommendation for selection and award to FSD. The Minutes of that meeting
are attached as Appendix B.

5.2 DISPLAY SUBSYSTEM DESIGN

5.2.1 CONFIGURATION AND REQUIREMENTS

As explained earlier in Section 3.2.2, the display subsystem will have the basic form shown in Figure 5-2. Scene elements originate in the projector subsystem as individual collimated sources and are directed into the first spherical primary which serves to form an image of each element on the dimpled mirror surface. The dimpled mirror acts as a controlled diffuser, expanding the output beam to fill the 5" diameter seeker pupil. The second primary serves as the output collimator, producing a virtual image at infinity of the entire 7 degree display field. Articulation of the display window is then provided by the display arm, producing azimuth motion through rotation of the entire arm and elevation motion through rotation and vertical translation of the final plane mirror in the optical train.

The display subsystem requirements listed below are derived from the basic system requirements and reflect the need to apportion total errors among the various subsystems.

General

Optical Resolution	.7 m rad
Exit Pupil diameter	5.0 inches
Display Window diameter	7 degrees

Display Arm

Range of motion	$\pm 90°$ – Azimuth
	$\pm 30°$ – Elevation
Maximum velocity (both axes)	100° /sec
Maximum Acceleration (both axes)	400° /sec^2
Position Accuracy (both axes)	$\pm .5°$
Position readout accuracy (both axes)	.1 m rad

5.2.2 SIZING

Since the physical size of the display subsystem not only largely determines the overall size of the IRSS but also strongly influences the cost and design problems associated with each of the subsystems components, it is important that this size be kept to a minimum. In assessing the impact of several design variables on size, it develops that since the sensor pupil diameter and display window field are fixed, only two

PRIMARY MIRRORS

FOLDING
MIRRORS

DIMPLED
MIRROR

DISPLAY ARM

3.5°   3.5°

SEEKER

DISPLAY EXIT PUPIL

TARGET PROJECTION SUBSYSTEM
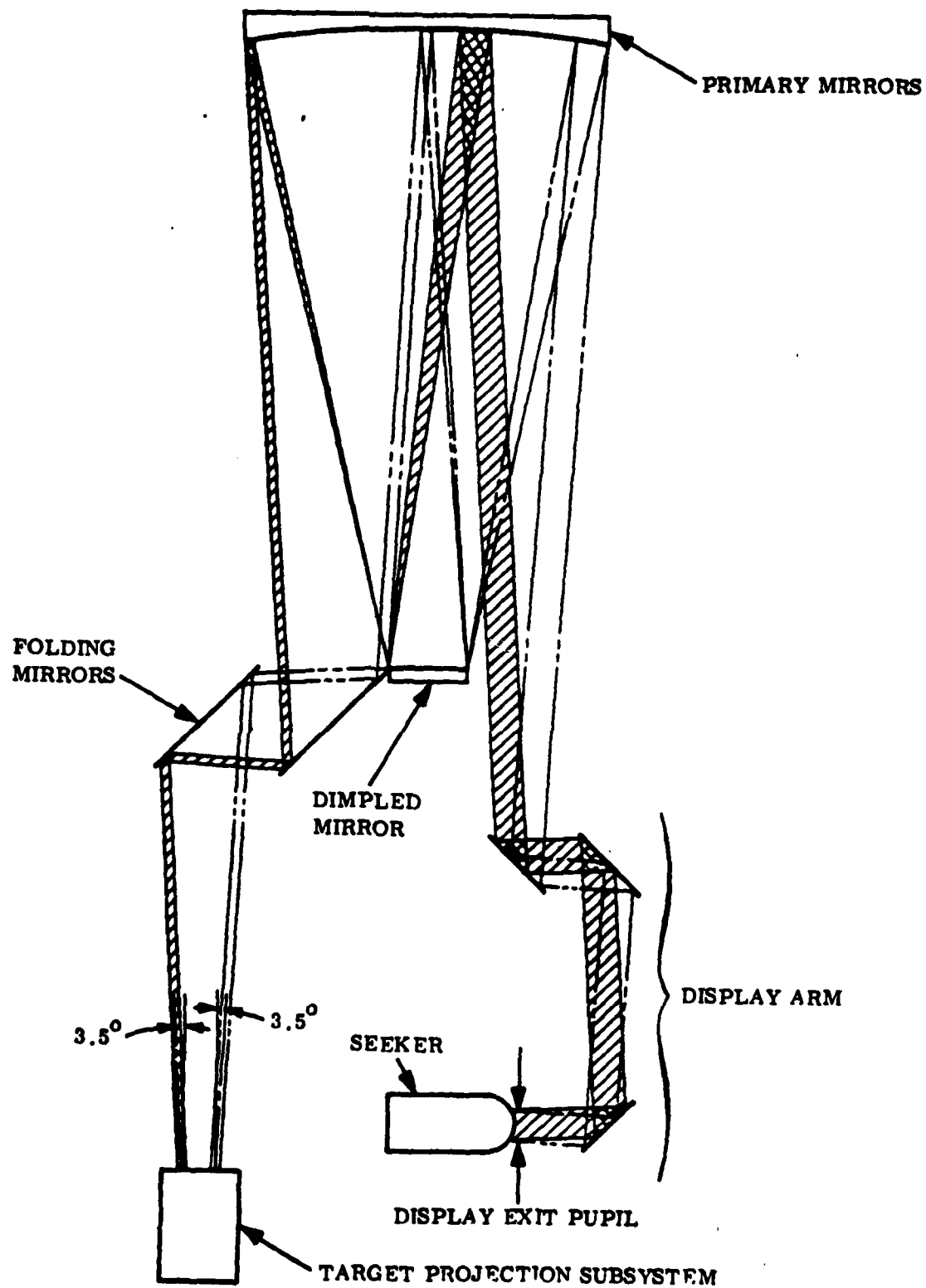
Figure 6-2. Display System - Optical Layout

parameters have any effect. They are the vertical clearance between the guidance unit mount and display arm (X), and the height of the arm's azimuth hub (H). These parameters as well as all of the important component dimensions are shown schematically in Figure 5-3. In determining these values, X was required to be 52 inches because of the guidance unit mount size and H was assumed to be 30 inches, the amount required for hub height, structure, and dimpled mirror mounting.

Some explanation should be given here for showing the display exit pupil diameter (Dp) as a dependent variable since the seeker pupil is fixed at 5 inches. Because mirror #1 of the display arm must move translationally as display window elevation changes, the seeker is not always at a position conjugate to the display entrance pupil but, in effect, is being moved along the display optical axis as shown in Figure 5-4. The seeker pupil must be conjugate to the display entrance pupil at the 0° elevation position; hence, the exit pupil must be large enough to prevent vignetting at ±30° elevation. Additionally, the vertical dimension of the exit pupil must be increased by some amount to allow for tracking errors in the vertical translation mechanism. This error will have no effect on the display window's angular position since angular motion is provided by a separate mechanism, but would cause vignetting if not accounted for. As a practical compromise between additional size and servo complexity, it was decided to increase this dimension by .5 inches to allow for a ±.25 inch tracking error.

5.2.3 OPTICAL DESIGN

5.2.3.1 Blur Caused by Collimating Optics

Before moving to the detailed design of the individual mirrors, with specification of the manufacturing tolerances, we must first determine what aberrations are inherent in the spherical system. A generalized skew ray trace computer program was used for these calculations. To determine what calculations are really necessary, we can refer to Figure 5-5. The primary and secondary mirrors are spherical with a common center of curvature at point CC. Since the system is completely symmetric about point CC, we may consider any ray leaving the entrance pupil at some angle $\theta \neq 0$ as being an axial ray (i.e., parallel to the optical axis) in a system that has been rotated by θ. Thus, all rays are axial rays and aberrations are independent of field angle.

The display entrance pupil, as explained in 5.2.1, is 6.44 inches in diameter and centered 18.83 inches above the optical axis. A meridional ray trace (i.e., a trace of rays lying in the Y-Z plane of Figure 5-5) of a system having a 250 inch radius primary and a 125 inch radius secondary yielded a meridional blur of 1.4 mrad. as shown in Figure 5-6. If we look at only those rays of interest (i.e., those rays passing through the entrance pupil), we can consider the output beam as having a 0.89 mrad blur with a 0.95 mrad offset. This offset is equivalent to a position error and can be removed by adjusting mirror 4 or 5. The blur, however, is clearly too large and must be reduced. It was discovered that by increasing the secondary's radius of curvature while maintaining concentricity, this could be

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D_{PM} (37.6 IN.) $\qquad$ D_{PM} MIRROR NO. 6

R_p (250 IN.)

PS (37.66 IN.)

MIRROR NO. 5
(125 IN.)

(21.80 IN.)
D_H

MIRROR NO. 4

(26.9 IN.) D_4

(15.36 IN.)

H
(30 IN.)

D_5 (32.0 IN.)
MIRROR NO. 5

MIRROR NO. 2
(ELLIPSE)

(14.52 IN. X 21.16 IN.)

D_{PM} = primary mirror dia.

R_P = primary mirror rad.

D_{SM} = secondary mirror dia.

R_S = secondary mirror rad.

PS = pupil separation

D_H = clear hub dia.

H = hub height

X = guidance unit mount clearance height

Y = display arm offset

D_P = pupil dia.

θ = field angle

L_i = mirror length

W_i = mirror width

D_4 = folding mirror dia.

D_5 = folding mirror dia.

MIRROR NO. 3
(ELLIPSE)
(6.65 IN. X 24.15 IN.)

X (52 IN.)

$\theta/2$
(3.5°)

(6.44 IN.) D_P

MIRROR NO. 1
(ELLIPSE)
(7.55 IN. X 15.83 IN.)

Y
(17.25 IN.)

Figure 5-3. Display Subsystem

PATH DIFFERENCE $= \Delta = $ Y (SEC 30° + tan 30°–1)
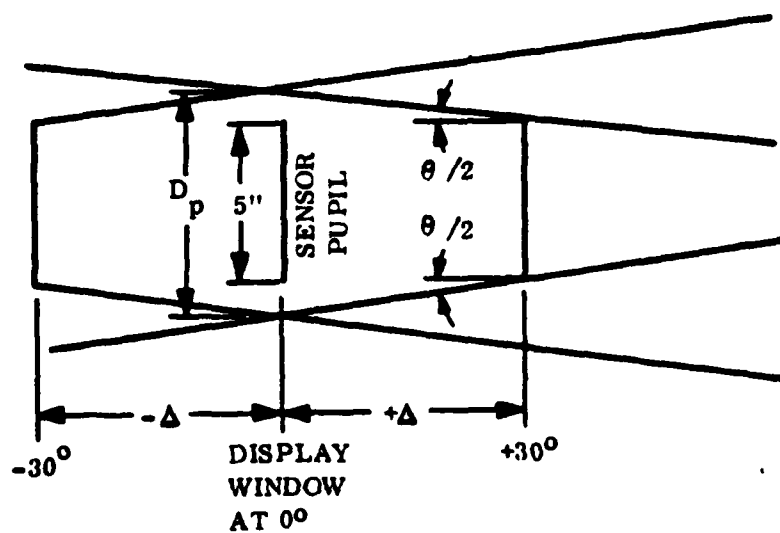
$$D_P = 5" + 2 \Delta \tan \theta /2$$

Figure 5-4. Display Pupil Diameter

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TOP VIEW

C.C.

SIDE VIEW

C.C.

PRIMARY MIRROR

DISPLAY ENTRANCE PUPIL

DISPLAY EXIT PUPIL

C.C.

Z

Y

X
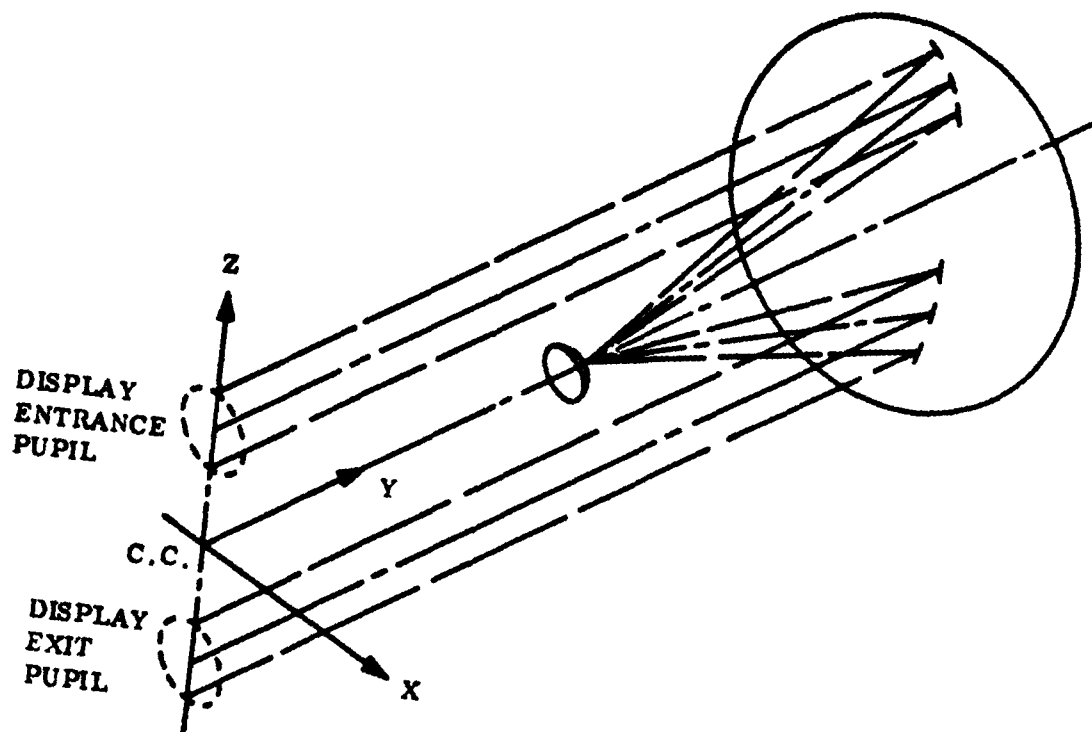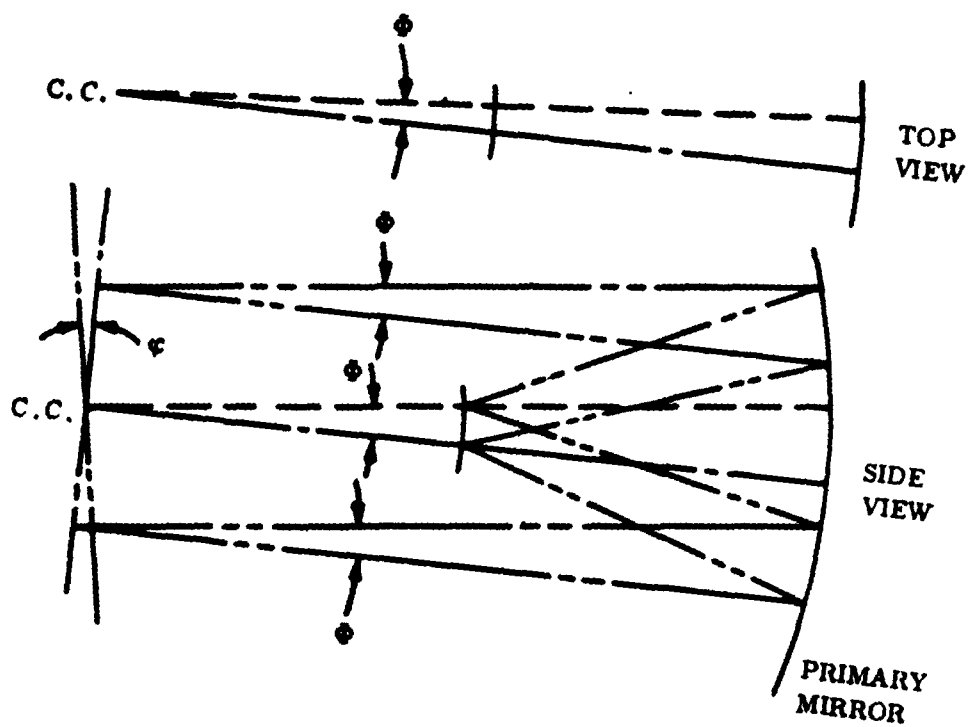
Figure 5-5. Collimating Optics
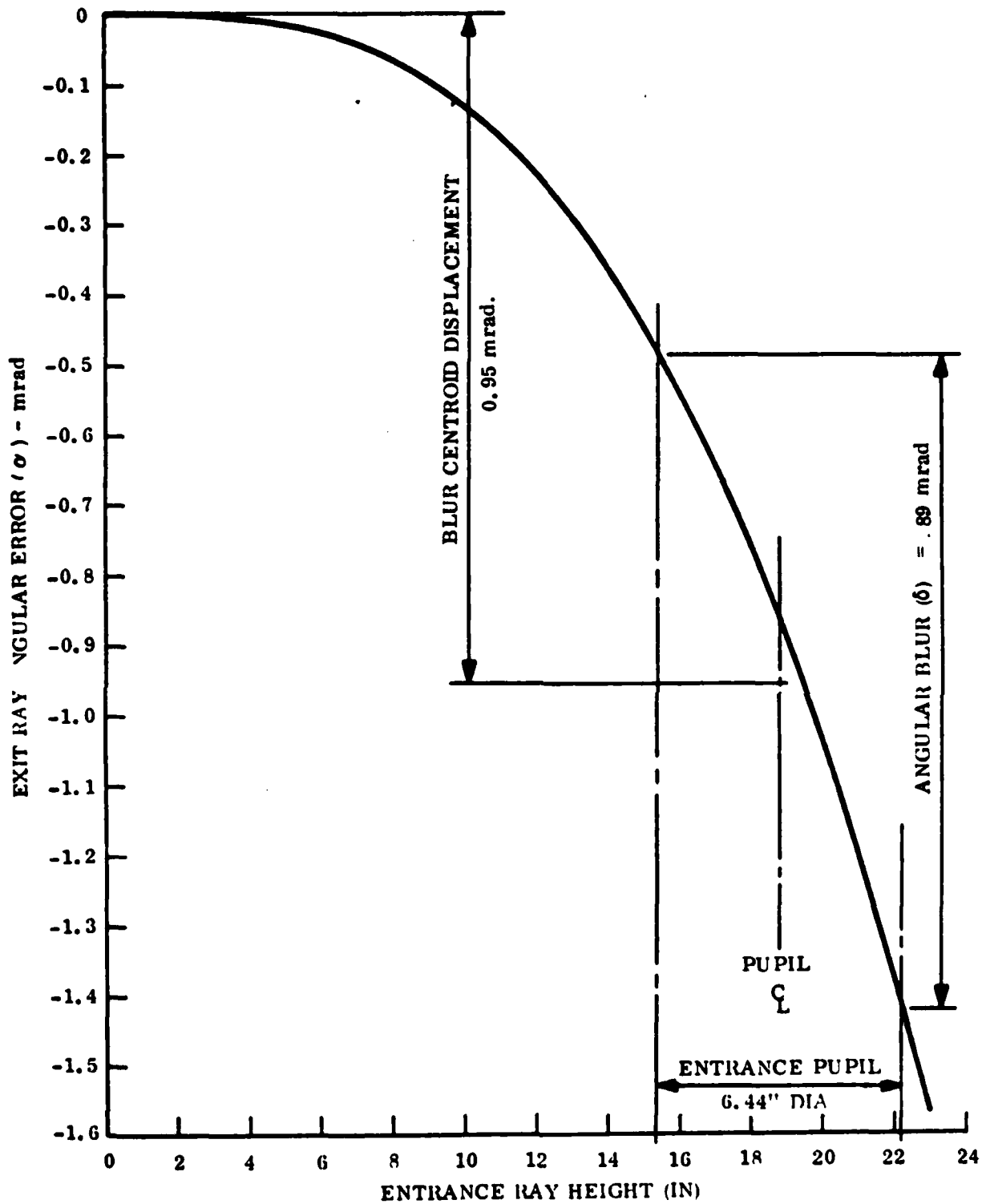
Figure 5-6. Meridional Exit Ray Angular Error vs Ray Height
for R_p = 250 Inch, R_s = 125 Inch

achieved. In Figure 5-7, output ray angular errors (α) are plotted against ray height for various secondary mirror radii. It would appear that a radius of 126.1 inches, with a .095 mrad blur (δ) and 1.75 mrad offset, is the optimum solution. This, however, is not quite true if we look at transverse blur in the X direction. We must, therefore, consider rays originating on the perimeter of the entrance pupil. This is done most simply by rotating the meridional plane by an angle Υ until the point of interest lies in that plane at some height (h) above the optical axis. The output angular error (α) calculated previously can now be broken into is X and Z components as shown in Figure 5-8. Obviously, α_x will be a minimum when α is smallest, but not (as it turns out) when δ is a minimum. The ideal solution, therefore, is to find a value for Rs where the vertical diameter (δ) and the horizontal diameter ($2\alpha_x$ max) are equal.

For a given Rs, α_x will be at a maximum when Υ is a maximum. This will occur when the meridional plane is tangent to the entrance pupil circumference as shown in Figure 5-8.

δ is plotted against $2\alpha_x$ max (diameter of the transverse blur) in Figure 5-9 for various values of Rs. Clearly, a secondary mirror radius of 125.7 inches will be the best solution, yielding the .3 mrad diameter blur circle shown in Figure 5-10. As stated earlier, the offset of .755 mrad is constant and can be removed by adjusting mirror 4 or 5.

5.2.3.2 Mirror Design

There are eight mirrors in the display subsystem, as shown in Figure 5-3. Five of the mirrors (i.e., numbers 1 through 5) are plane surfaces and are used for folding the optical path. Mirrors 6 (two required) and 7 are spherical elements. Image blur caused by the manufacturing tolerances of such elements can be reduced to almost zero if one is willing to pay the cost. It is our desire to arrive at a compromise between cost and performance to assure the most cost-effective system. There exists a degree of surface accuracy below which no significant cost advantage is gained because it is obtained with normal optical shop practice. After lengthy discussion with several vendors, this break point was identified and is reflected in the following specifications.

All mirrors will have a reflective aluminum coating with a protective overcoating of silicon monoxide. Aluminum was chosen because of its high reflectivity in the .3 to 5 micron region and its high durability. Each mirror will be supported by a 3-point kinematic mount which permits angular alignment and allows for differential thermal expansion between mount and mirror. Included in Appendix C is GE Drawing No. 47R196990 which shows one of the mounting points with its adjustment screw and safety latch.

Since mirrors 1, 2, and 3 are mounted on the display arm, it is desirable to minimize their weight and hence their effect on arm load inertia. For high quality flat
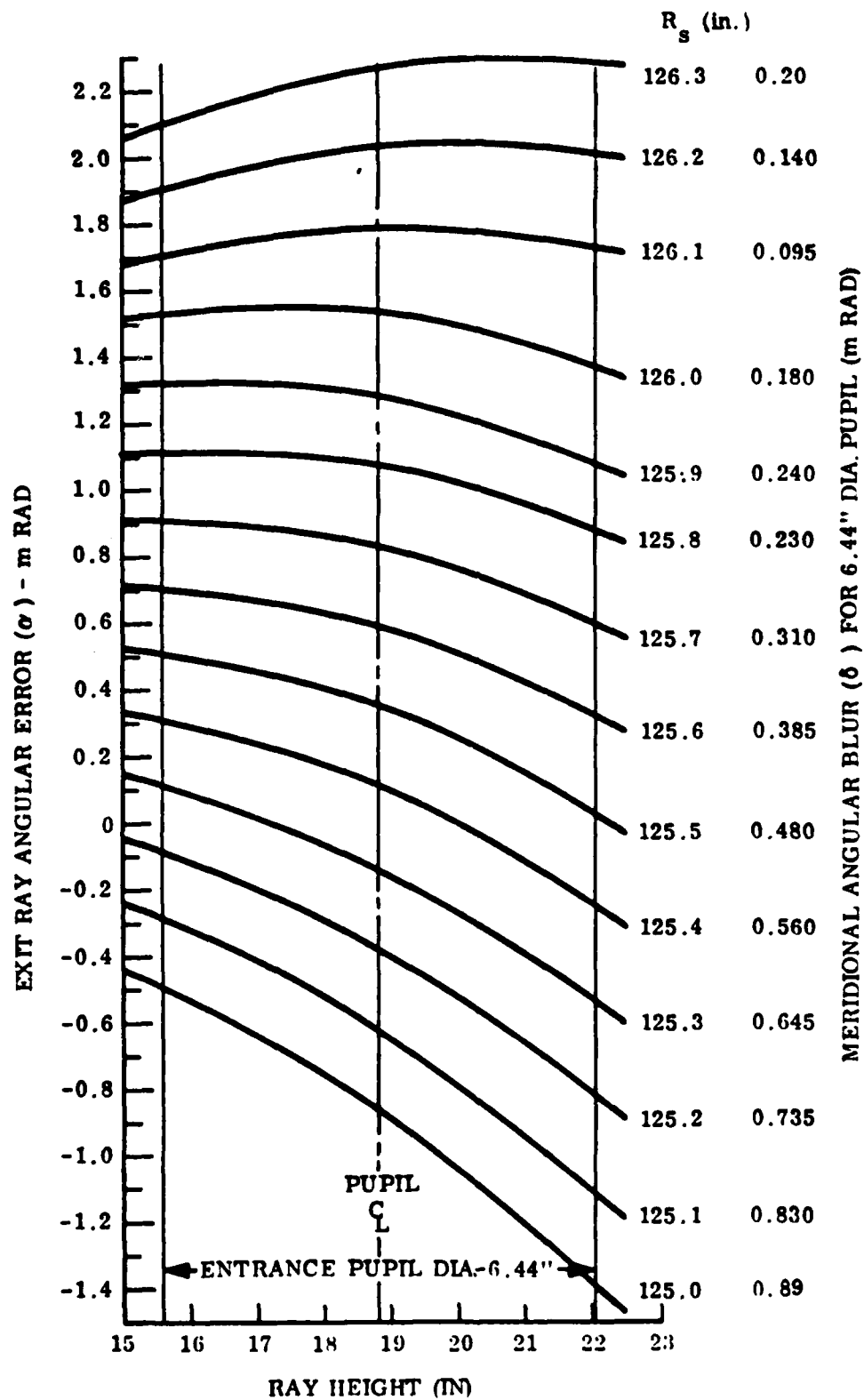
Figure 5-7. Meridional Angular Blur vs
Ray Height

MERIDIONAL
ANGULAR ERROR $= \alpha$

$\alpha_X = \alpha \sin\psi$

$\alpha_Z = \alpha \cos\psi$

ENTRANCE
PUPIL

6.44"

MERIDIONAL
PLANE
ROTATED
BY ψ°

h

18.83"

ψ

ψMAX $= 9^\circ$ 51'

OPTICAL
AXIS INTO
PAPER

Z

X
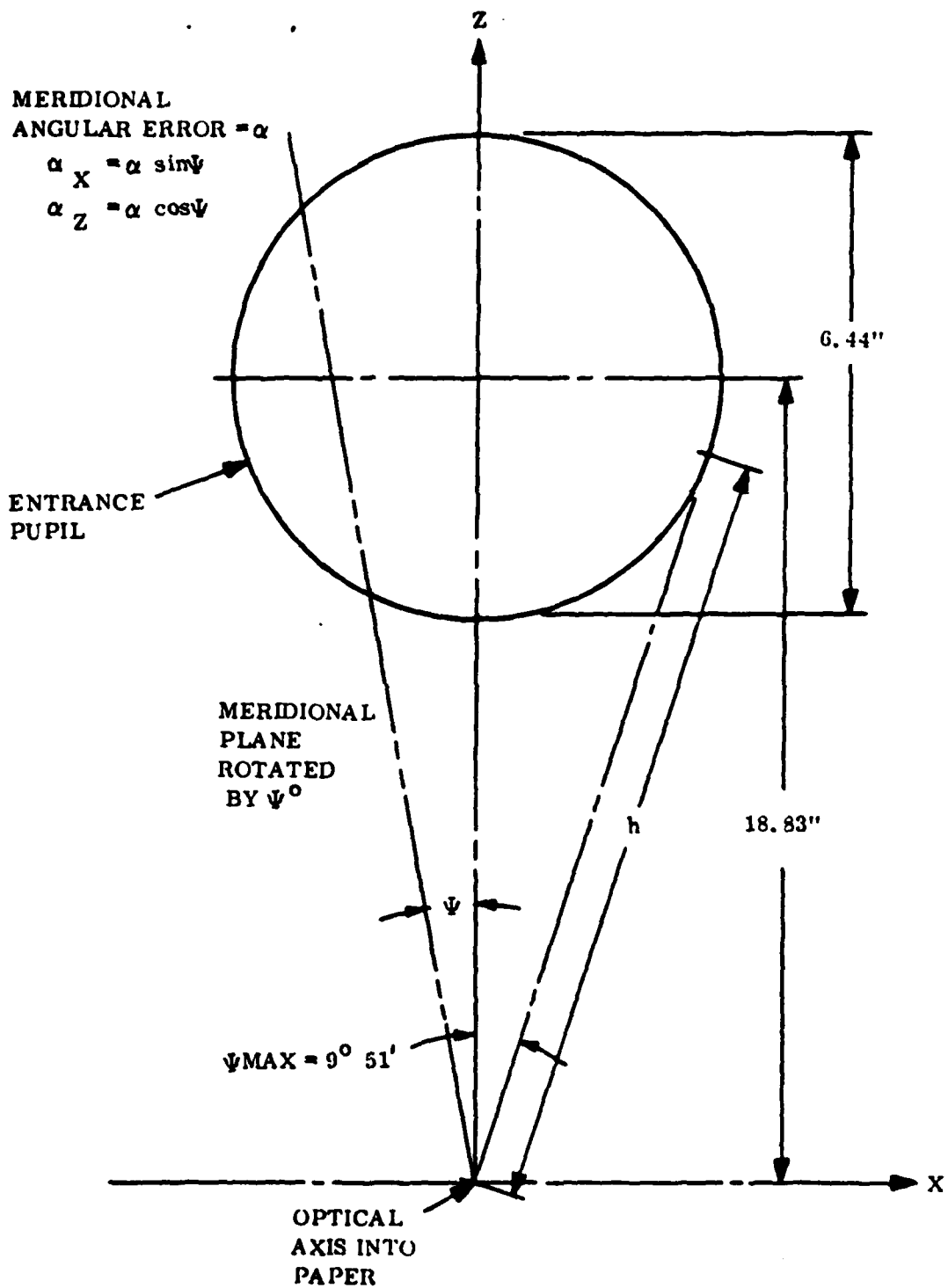
Figure 5-8. Entrance Pupil

61
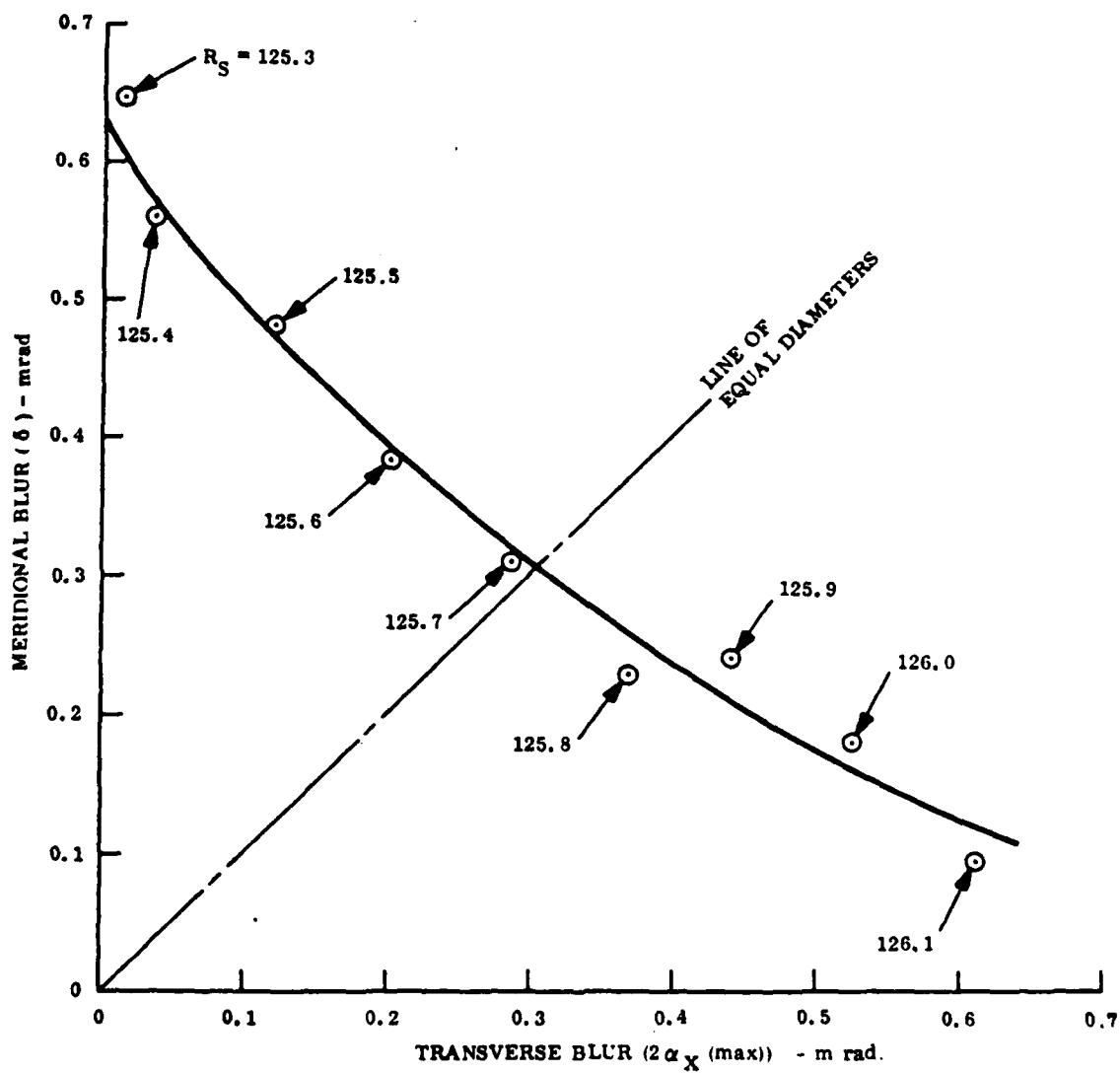
Figure 5-9. δ vs 2α$_x$ (max)
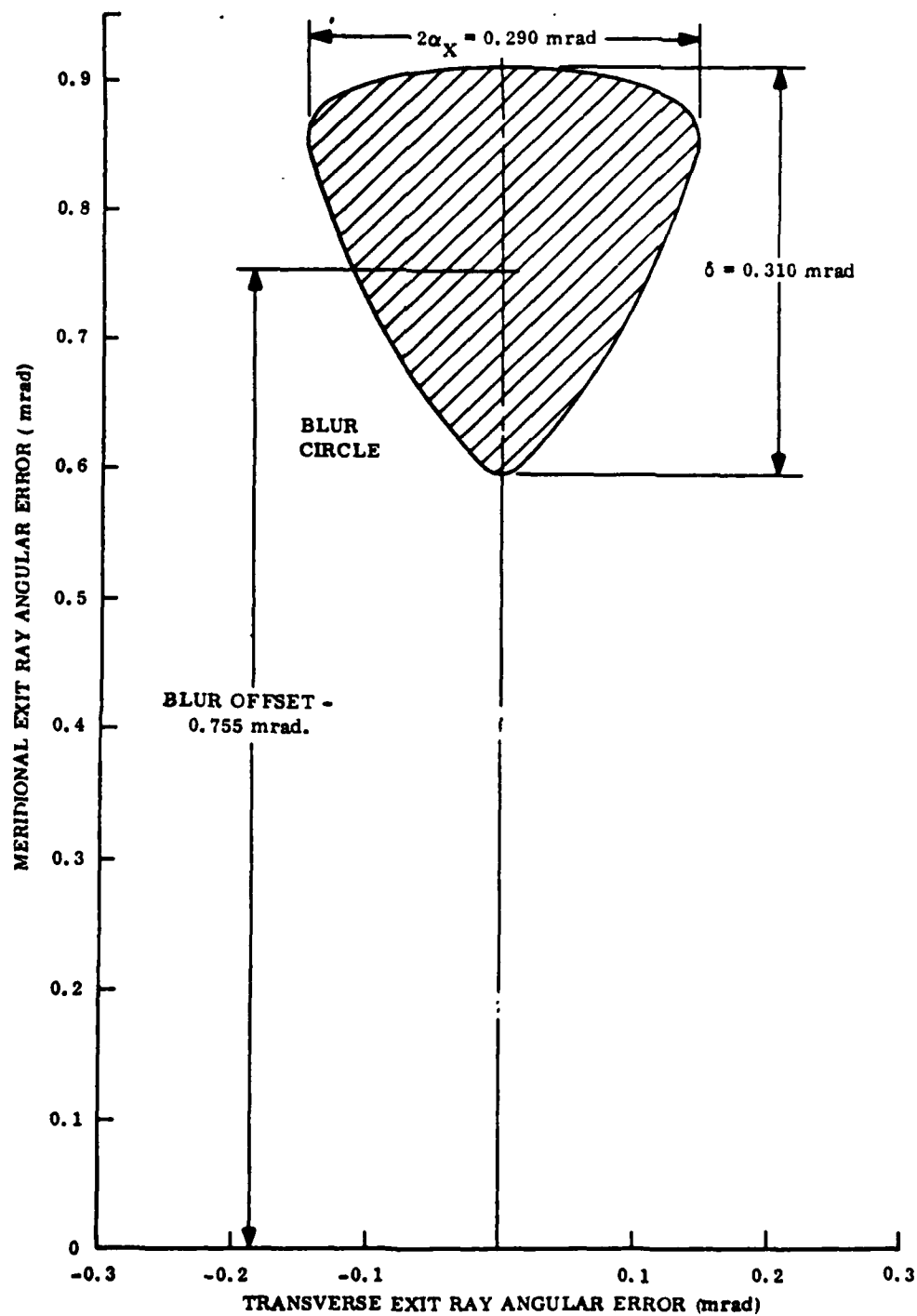
Figure 5-10. Blur Circle Due to Collimating Optics

glass mirrors, the thickness is usually given as 1/6 the longest dimension. This, however, would yield extremely heavy mirrors. By using light-weight glass fabrications, weight can be removed while maintaining performance, but at increased cost. To keep the cost increase to a minimum, we will use the rather simple technique of coring out slugs of glass from the back face, thus increasing effective stiffness while decreasing weight. Also, on all mirrors, the surface flatness tolerances have been specified in such a way as to minimize cost and weight while meeting system requirements. Thus mirrors 4, 5, and 6 can have length-to-thickness ratios of 10.

Table 5-3 shows the performance specifications for all display subsystem mirrors. The effect on image blur of slope errors caused by residual sphericity and surface irregularity is treated in Section 5.2.3.3. The referenced GE drawings are included in Appendix C.

TABLE 5-3. DISPLAY SUBSYSTEM MIRROR SPECIFICATIONS

Mirror No.	Weight of Conventional Fabrication (lbs)	Weight of Light-Weight Fabrication (lbs)	Residual Sphericity ($\lambda = .5\,\mu$)	RMS Slope Error Caused by Surface Irregularity (radians)	GE Drawing Number
1	22	9	1.5 λ	2×10^{-6}	47D178914
2	60	20	1.5 λ	2×10^{-6}	47D178910
3	84	35	1.0 λ	2×10^{-6}	47D178912
4	170	NA	.5 λ	2×10^{-6}	47D178946
5	280	NA	.5 λ	2×10^{-6}	47D178947
6	420	NA	NA	2×10^{-6}	47D178918
7	31	NA	NA	3×10^{-6}	47D178948

5.2.3.3 Blur Caused by Manufacturing Tolerances

The total blur (β_M) caused by manufacturing tolerances of the display subsystem mirrors is given by

$$\beta_M = \sum_{i=1}^{5} \gamma_{s_i} + \left[\sum_{i=1}^{6} \gamma^2_{RMS_i} \right]^{1/2}$$

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where

γ_s = angular blur due to sphericity of the mirror

γ_{RMS} = root mean square value of angular blur caused by random irregularity of the surface

The angular deviation of the output ray due to sphericity is given by

$$\gamma_s = \frac{8\delta}{r}$$

where δ and r are defined in Figure 5-11. Also shown in this figure is the computation of γ_{s_i} for each mirror and the summation of these values. An admittedly conservative approach was taken here in assuming that all of the errors have the same algebraic sign. In actual practice, this should not be true and the total error should be something less than that shown.

The contribution caused by surface irregularity will be extremely small. The RMS slope error is 2×10^{-6} radians, and the output ray deviation will be twice this. Thus,

$$\sum_{i=1}^{6} \gamma_{RMS_i}^2 = \left[6 \times 16 \times 10^{-12} \right]^{1/2} = 9.8 \times 10^{-6} \text{ radians}$$

The total angular blur due to manufacturing tolerance is then calculated to be:

$$\beta_M = 7.6 \times 10^{-5} + .98 \times 10^{-5} \text{ radians}$$

$$\beta_M = 8.6 \times 10^{-5} \text{ radians}$$

5.2.3.4 Dimpled Mirror Design

The dimpled mirror design is rather straightforward in that only two parameters need be calculated (i.e., dimple diameter – d, and dimple radius – r).

d must be 1/4 to 1/3 of the optical resolution, which is given by

$$\delta = 1/4 \ F\beta$$

where F is the primary mirror focal length and β is the permissible angular blur. F is 125 in. and β is 1×10^{-3} radians; therefore,

$$\delta = .030 \text{ in.}$$

$$\epsilon = \frac{2\delta}{r}$$

$$\gamma_S = \frac{8\delta}{r}$$
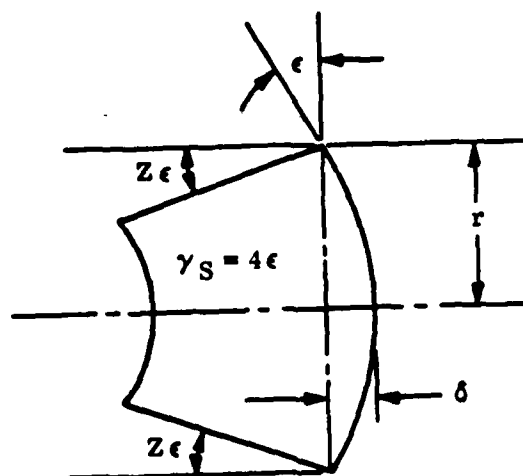
MIRROR#	r (IN.)	δ (IN.)	γ_{S_i} (radians)
1	7.9	3×10^{-5}	3.0×10^{-5}
2	10.6	3×10^{-5}	2.2×10^{-5}
3	12.1	2×10^{-5}	1.3×10^{-5}
4	13.4	1×10^{-5}	0.6×10^{-5}
5	16	1×10^{-5}	0.5×10^{-5}

$$\sum_{i=1}^{5} \gamma s_i = 7.6 \times 10^{-5}$$

Figure 5-11. Blur Caused by Sphericity of the Plane Display Mirror

r is defined by

$$r = \frac{2 \delta F}{D + d}$$

where D is the required system exit pupil diameter (6.44") and d, which is determined in the next Section, is the diameter of the smallest circle inclosing all of the directional mirror centers (5.20"). Therefore, r = 0.65".

The dimpled mirror is a field element and has no effect on image quality; thus, the surface quality and dimple accuracy need only be those required for proper light distribution.

5.2.4 DISPLAY ARM MECHANICAL DESIGN

5.2.4.1 Functional Description

As explained earlier in Section 3.2.2.4, the display window motion will be provided by an articulated display arm as shown in Figure 5-12. The azimuth drive is rather straightforward in that a hollow hub with a remote drive must be provided. The elevation drive mechanism is somewhat more complicated. Both rotary and translational motion must be provided, and several possible solutions exist. It is also important that the arm be as compact as possible at the bottom so that its effect on guidance unit mount size is minimized.

It is required that all of the drive mechanisms as well as the structure be extremely stiff. The 16 bit optical encoder needed to measure the display arm's azimuth position must be mounted on the drive motor output shaft rather than on the driven hub. For this reason, deflections in the drive belt as well as tangential and torsional deflections of the arm structure add to target position error and must be kept below 5×10^{-5} radians total.

In the elevation direction, the arm structure itself serves as the ground point reference for the 16 bit optical encoder used to measure elevation mirror tilt angle. In this case, any axial runout of the azimuth bearing, radial deflection of the arm structure, or angular error introduced by the mirror translation mechanism will add to the target position error; thus, it must be kept below 5×10^{-5} radians also.

5.2.4.2 Azimuth Drive

The display arm must be cantilevered from the top so that it is physically separate from the guidance unit mount while sharing the same azimuth axis. The possibility of supporting the lower end of the arm on a bearing mounted at the bottom of the guidance unit mount yaw yoke was considered, but rejected because of increased size and cost of the Guidance Unit Mount and because of serious potential vibration, alignment, and disturbance torque problems expected from the mechanical coupling

ELEVATION MIRROR

MISSILE

+90°

−90°

DISPLAY WINDOW
AZIMUTH CONTROL

INPUT

DISPLAY ARM
STRUCTURE

AZIMUTH
AXIS

MISSILE

+30°

−30°

ELEVATION MIRROR

DISPLAY
WINDOW
ELEVATION
CONTROL
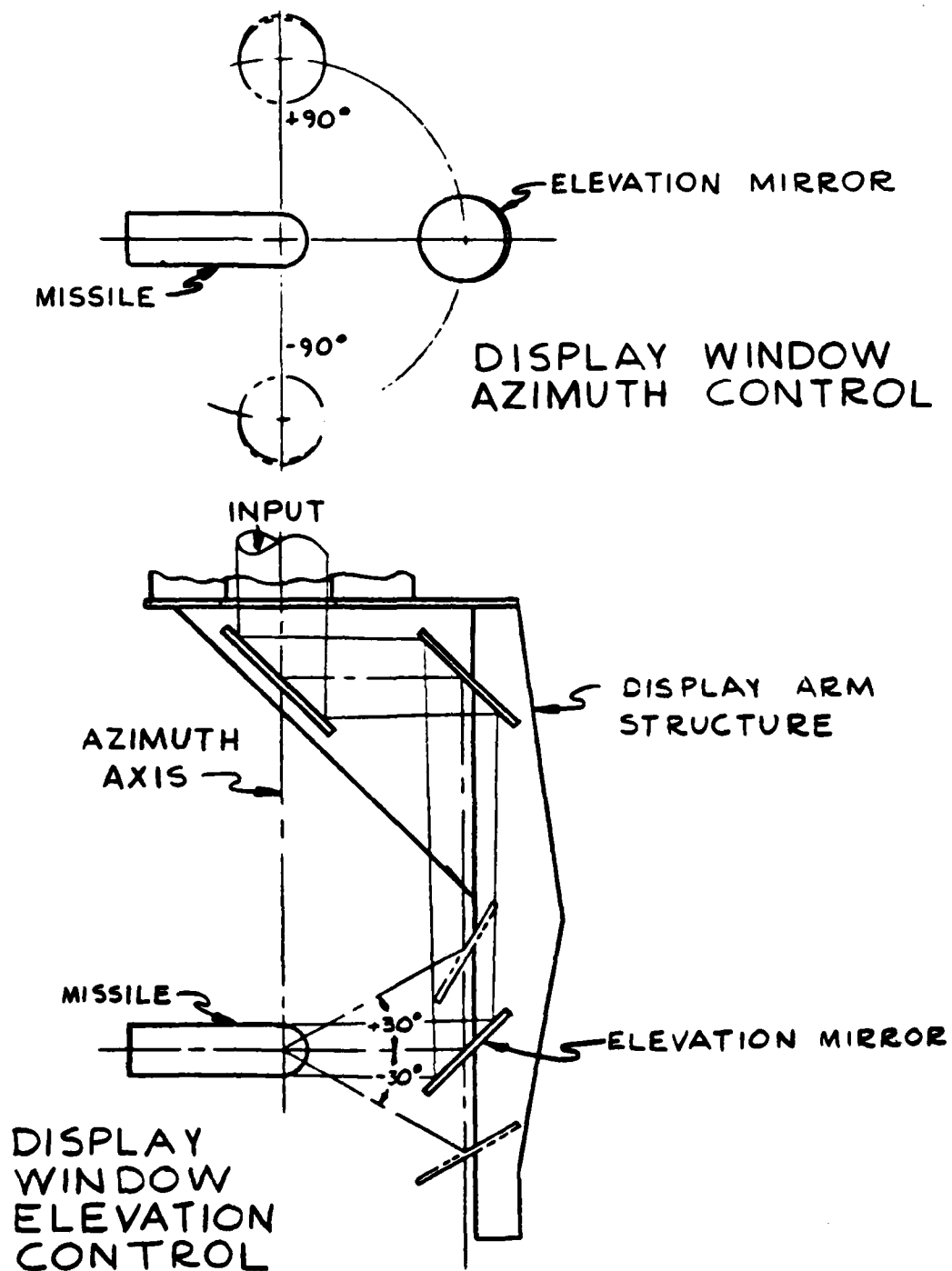
Figure 5-12. Display Arm Configuration

of the two. The cantilever configuration with the resulting overturning moment acting on the hub bearings will not be a problem, however, because a bearing large enough to accommodate a 20.5" inside diameter hub is designed to take loads many times greater than will be imposed by the display arm.

To keep the bearing axial runout on the order of 2.5×10^{-5} radians, a total indicated runout of less than 3×10^{-4} inches is required; thus indicating a bearing of precision class 5. In order to maintain the low rate torque ripple of the azimuth drive at a minimum level while also keeping bearing deflections to a minimum, a selection of two angular contact bearings in a preloaded back-to-back configuration was made. Other bearing types considered were the four-point contact bearing and the "x" roller bearing.

Principal reasons leading to the selection of the angular contact bearing were that 1) pre-loading significantly reduces deflection and 2) angular contact bearings are more tolerant of preload (which intensifies starting and ripple torque problems) than are the other bearing configurations.

The drive train will consist of a pulley driven by a D.C. torquer and connected to the display arm hub with a high stiffness, high fatigue life copper-beryllium belt. The belt will be fastened to each pulley to eliminate slippage and preloaded to eliminate backlash. Beryllium copper alloy was chosen as the drive band material because of its high yield strength and fatigue limit. This material is also more easily heat-treated than steel since its hardness is obtained by precipitation at low temperatures. Steel has a slightly higher modulus of elasticity (an advantage in avoiding resonance problems) but not enough to outweigh beryllium copper's other advantages.

The band is sized to have a mechanical resonance frequency of greater than 5 times the servo bandwidth of 10 Hz in order to prevent any interaction between these elements. The angular position error (ϵ) caused by strain in the drive belt is given by

$$\epsilon = \frac{I \, \alpha \, L}{2R^2 AE}$$

where

I = load inertia (3.17×10^3 slug in^2)

α = Maximum acceleration (7 rad/sec^2)

L = Length of one belt (4 ft)

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R = Hub radius (12 in.)

A = Belt cross sectional area (6" x .080" = 4.8 x 10^{-1} sq. in.)

E = Young's Modulus of belt material (2 x 10^7 psi for Copper-Beryllium)

Thus, ϵ equals 3.2 x 10^{-5} radians. The display arm assembly (G.E. drawing number SK56205-538) is included in Appendix C.

5.2.4.3 Elevation Drive

The elevation mirror must undergo vertical translational as well as rotary motion. The requirements are that the linear travel (x) be related to the tilt angle (α) by x = y tan 2α, where y is the display arm offset (17.25 in.).

If a single servo motor is to provide both linear and rotational motion, some type of cam or crank-follower mechanism such as that shown in Figure 5-13 would be required. The crank-follower technique would use a four-bar linkage to provide the vertical reference for a sixteen-bit shaft encoder used to measure mirror tilt. The reference link must remain vertical to within less than the 10^{-4} radian resolution capability of the encoder. Because of other error sources in the system, such as display arm bending and bearing play in the display arm hub, the actual tolerance should be less than 3 x 10^{-5} radian. If a 10 inch reference bar is used, then the shaft-hole clearance at each pin joint must be less than 1.3 x 10^{-4} inches. Also,
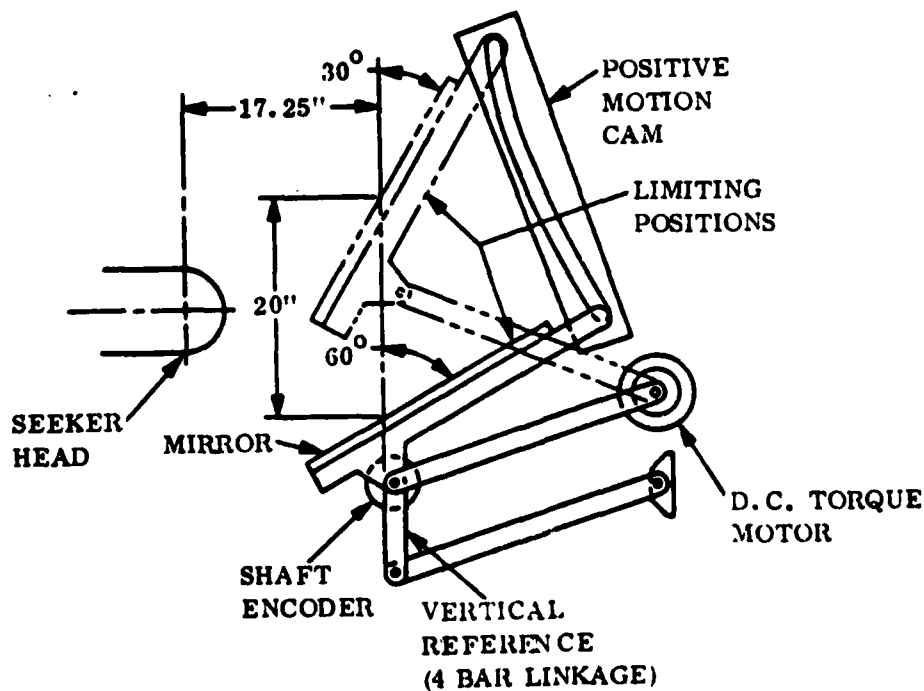
Figure 5-13. Crank-Follower Elevation Drive Mechanism

a layout of the system showed that the line of action of the follower is almost perpendicular to the cam at low elevation angles. For these and other reasons, an alternate approach, using a slider-guide mechanism as shown in Figure 5-14, was also considered. A comparison of this class of mechanism with the crank-follower is given in Table 5-4. The comparison clearly favors the slider-guide mechanism and this approach has been selected for implementation. Several available implementation schemes are compared in Table 5-5.

As for the mirror elevation drive system, it was decided to use a metal belt and pulley arrangement, thus avoiding the dead weight and backlash associated with a geared system or the high rotational speeds which would be necessary if a nut and lead screw were used. The metal band system keeps the c.g. of the vertical drive mechanism high in the display arm, thus minimizing kinetic deflections of the structure.

TABLE 5-4. COMPARISON OF SLIDER - GUIDE & CRANK
FOLLOWER MECHANISMS

| Characteristic | MECHANISM | |
	Crank - Follower	Slider - Guide
Vertical reference for position encoder	Moving	*Stationary
Type of guideways	Positive motion cam	Vertical guide
Producibility of guideway	Complex curves are difficult to machine and grind to required accuracies.	*Straight guides easily machined with conventional techniques to required accuracies.
Impact on horizontal cross-section of display arm	Long lever arms (>20") require large separation of guidance unit mount yaw gimbals.	*Display arm is horizontal; cross section is compact.
Position of heavy components in display arm (which can cause deflections)	Below elevation mirror	*Above or at the same level as elevation mirror.
Number of servos	*1	1 or 2, depending on implementation

*Most desirable
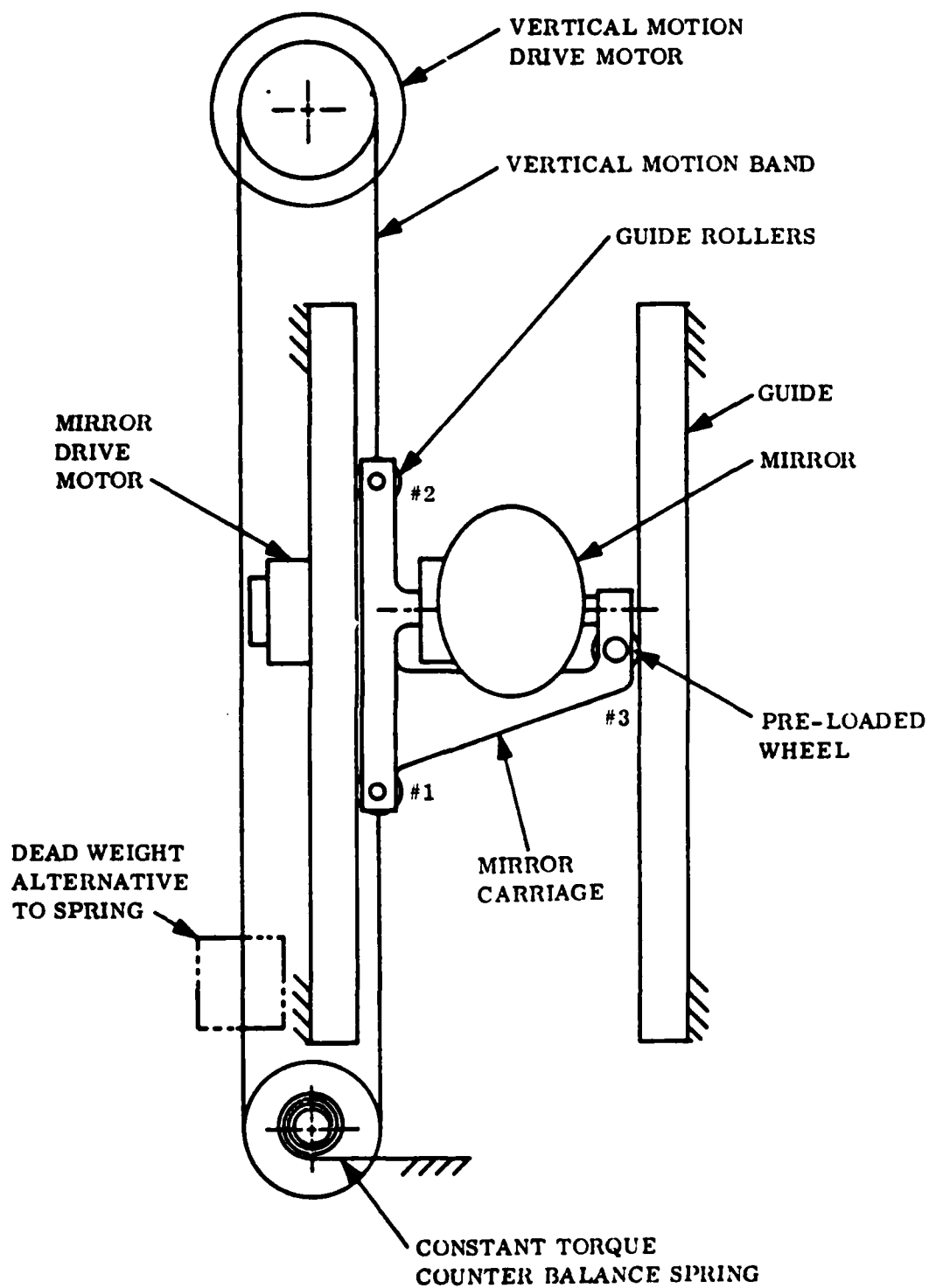
Figure 5-14. Slider-Guide Elevation Drive Mechanism

TABLE 5-5. IMPLEMENTATION OPTIONS FOR SLIDER – GUIDE MECHANISM

Linear Motion Drive			Angular Motion Drive		
Option	Characteristic	Compatible With Indicated Rotation Drive(s)	Option	Characteristic	Compatible With Indicated Linear Drive(s)
*(1) Metal belt	Drive motor at top of display arm; good compatibility with mechanism; mechanical resonance must be considered.	A, B	*(A) Direct servo drive	Good compatibility with mechanism; excellent position accuracy is possible; fewest mechanical fabrication problems.	1,2,3
(2) Gearing	Simple rack and pinion drive; backlash is problem area although vertical position accuracy requirements are low. Vibration and motor placement are major problems.	A,C	(B) Differential belt	Will require cam or second servo to produce X=Y tan 2X motion	1
(3) Lead screw	35"/sec linear velocity requires 3×10^{-1} rpm motor or gearbox output for 16 threads/inch screw; heavy components located below mirror.	A	(C) Cam	Good compatibility but mechanical tolerances could create problems of mirror rotation accuracy.	2

*Selected approach

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The vertical position of the elevation mirror controls only the vertical coincidence of the display exit pupil and seeker entrance pupil, and has no effect on target angular position. As stated earlier, the exit pupil has been enlarged by .5 inches to provide for any such errors. One problem does occur, however, and that is mechanical resonance. This is avoided by using a 4" wide by .016" thick copper-beryllium band whose length is equal to the required stroke. The resulting resonant frequency of 70 Hz is then safely above the 11 Hz servo bandwidth.

It has been decided that in view of the low fatigue life of such counterweight components as the Hunter "negator" spring and their large overall size, a simple dead weight system will be used.

The vertical guide rails on which the mirror carriage will ride consist of two fully supported ground circular bars as shown in GE Drawing No. SK56205-538. A linear motion bearing assembly, such as that manufactured by SKF Industries and others, will be used to provide a three-point kinematic mount for the mirror carriage. The bearing rollers within this assembly will be preloaded to eliminate any running clearances, and, by maintaining adequate separation between rollers, the angular target position errors caused by straightness errors in the rails will be limited to 2×10^{-5} radians in azimuth and elevation. Any deviation of the rails from true vertical is compensated for in the initial alignment of the elevation mirror.

The elevation mirror rotary motion is obtained with a direct-drive D.C. torquer as shown in GE Drawing Number SK56205-534 (see Appendix C).

The carriage material requirement is for high modulus of elasticity together with low density, high yield, resistance to creep at room temperatures, and low thermal expansion. Magnesium, zinc, and aluminum alloys were considered. Magnesium alloy was chosen because while its lighter weight is offset by a lower modulus, it has a higher yield strength than aluminum in the annealed condition. This fully stress-relieved condition will eliminate creep after machining. Pressed-in threaded inserts will be used where necessary. Zinc alloys were found to be unsuitable because of their low strength characteristics.

5.2.4.4 Display Arm Structural Analysis

The structural design was dictated by several limitations imposed on the system. The design envelope, which was chosen to accommodate the guidance unit mount, imposes

the greatest design limitation. Weight was also a constraint inasmuch as it affects the motor selection. A final·necessary constraint was the restriction of structure in the optical path of the system.

The structural requirements which dictated design were angular deflections and natural frequencies. Allowable angular deflection of the display arm was selected to be 10^{-5} rad. This allows the maximum amount of tolerance for the bearings and other moving mechanisms. These tolerances are considered to be critical from a cost and assembly viewpoint. Natural frequency requirements were set at 100 cps. This is a conservative value assuring a negligible interference with the servo-mechanisms in the system.

Significant loads on the system reduced to the lateral g loads caused by angular acceleration and velocity of the system. The maximum angular acceleration of $400°/sec^2$ produces a g load of

$$G_T = \frac{\alpha r}{g}$$

where

G_T = tangential g load (g's)

α = angular acceleration (rad/sec^2)

r = radius to c.g. of component of interest

The maximum angular velocity of 100°/sec produces a g load of

$$G_R = \frac{\omega^2 r}{g}$$

where

G_R = radial g load (g's)

ω = angular velocity (rad/sec)

r = radius to c.g.

The arm structure was analyzed as a beam where the angular deflection under g load is given by

$$\theta = \frac{wGL^3}{6EI}$$

where

θ = angular deflection (radians)

w = weight per unit length of structures and components

L = length of arm (therefore, W=wL · total weight)

E = modulus of elasticity of structural material

I = inertia of cross section

For preliminary analysis the components and structure were considered as a distributed load along the structure. The component weight was estimated to be 80 lbs. The structural weight was estimated to be 1.6 lbs./in.

Angular deflection with the baseline design using magnesium as the structural material is given below:

$$\theta_T \text{ (due to } G_T) - \frac{2.6 \times .49 \times 80^3}{6 \times 6 \times 10^6 \times 1077} = 1.15 \times 10^{-5} \text{ rad}$$

$$\theta_R \text{ (due to } G_R) = \frac{2.6 \times .214 \times 40^3}{6 \times 6 \times 10^6 \times 185} = .835 \times 10^{-5} \text{ rad}$$

These values are within acceptable range of the limit set forth earlier of 1×10^{-5} rad.

Material selection was based on an idealized situation which for purposes of analysis is valid. The angular deflection of a beam is given by

$$\theta = \frac{WGL^2}{6EI}$$

Let

$$W = W_c + w'L$$

where

W_c = weight of components mounted on arm

$w'L$: $A\rho L$ = wt of structure only

where

ρ = density of structure material

A = cross-sectional area of structure

I = Ad^2; d is an arbitrary value

Substituting, we get

$$\theta = \frac{(W_c + w'L)\,GL^2}{6EAd^2}$$

As Lw' gets significantly larger than W_c, θ approaches

$$\theta = \frac{A\rho GL^3}{6EAd^2} = \frac{\rho}{6E}\,\frac{GL^3}{d^2}$$

Since E is approximately the same for all candidate materials (steel, magnesium, and aluminum), weight is minimized for the lightest weight structure. Since structural weight is significantly greater than component weight, it is advantageous to use magnesium.

Torsional stiffness and deflections were calculated for the arm. Stiffness requirements are determined by the equation

$$K = \frac{TL}{G\theta}$$

where

T = applied torque

L = arm length

G = shear modulus

K = torsional stiffness

θ = allowable deflection

The upper part of the arm is a box structure which is ideal for torsion. The lower portion is weak in torsion and analysis was restricted to it. The torque on the lower portion of the arm was approximated to be 150 in. lbs. The stiffness requirement under this torque is

$$KG = \frac{(150)\ (40)\ lb\text{-}in^2}{10^{-5}}$$

$$= 6 \times 10^8\ lb\text{-}in^2$$

The present structure is about 10% of this value. A 7 inch diameter steel tube 0.2 inch thick will meet the torsional stiffness requirements, but further analysis indicates that the torsional deflections actually produce a lead in apparent target angle which partially offsets the dynamic lag of the directional mirror servos. Torsional stiffness is, therefore, not a critical design parameter and will be considered only for its effect on torsional natural frequency which is approximately 125 Hz.

5.2.4.5 Display Arm Alignment

The general alignment procedures described earlier (Section 4.3) are to be used for fine tuning and general system checkout. Initially, however, the following procedure must be followed for alignment of the display arm azimuth hub and the display arm mirrors. During normal operation the hub alignment can be checked by examining the 20 second level attached to it, and any minor mirror misalignment is compensated for with easily accessible bias adjustments in the directional mirror controls.

Azimuth Hub Alignment Procedure

1. Mount an autocollimator below the azimuth hub and adjust it so that its axis is vertical to within ±10 seconds.

2. Temporarily mount an adjustable flat mirror to the inner race of the hub so that it is approximately perpendicular to the azimuth axis.

3. Rotate the display arm in azimuth and adjust the mirror so that the error sensed by the autocollimator is constant through an 180° rotation. The mirror is now perpendicular to the azimuth axis.

4. Adjust the hub mounting screws until the error sensed by the autocollimator is zero. The azimuth axis is now exactly vertical.

5. Mount a 20 second level to the hub structure and adjust the level until it reads zero error. The mirror and autocollimator are now removed and the level serves as the primary indicator of hub alignment.

Mirror Alignment Procedure

1. Move the display arm to the ±90° position and mount an adjustable flat mirror in the Guidance Unit Mount roll fixture so that it is approximately perpendicular to the roll axis.

2. Position an autocollimator in front of the mirror and adjust its axis to be horizontal to within ±10 seconds.

3. Rotate the GUM roll fixture and adjust the mirror so that the error sensed by the autocollimator is constant through 360° rotation. The mirror is now perpendicular to the roll axis.

4. Rotate the autocollimator in azimuth and the pitch gimbal in elevation until the error sensed by the autocollimator is zero.

5. Remove the autocollimator, place the elevation mirror in its support bracket, and return the display arm to the zero-zero position.

6. Mount the autocollimator above the elevation mirror, adjust its axis to within ±10 seconds of vertical, and adjust the elevation mirror until the autocollimator error is zero.

7. Repeat step 6 for each of the other display arm mirrors.

5.2.5 DISPLAY ARM SERVO ANALYSIS

5.2.5.1 Accuracy Requirements

Because the display window is one degree larger than the maximum seeker field of view, the azimuth and elevation tracking accuracies must be better than 0.5 degree. Considering the accuracy to which the seeker gimbal angles can be determined, and computational errors involved in transforming these angles from missile body angles to inertial angles, the dynamic lag errors must be less than .36 degrees. Other requirements are discussed in the following paragraphs.

5.2.5.2 Transformation of Seeker Line of Sight from Missile Body to Inertial Space

In the IRSS, the missile body axis is positioned in inertial space by the three-axis guidance unit mount. The seeker head is then set at some angle with respect to the missile axis.

In order to command a position for the display window in the simulator, it is necessary to determine the position of the seeker itself with respect to the inertial coordinates. The problem, therefore, is to determine two Euler angles, Ψ_c (the azimuth angle) and θ_c (the elevation angle), which define the position of the seeker head in inertial space. These two angles are found as functions of the three angles (Y, P, R) of the guidance unit mount, and the two Euler angles, α and β, by which the seeker head position is defined with respect to the missile coordinate system.

The angles, Ψ_c and θ_c, are solved for by transforming the seeker head axis back through its positioning angles, β and α, and the three angles of the three-axis gimbal, R, P, and Y, which results in the components of the seeker axis vector in the inertial system. If the seeker head is also transformed from its original position back through the unknown Euler angles, θ_c and Ψ_c, the components of the seeker axis vector are defined in the inertial frame in terms of θ_c and Ψ_c. The components of the seeker axis vector are then equated in the inertial frame for the two methods of transformation, thereby defining Ψ_c and θ_c in terms of α, β, Y, P, and R.

The position of the seeker with respect to the missile coordinate system is shown in Figure 5-15.

The missile coordinate system components of $\vec{S}$ are found by rotating $\vec{S}$ back through β and α:

$$\begin{bmatrix} S_{xm} \\ S_{ym} \\ S_{zm} \end{bmatrix} = [\alpha][\beta] \begin{bmatrix} S_{xs} \\ S_{ys} \\ S_{zs} \end{bmatrix}$$

Substituting the pitch and yaw Euler matrices for β and α, respectively, results in:

$$\begin{bmatrix} S_{xm} \\ S_{ym} \\ S_{zm} \end{bmatrix} = \begin{bmatrix} C\alpha & S\alpha & 0 \\ -S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\beta & 0 & -S\beta \\ 0 & 1 & 0 \\ S\beta & 0 & C\beta \end{bmatrix} \begin{bmatrix} S_{xs} \\ S_{ys} \\ S_{zs} \end{bmatrix}$$

$$\vec{S} = S_{x_m}\vec{i}_m + S_{y_m}\vec{j}_m + S_{z_m}\vec{K}_m$$

$$\text{also } \vec{S} = S_{x_s}\vec{i}_s$$
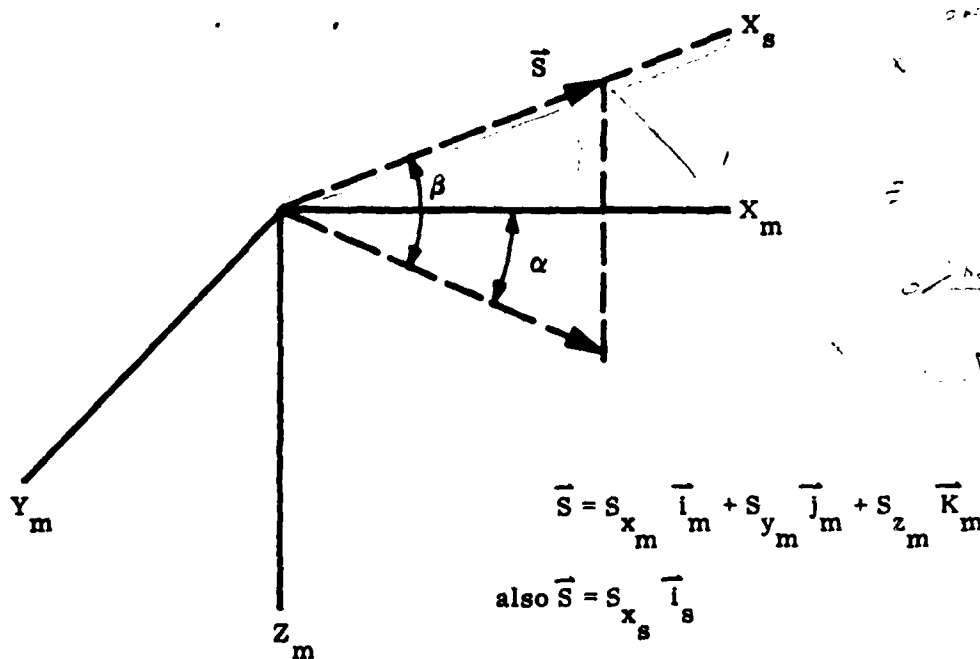
Figure 5-15.   Seeker Position with Respect to the Missile Coordinate System

or.

$$\begin{bmatrix} S_{xm} \\ S_{ym} \\ S_{zm} \end{bmatrix} = \begin{bmatrix} C\alpha \cdot C\beta & S\alpha & -C\alpha \cdot S\beta \\ -S\alpha \cdot C\beta & C\alpha & S\alpha \cdot S\beta \\ S\beta & 0 & C\beta \end{bmatrix} \begin{bmatrix} S_{xs} \\ S_{ys} \\ S_{zs} \end{bmatrix}$$

where

$S\alpha = \sin \alpha$, and $C\alpha = \cos \alpha$

$S\beta = \sin \beta$, and $C\beta = \cos \beta$

It must be noted that the Euler angles (β, α) through which $\vec{S}$ is rotated are negative angles.

Also for computational purposes $\vec{S}$ is defined as a unit vector.

$$|\vec{S}| = 1$$

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Therefore, the seeker head vector components expressed in the seeker's coordinate system are

$$
\begin{bmatrix} S_{xs} \\ S_{ys} \\ S_{zs} \end{bmatrix} = |S| \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}
$$

Substituting this result into the previous equation yields:

$$
\begin{bmatrix} S_{xm} \\ S_{ym} \\ S_{zm} \end{bmatrix} = \begin{bmatrix} \cos\alpha \cdot \cos\beta \\ -\sin\alpha \cdot \cos\beta \\ \sin\beta \end{bmatrix}
$$

which are the seeker vector components referred to the missile reference frame.

Next, the components in the missile reference frame are referred back to the inertial frame. This is done by rotating backwards through the three gimbal angles (R, P, and Y) as shown in Figure 5-16.
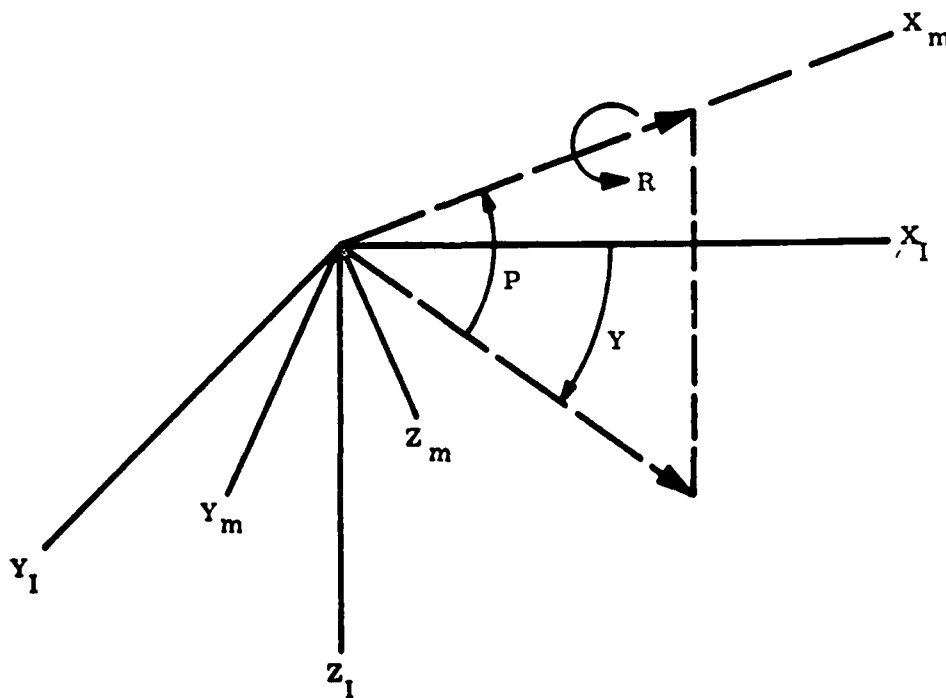
Figure 5-16. Rotation of the Missile Body by the Guidance Unit Mount

The Euler expressions of these transformations are:

$$\begin{bmatrix} S_{xI} \\ S_{yI} \\ S_{zI} \end{bmatrix} = [Y][P][R] \begin{bmatrix} S_{xm} \\ S_{ym} \\ S_{zm} \end{bmatrix}$$

Substituting the angles:

$$\begin{bmatrix} S_{xI} \\ S_{yI} \\ S_{zI} \end{bmatrix} = \begin{bmatrix} CY & SY & 0 \\ -SY & CY & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} CP & 0 & -SP \\ 0 & 1 & 0 \\ SP & 0 & CP \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & CR & SR \\ 0 & -SR & CR \end{bmatrix} \begin{bmatrix} S_{xm} \\ S_{ym} \\ S_{zm} \end{bmatrix}$$

$$\begin{bmatrix} S_{xI} \\ S_{yI} \\ S_{zI} \end{bmatrix} = \begin{bmatrix} CY \cdot SY \cdot CP & CY \cdot SY \cdot SP \cdot SR + SY \cdot CR & -CY \cdot SP \cdot CR + SY \cdot SR \\ -SY \cdot CP & -SY \cdot SP \cdot SR + CY \cdot CR & SY \cdot SP \cdot CR + CY \cdot SR \\ SP & -CP \cdot SR & CP \cdot CR \end{bmatrix} \begin{bmatrix} C\alpha \cdot C\beta \\ -S\alpha \cdot C\beta \\ S\beta \end{bmatrix}$$

Therefore, $\vec{S}$ expressed in the inertial frame is:

$$\begin{bmatrix} S_{xI} \\ S_{yI} \\ S_{zI} \end{bmatrix} = \begin{bmatrix} CY \cdot SY \cdot CP \cdot C\alpha \cdot C\beta \\ \quad -CY \cdot SY \cdot SP \cdot SR \cdot S\alpha \cdot C\beta - SY \cdot CR \cdot S\alpha \cdot C\beta \\ \quad -CY \cdot SP \cdot CR \cdot S\beta + SY \cdot SR \cdot S\beta \\ -SY \cdot CP \cdot C\alpha \cdot C\beta \\ \quad +SY \cdot SP \cdot SR \cdot S\alpha \cdot C\beta - CY \cdot CR \cdot S\alpha \cdot C\beta \\ \quad +SY \cdot SP \cdot CR \cdot S\beta + CY \cdot SR \cdot S\beta \\ \\ SP \cdot C\alpha \cdot C\beta \\ \quad +CP \cdot SR \cdot S\alpha \cdot C\beta \\ \quad +CP \cdot CR \cdot S\beta \end{bmatrix}$$

Again, the angles rotated through are negative angles.

The seeker head vector, $\vec{S}$, expressed in inertial coordinates through two Euler rotations, Ψ_c and θ_c, is shown in Figure 5-17. The direction of transformation also makes θ_c and Ψ_c negative angles.
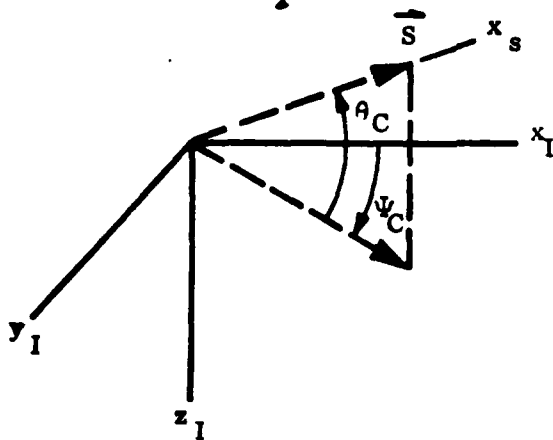
$$\left[S_I \right] = \left[\Psi_c \right] \left[\theta_c \right] \left[S_s \right]$$

Figure 5-17. Seeker Line of Sight in Inertial Coordinates

The Euler rotations are:

$$\begin{bmatrix} S_{xI} \\ S_{yI} \\ S_{zI} \end{bmatrix} = \begin{bmatrix} C\Psi_c & S\Psi_c & 0 \\ -S\Psi_c & C\Psi_c & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\theta_c & 0 & -S\theta_c \\ 0 & 1 & 0 \\ S\theta_c & 0 & C\theta_c \end{bmatrix} \begin{bmatrix} S_{xs} \\ S_{ys} \\ S_{zs} \end{bmatrix}$$

$$= \begin{bmatrix} C\Psi_c \cdot C\theta_c & S\Psi_c & -C\Psi_c \cdot S\theta_c \\ -S\Psi_c \cdot C\theta_c & C\Psi_c & S\Psi_c \cdot S\theta_c \\ S\theta_c & 0 & C\theta_c \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

and,

$$\begin{bmatrix} S_{xI} \\ S_{yI} \\ S_{zI} \end{bmatrix} = \begin{bmatrix} C\Psi_c \cdot C\theta_c \\ -S\Psi_c \cdot C\theta_c \\ S\theta_c \end{bmatrix}$$

Thus, we have two expression for the components of the vector, $\vec{S}$, expressed in the inertial frame. Equating these results in three simultaneous equations, which may be written as:

(1) $S\theta_c = SP \cdot C\alpha \cdot C\beta + CP \cdot SR \cdot S\alpha \cdot C\beta + CP \cdot CR \cdot S\beta$

(2) $-S\Psi_c \cdot C\theta_c = - SY \cdot CP \cdot C\alpha \cdot C\beta + SY \cdot SP \cdot SR \cdot S\alpha \cdot C\beta - CY \cdot CR \cdot S\alpha \cdot C\beta$
$$+ SY \cdot SP \cdot CR \cdot S\beta + CY \cdot SR \cdot S\beta$$

(3) $C\Psi_c \cdot C\theta_c = CY \cdot SY \cdot CP \cdot C\alpha \cdot C\beta - CY \cdot SY \cdot SP \cdot SR \cdot S\alpha \cdot C\beta - SY \cdot CR \cdot S\alpha \cdot C\beta$
$$- CY \cdot SP \cdot CR \cdot S\beta + SY \cdot SR \cdot S\beta$$

Since all angles involved are negative, we can replace:

$$\sin (-x) = -\sin (x)$$

and

$$\cos (-x) = +\cos (x)$$

and the solution then is for positive input angles. Substituting these relationships and solving for θ_c and Ψ_c:

(1) $\theta_D = \arcsin [SP \cdot C\alpha \cdot C\beta - CP \cdot SR \cdot S\alpha \cdot C\beta + CP \cdot CR \cdot S\beta]$

(2) $\Psi_D = \arcsin \left[\dfrac{\begin{array}{l} SY \cdot CP \cdot C\alpha \cdot C\beta + SY \cdot SP \cdot SR \cdot S\alpha \cdot C\beta + CY \cdot CR \cdot S\alpha \cdot C\beta \\ -SY \cdot SP \cdot CR \cdot S\beta + CY \cdot SR \cdot S\beta \end{array}}{C\theta_c} \right]$

Also:

(3) $\Psi_c = \arccos \left[\dfrac{\begin{array}{l} -CY \cdot SY \cdot CP \cdot C\alpha \cdot C\beta - CY \cdot SY \cdot SP \cdot SR \cdot S\alpha \cdot C\beta - SY \cdot CR \cdot S\alpha \cdot C\beta \\ -CY \cdot SP \cdot CR \cdot S\beta - SY \cdot SR \cdot S\beta \end{array}}{C\theta_c} \right]$

The display window azimuth (Ψ_c) and elevation (θ_c) commands must, therefore, be derived from rather involved transformations. The implementation of these transformation in the control console is discussed in Section 5.5.

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5.2.5.3 Display Azimuth Servo

5.2.5.3.1 Requirements and Design Rationale

The azimuth servo's position range is ± 90 degrees. The servo's bias plus dynamic lag error shall be less than 0.36 degrees. The servo must follow position commands that move with an acceleration of 400 deg/sec^2 up to a velocity of 100 deg/sec.

The azimuth servo's position must be sensed with an accuracy of 0.1 mrad (for a reference input to the directional servos) and velocity with a linearity of 5% (for recording target line of sight rate).

A 16 bit encoder senses azimuth servo position with an accuracy 0.1 mrad. The servo's compensation and open loop crossover frequency are selected to keep dynamic lag error plus the error caused by friction to less than 0.36 degrees.

A tachometer is used to limit servo azimuth velocities to low values during mode switching. This tachometer will also sense velocity with an linearity of 5% for recording purposes as required.

In order to insure that the servo's settling time is less than the time it takes its position command to reach a velocity of 100 deg/sec moving with an acceleration of 400 degree/sec^2, an open loop crossover frequency, ω_c, of 60 rad/sec. is selected. Assuming a reasonable setting time, t_s, of one-third the time it takes to reach the 100 deg/sec velocity, it follows that $t_s = 1/3\ (100/400) = 1/12$ sec. The relation between crossover frequency and settling time is approximately $\omega_c = 5/t_s$ and, therefore, the azimuth servo's crossover frequency is ω_c (5)(12) 60 rad/sec.

5.2.5.3.2 Component Definition

The azimuth servo motor load inertia is 20 slug ft^2. The motor is required to accelerate the load to 400 deg/sec^2 (7 rad/sec^2). An Inland (T-12008) 200 ft-lb motor is selected. An Inland Dual 1000A 1800 watt amplifier will be used with this motor.

A Wayne George (RA 16/555) 16 bit encoder is selected as the position sensor and an Inland TG2138 tach is selected as the velocity sensor.

The azimuth servo components are given in Figure 5-18.

5.2.5.3.3 Servo Amplifier Gains and Compensation Network Definition

The servo amplifier gains and compensation networks are given in Figure 5-18. The series compensation was chosen so that the open loop transfer function's crossover frequency is 60 rad/sec, as required, and the open loop gain (6000) is large enough to reduce the dynamic lag error below the 0.36 degrees required. The series

ENCODER
(W.G. RA16/555)
+
D/A CONVERTER

γ_c +

$0.02 \dfrac{V}{mrad}$

AMP + COMPENSATION

$660 \, V \dfrac{\left(\frac{s}{20}+1\right)\left(\frac{s}{70}+1\right)}{\left(\frac{s}{0.2}+1\right)\left(\frac{s}{600}+1\right)}$

PRE AMP
+
COMPENSATION
+
POWER AMP
("INLAND DUAL"
1000 A)

$370 \, V \dfrac{\left(\frac{s}{20}+1\right)}{\left(\frac{s}{1000}+1\right)}$

MOTOR (INLAND
T-12008)
+
LOAD

$\dfrac{667 \, mrad/sec}{s\left(\frac{s}{0.11}+1\right)\left(\frac{s}{120}+1\right)}$

γ

TACH
INLAND
TG2138

$0.0022 \dfrac{V}{m\frac{rad}{sec}} \, s$

Figure 5-18. Display Azimuth Servo Block Diagram

compensation's lag-lead network $\frac{(S/20 + 1)}{(S/0.2 + 1)}$ is needed to reduce the open loop gain to 0 db at the 60 rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response. The compensation's lead network $\frac{(S/60 + 1)}{(S/600 + 1)}$ cancels the closed tach loop transfer function pole at 60 rad/sec and replaces it with a pole at 600 rad/sec. This pole only adds 6 degrees of phase shift at the 60 rad/sec crossover frequency.

The tachometer feedback loop acts to increase the motor mechanical pole from 0.11 rad/sec to 60 rad/sec and the tach loop compensation $\frac{(S/120 + 1)}{(S/1000 + 1)}$ cancels the motor electrical pole at 120 rad/sec.

The open loop transfer function can be determined from Figure 5-18 by first determining the closed tach loop transfer function:

$$\frac{G}{1 + GH} = \frac{455}{S(S/60 + 1)(S/1000 + 1)}$$

and then multiplying all transfer functions. Neglecting the pole at 1000 rad/sec, the open loop transfer function is:

$$GOL = \frac{6000 (S/20 + 1)}{S (S/0.2 + 1) (S/600 + 1)}$$

5.2.5.3.4 Servo Performance

Since a 16 bit encoder (0.1 mrad/increment) is used as the azimuth servo angle error sensor and the azimuth servo torque disturbance response is less than 0.01 mrad/ft-lb. at all frequencies (see Figure 5-19), the servo bias error is less than 0.01 degrees.

The dynamic lag error, E, for an open loop transfer function, GOL, of the form $\frac{K (\tau_2 S + 1)}{S (\tau_1 S + 1) (\tau_3 S + 1)}$ is: $E = \frac{\dot{\psi}}{K} + \ddot{\psi} \frac{K (\tau_1 + \tau_3 - \tau_2) - 1}{K^2}$

where ψ is the servo input command and $\dot{\psi}$ and $\ddot{\psi}$ are the velocity and acceleration of this command, respectively.

Substituting the azimuth servo parameters into this formula results in a dynamic lag error of 0.35 degrees. Therefore, the azimuth servo meets its bias plus dynamic lag error requirement of less than 0.36 degrees.

Figure 5-19. Display Azimuth Servo Bode Diagram

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5.2.5.4 Display Elevation Servo

5.2.5.4.1 Requirements and Design Rationale

The elevation servo's position range is ± 15 degrees, and its bias plus dynamic lag error shall be less than 0.36 degrees. The servo must follow position commands that move with an acceleration of 200 deg/sec^2 up to a velocity of 50 deg/sec.

The elevation servo's position must be sensed with an accuracy of 0.1 mrad (for a reference input to the directional servos) and velocity with a linearity of 5% (for recording target line of sight rate).

A 16 bit encoder will sense elevation servo position with an accuracy 0.1 mrad as required. The servo's compensation and open loop crossover frequency are selected to keep the servo's dynamic lag error plus the error caused by friction to less than 0.36 degrees.

A tachometer is used to limit servo elevation velocities to low values during mode switching. This tachometer will also sense velocity with an accuracy of 5% for recording purposes as required.

In order to insure that the servo's settling time is less than the time it takes a position command to reach a velocity of 50 deg/sec moving with an acceleration of 200 deg/sec^2, an open loop crossover frequency, ω_c, of 60 rad/sec is selected. Assuming a reasonable settling time, t_s, of one-third the time it takes to reach the 100 deg/sec velocity, it follows that $t_s = 1/3 \frac{100}{(400)} = 1/12$ sec. The relation between crossover frequency and settling time is approximately $\omega_c = 5/t_s$ and therefore, the elevation servo's crossover frequency is $\omega_c = (5)\ (12) = 60$ rad/sec.

5.2.5.4.2 Component Definition

The elevation servo motor load inertia is 0.2 slug ft^2. The motor is required to accelerate the load to 200 deg/sec^2 (3.5 rad/sec). An Inland (T-2955) 0.85 ft-lb motor is selected.

An Inland 150A 150 watt amplifier is used with this motor.

A Wayne George (RA 16/555) 16 bit encoder is selected as the position sensor and an Inland TG 2138 tach is used as the velocity sensor.

The elevation servo components are given in Figure 5-20.

5.2.5.4.3 Servo Amplifier Gains and Compensation Network Definition

The servo amplifier gains and compensation networks are given in Figure 5-20. The series compensation was chosen so that the open loop transfer function's crossover

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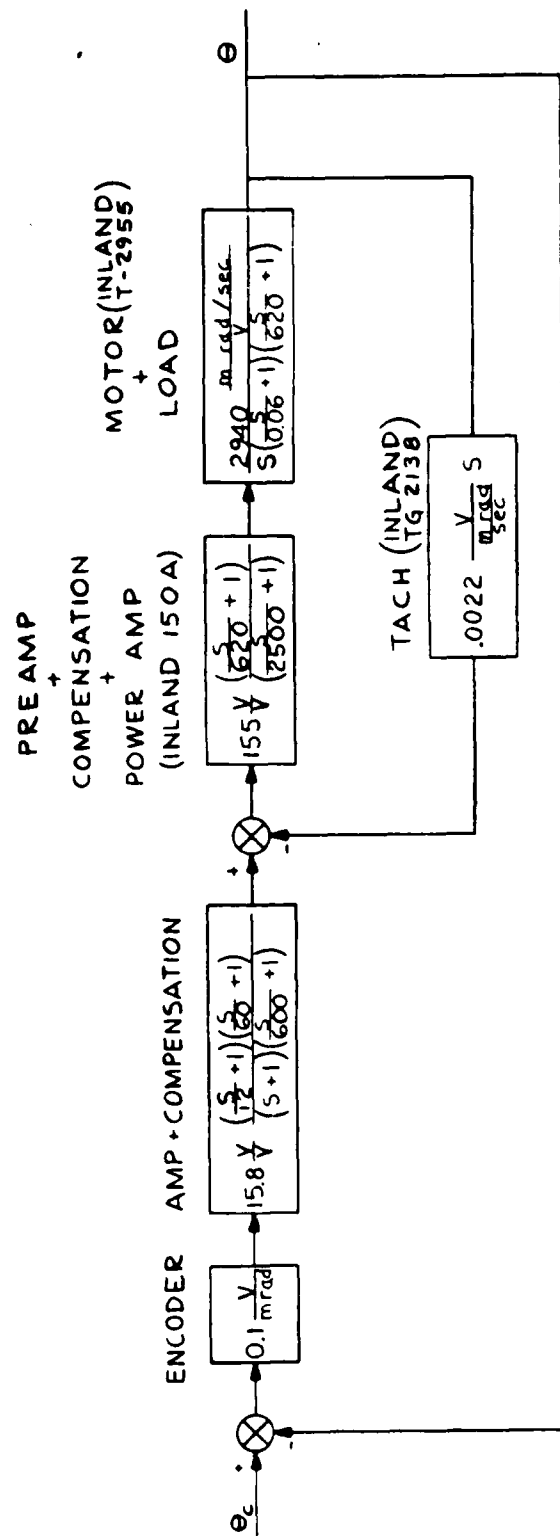
Figure 5-20. Display Elevation Servo Block Diagram

91

907

1.0

1.1

1.25

4.5
5.0
5.0

2.8

3.2

3.6

4.0

1.4

2.5

2.2

2.0

1.8

1.6
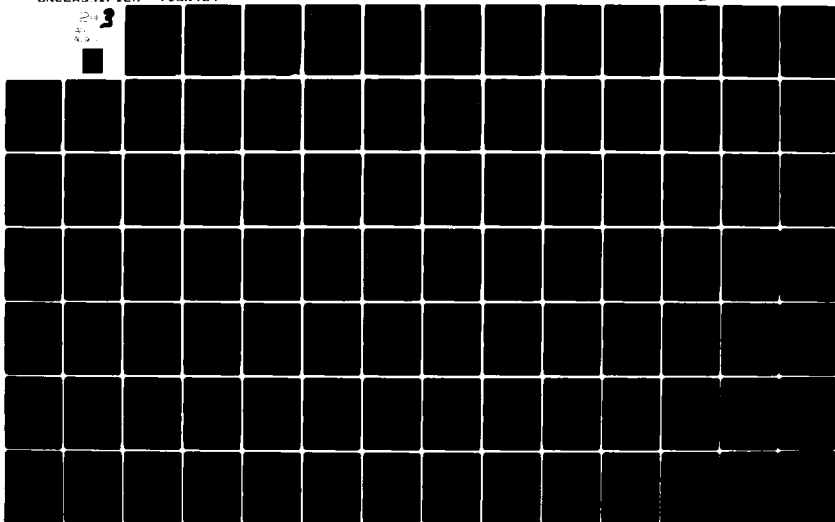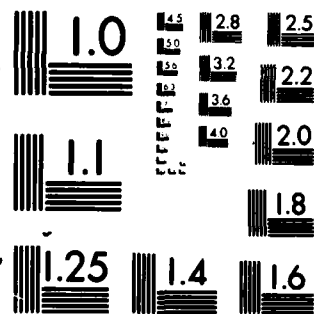
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

frequency is 60 rad/sec. as required, and the open loop gain (720) is large enough to reduce the dynamic lag error below the 0.36 degrees required. The series compe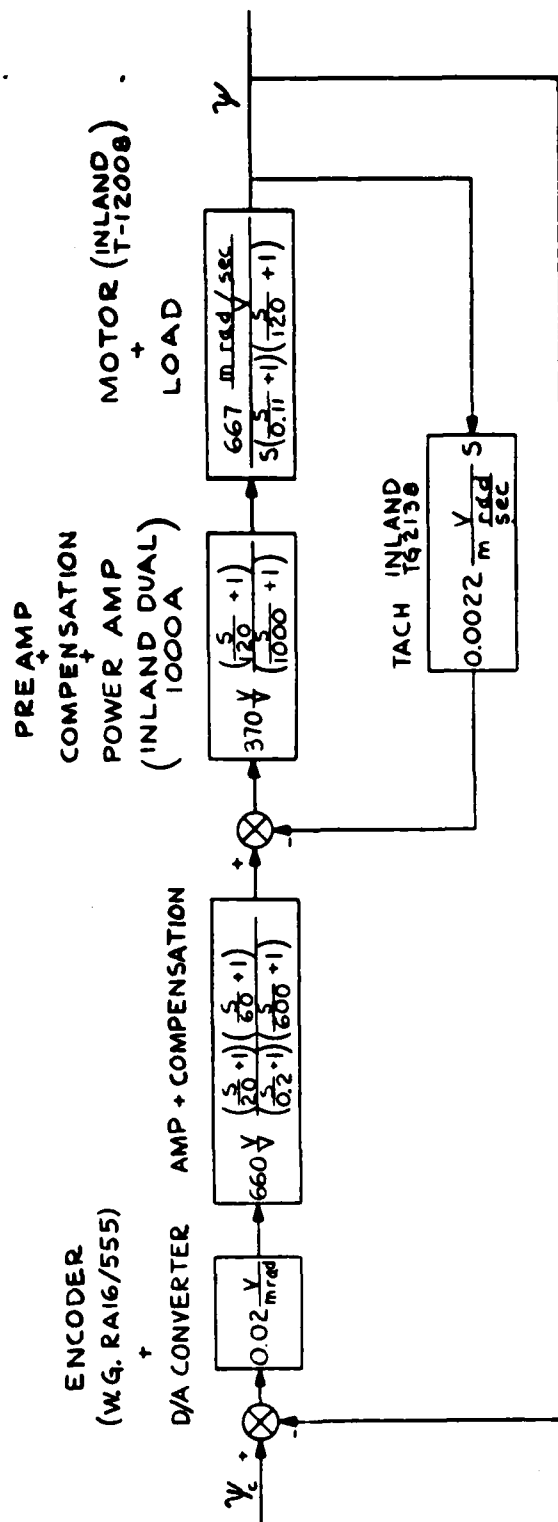nsation's lag-lead network $\frac{(S/12+1)}{(S/1+1)}$ is needed to reduce the open loop gain to 0 db at the 60 rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response. The compensation's lead network $\frac{(S/60+1)}{(S600+1)}$ cancels the closed tach loop transfer function pole at 60 rad/sec and replaces it with a pole at 600 rad/sec. This pole only adds 6 degrees of phase shift at the 60 rad/sec cross-over frequency.

The tachometer feedback loop acts to increase the motor mechanical pole from 0.06 rad/sec to 60 rad/sec and the tach loop compensation $\frac{(S/620+1)}{(S/2500+1)}$ cancels the motor electrical pole at 620 rad/sec. The open loop transfer function can be determined from Figure 5-20 by first determining the closed tach loop transfer function

$$\frac{G}{1+GH} = \frac{455}{S(S/60+1)\,(S/2500+1)}$$

and then multiplying all functions. Neglecting the pole at 2500 rad/sec, the open loop transfer function is:

$$GOL = \frac{720\,(S/20+1)}{S(S/0.2+1)\,(S/600+1)}$$

5.2.5.4.4 Servo Performance

Since a 16 bit encoder (0.1 mrad/increment) is used as the elevation servo angle error sensor and the elevation servo torque disturbance response is less than 0.01 mrad/in-oz at all frequencies (see Figure 5-21), the servo bias error is less than 0.01 degrees.

The dynamic lag error, E, for an open loop transfer function, GOL, of the form $\frac{K\,(\tau_2 S+1)}{S\,(\tau_1 S+1)\,(\tau_3 S+1)}$ is: $E = \frac{\dot{\theta}}{K} + \frac{\ddot{\theta}\,K\,(\tau_1 + \tau_3 - \tau_2) - 1}{K^2}$

where θ is the servo input command and $\dot{\theta}$ and $\ddot{\theta}$ are the velocity and acceleration of this command, respectively.

Substituting the elevation servo parameters into this formula results in a dynamic lag error of 0.35 degrees. Therefore, the elevation servo meets its bias plus dynamic lag error requirement of less than 0.36 degrees.
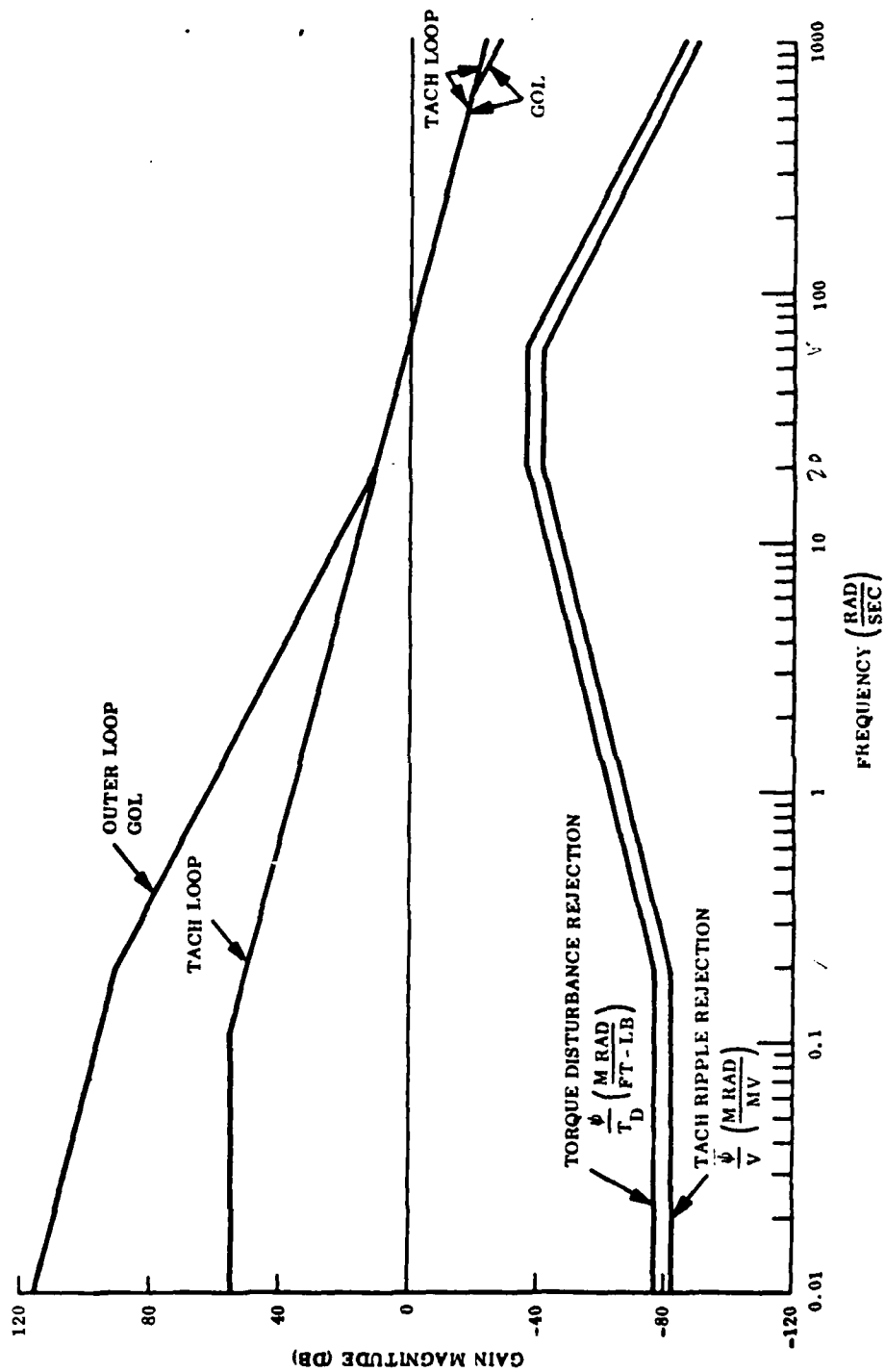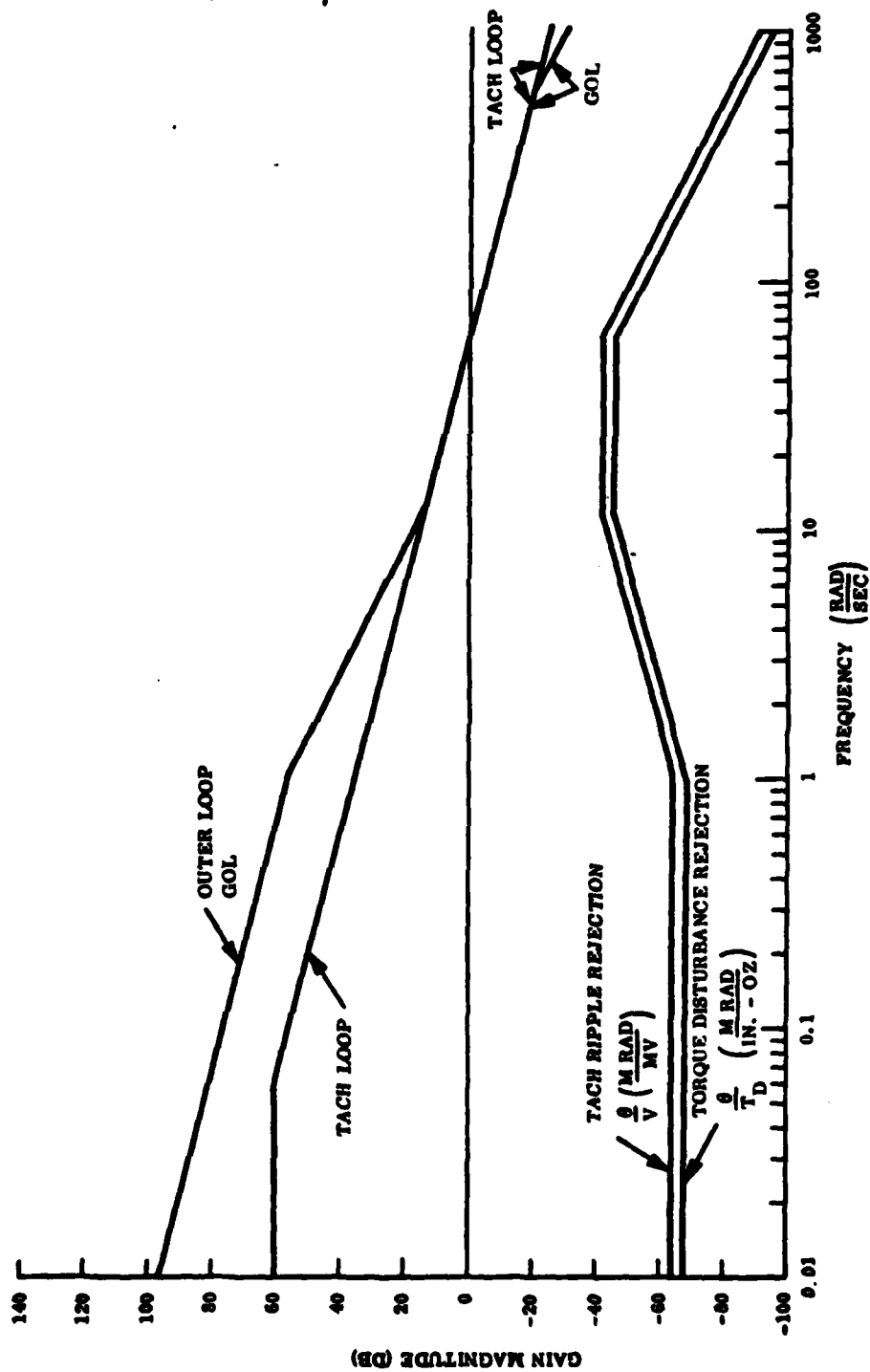
Figure 5-21. Display Elevation Servo Bode Diagram

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5. 2.5.5 Vertical Drive Servo

5. 2.5.5.1 Requirements and Design Rationale

The vertical ... servo's position range is ±9.9 inches and the total servo error is ... less than 0.25 inches. This servo must follow vertical drive commands ... move with ... acceleration of 170 ins/sec² up to a velocity of 37 ins/sec.

A vertical ... sensor with an error of much less than 0.25 inches is selected.
The servo ... ... and open loop crossover are selected to keep the servo
dynamic ... ... the servo errors caused by friction to less than 0.25 inches.

An open loop ... frequency, ω_c, of 70 rad/sec has been selected because this
servo must ... command that moves with an acceleration of 170 ins/sec² up to
a velocity ... ... ec. Assuming a reasonable settling time, t_s, of one-third the
time it take ... the 37 ins/sec velocity, then it follows that $t_s = 1/3 \, (37/170) =$
.0725 sec. ... in the previously used relation between crossover frequency
and settling ... $/t_s = 70$ rad/sec. This same rationale was used in selecting
the maximum ... ... servos' open loop crossover frequency.

5.2.5.5.2 ... ... finition

The vertical ... ... motor load inertia and load friction torque are estimated to
be 72 s... ... -lb., respectively. The motor is required to accelerate
the load to ... 170 in/sec² times a 1/6 rad/in linear-to-rotational motion
belt scale ... ... -lb. Inland (T-10036) DC torque motor can overcome this
load friction ... this load to the 28.4 rad/sec² required.

An Inland ... ... power amplifier will be used with this motor.

A 0.1% Max ... ... tiometer directly coupled to the motor shaft and operating
throughout ... degrees (±9.9 inches times a $\frac{57.3}{6.45}$ deg/in belt scale factor)
will provide ... tion accuracy of .058 inches.

An Inland ... ... he used to limit the vertical servo drive rates to low
values dur ... ... g. This tach will also reduce servo errors caused by
friction.

The vertical ... ... mponents are given in Figure 5-22.

5.2.5.5.3 ... ... Gains and Compensations Network Definition

The ... ... and compensation networks are given in Figure 5-22. The
servo ... ... son so that the open loop transfer function's crossover
frequency ... required, and the open loop gain (1630) is large enough

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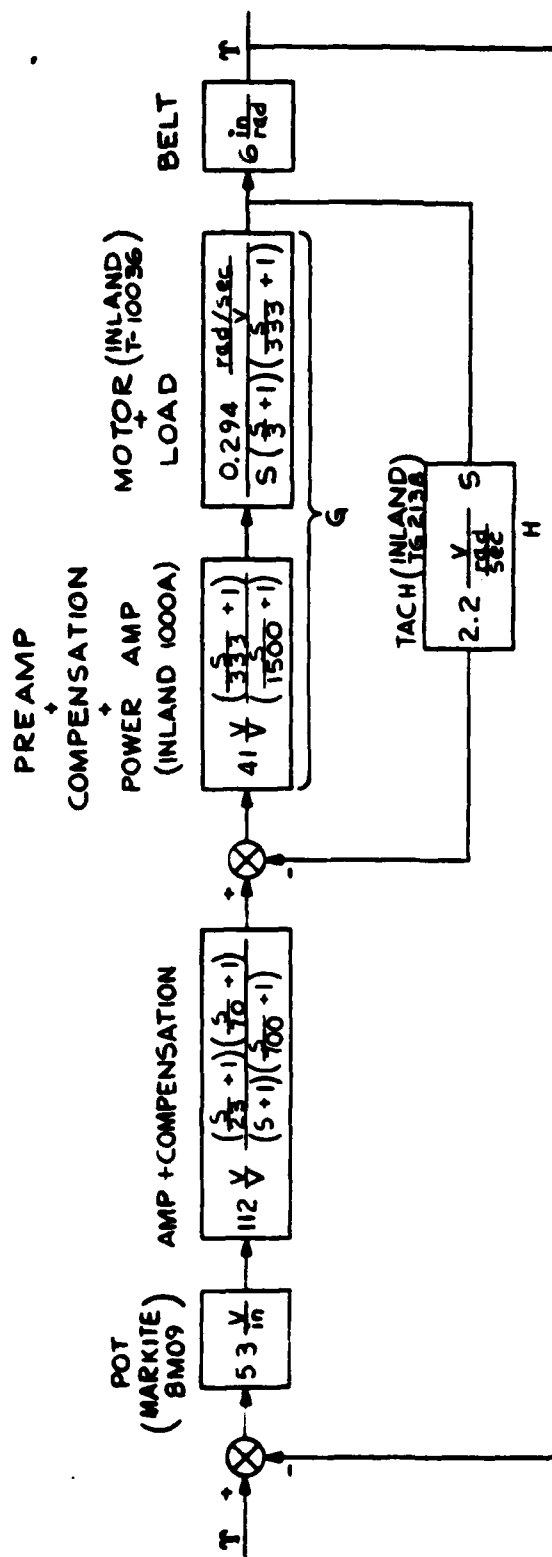
Figure 5-22. Vertical Drive Servo Block Diagram

to reduce the dynamic lag error below the 0.25 inches required. The series compensation's lag-lead network $\frac{(S/23 + 1)}{(S/1 + 1)}$ is needed to reduce the open loop gain to 0 db at the 70 rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response. The compensation's lead network $\frac{(S/70 + 1)}{(S/700 + 1)}$ cancels the closed tach loop transfer function pole at 70 rad/sec and replaces it with a pole at 700 rad/sec. This pole only adds 6 degrees of phase shift at the 70 rad/sec crossover frequency.

The tachometer feedback loop acts to increase the motor mechanical pole from 3 rad/sec to 70 rad/sec and the tach loop compensation $\frac{(S/333 + 1)}{(S/1500 + 1)}$ cancels the motor electrical pole at 333 rad/sec.

The open loop transfer function can be determined from Figure 5-22 by first determining the closed tach loop transfer function:

$$\frac{G}{1 + GH} = \frac{1630 \, (S/23 + 1)}{S \, (S/1 + 1) \, (S/700 + 1)}$$

5.2.5.5.4 Servo Performance

The vertical drive servos torque disturbance response is not much greater than a .001 in/ft-lb (see Figure 5-23) and the vertical position sensor accuracy is 0.058 inches. The servo's dynamic lag error (using the formula given in paragraph 5.2.5.4.4 for 170 in/sec^2 acceleration and 37 in/sec velocity) is 0.125 inches. Therefore, the servo's total error will be less than the 0.25 inches allowed.
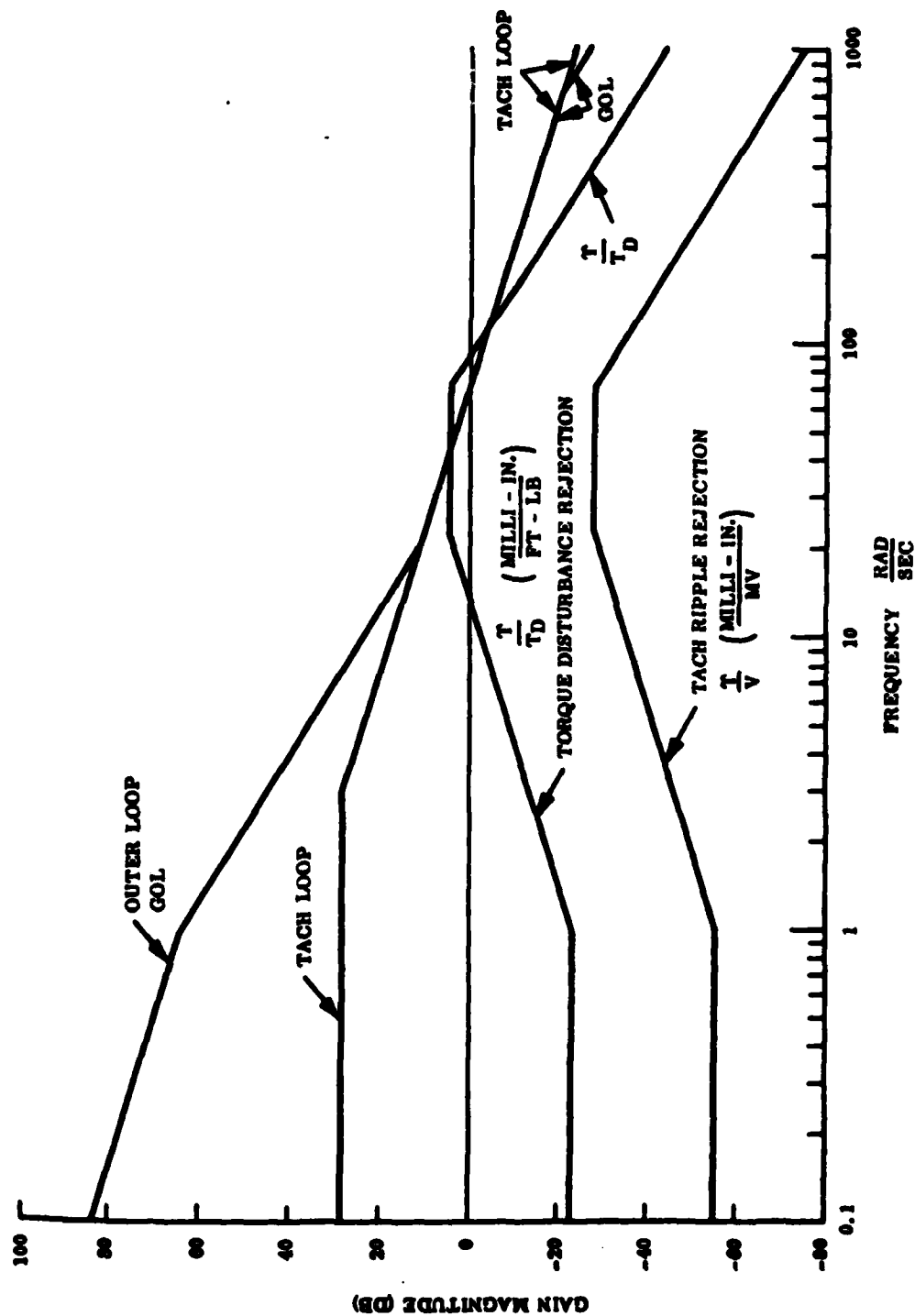
Figure 5-23. Vertical Drive Servo Bode Diagram

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5.3 TARGET PROJECTION SUBSYSTEM DESIGN

5.3.1 CONFIGURATION AND REQUIREMENTS

As discussed earlier in Section 3.2.3, the target projection subsystem consists of eight element projectors feeding into the directional control assembly. This assembly, in turn, consists of 7 small mirrors, each mounted on a two-axis gimbal assembly to provide precise target position control within the display window. The eighth mirror is fixed since it directs the 7 degree infrared background only. These two assemblies are then mounted on the assembly core which is, in turn, fixed to the single axis-projector azimuth table as shown in Figure 5-24.

The requirements are as follows:

Target Characteristics	See Table 5-6	
Target position control	Azimuth	Elevation
Range of Motion	3.5°	
Position Accuracy	< .7 mrad	< .7 mrad
Position Repeatability	< .4 mrad	< .4 mrad
Maximum Velocity	100°/sec	100°/sec
Maximum Acceleration	400°/sec^2	400°/sec^2

Range Simulation (Apparent Size and Received Flux)

Range	50 meters to 5000 meters
Range simulation accuracy	5% up to 1500 meters
Repeatability	1% up to 1500 meters
Maximum Closure Rate	1500 m/sec
Maximum Closure Acceleration	None specified

5.3.2 DIRECTIONAL CONTROL ASSEMBLY

5.3.2.1 Configuration

Each of the two-axis gimballed mirrors will have the configuration shown in Figure 5-26. It is extremely important to pack these seven mirrors plus the one stationary mirror in as tight a configuration as possible in order to conserve system brightness by reducing the pupil expansion requirements. This requirement precludes the use of a direct drive or even a single belt drive. Of primary importance in this type of mechanism is the resonant frequency of the drive belt. Backlash is eliminated by preloading and slippage is eliminated by fastening the belt to each pulley. The natural frequency was calculated to be 310 Hz, which is so far above the 10 Hz servo bandwidth that it can be completely neglected in the servo analysis.

(4) DIRECTIONAL CONTROL ASSEMBLY

(3) SINGLE ELEMENT PROJECTOR

VIEW A-A

(2) ASSEMBLY CORE

(1) SINGLE AXIS TABLE
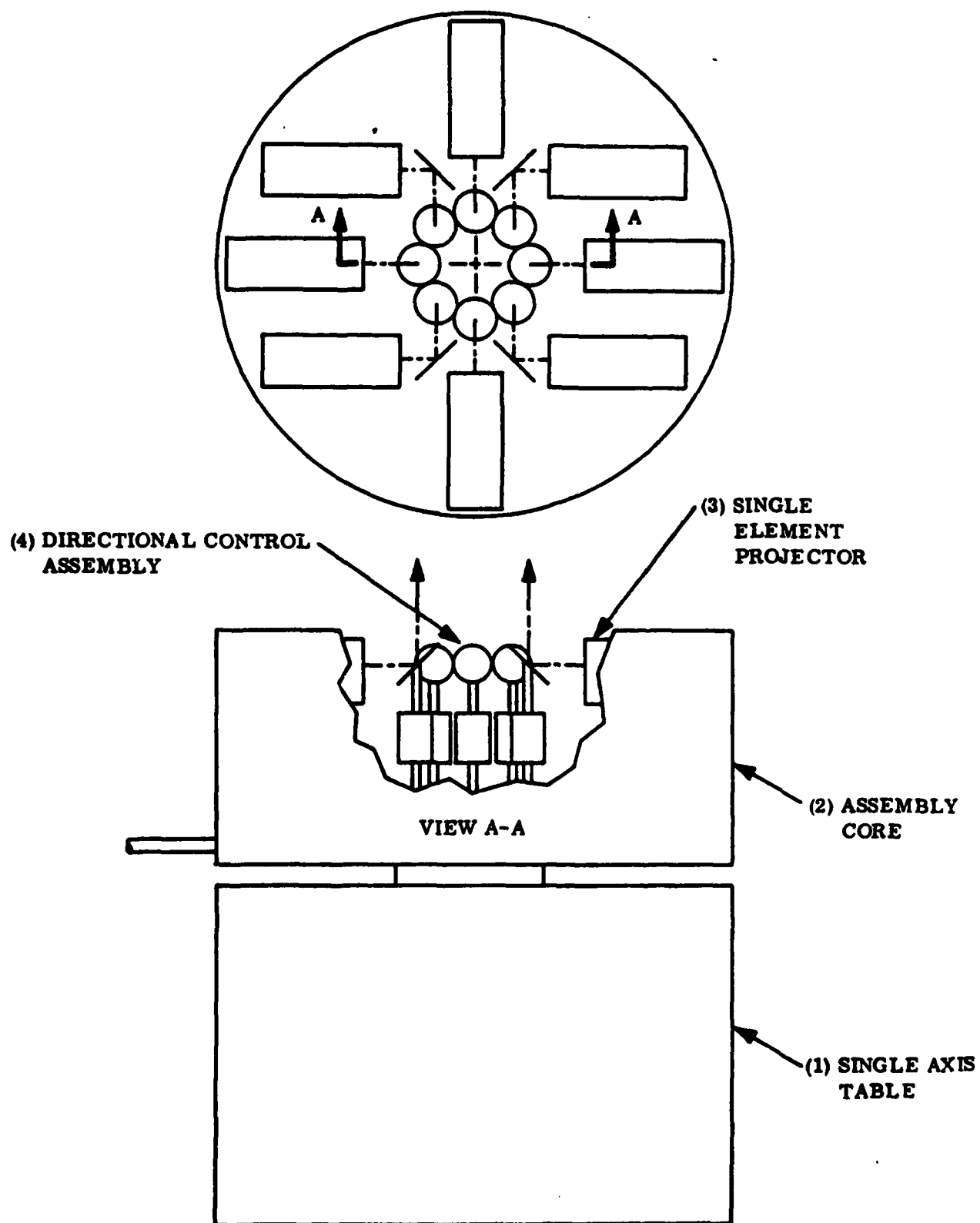
Figure 5-24. Target Projection Subsystem

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TABLE 5-6. TARGET CHARACTERISTICS

Target Type	Shape and Size	Radiant Intensity	Spectral Band	Quantity
Tailpipe	Circular-0.15 to 1 meter diam.	1-1000 watts/steradian	1-5μ	4
Plume	Triangular-1x1 meter to 1x5 meters variable with aspect angle	1-500 watts/steradian	3-5μ	1
Fuselage	Rectangular-1x1 meter to 3x20 meters variable with aspect angle	Contrast ratio -0.1 to -0.9, adjacent background variable over range 10^{-4} to 10^{-6} watts/cm^2/sr in each band	.3-.4μ .4-.7μ	1
Flare	Circular 0.1 to 1 meter diameter	Up to 10 times any target; spectral distribution to approximate a 2000°K black body	1-5μ	*
I.R. Background	---	$^+$5.4 x 10^{-3} watts/cm^2/sr	1-3μ	1
		1.4 x 10^{-4} watts/cm^2/sr	3-5μ	1

*Ejection rate - up to one per second for 15 seconds; maximum separation velocity - 30 meters per second.

With the ejection rates specified here, 15 flares could be in the field at one time at the maximum range, a clearly impractical goal. If one tailpipe and one infrared background are provided, 6 flares could be produced simultaneously with this projection scheme and should be adequate.

$^+$Since no infrared background requirements were specified, they were derived from Figure 5-25 which was extracted from the Handbook of Military Infrared Technology and other references.
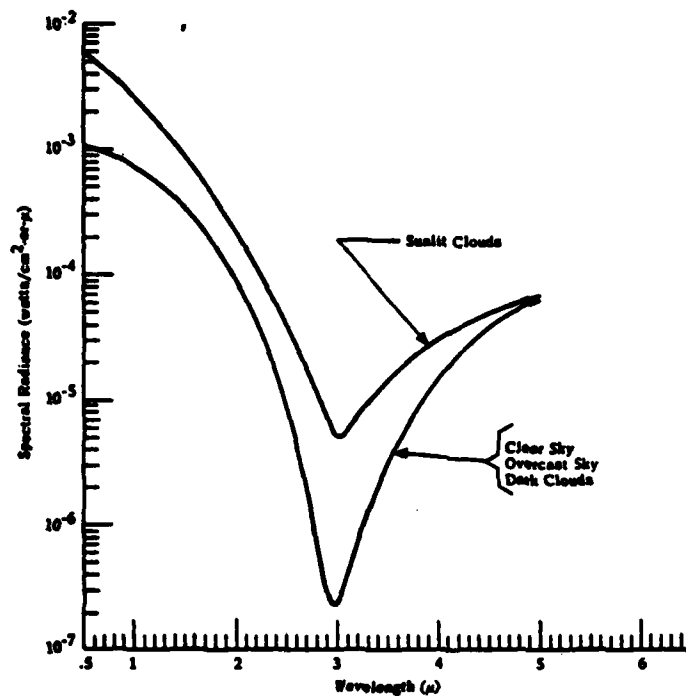
Figure 5-25. Spectral Radiance of Sky and Clouds
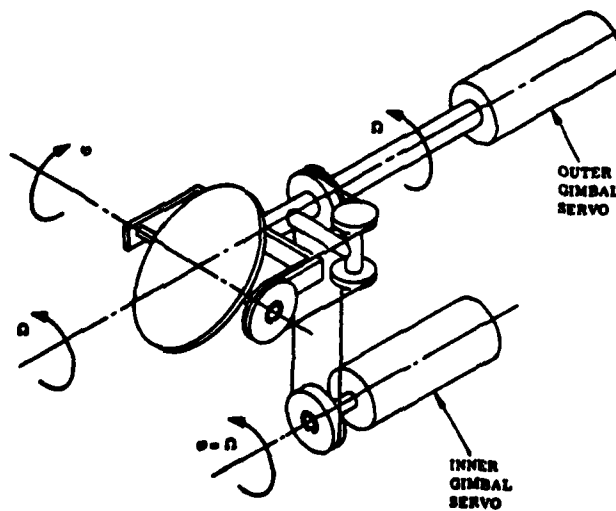
Figure 5-26. Directional Mirror Configuration

The directional control mechanism and assembly preliminary design are shown in GE drawing # 47R196992 which is included in Appendix C. The outer gimbal motor housings are arranged in step fashion to minimize the diameter of the packing circle, which is 5.2 inches.

The mirror gimbal angles (Ω and ϕ) do not correspond to the command signals generated by the subtraction of the target command from the display arm position (ϵ_θ and ϵ_ψ). The transformation that is necessary is discussed in detail in Section 5.3.2.3.

5.3.2.2 Directional Servo Analysis

5.3.2.2.1 Requirements and Design Rationale

The directional servos' inner axis position range is ±3.5 degrees and their outer axis position range is ±5.25 degrees. The bias plus dynamic lag error of the inner and outer axes shall each be less than 0.7 mrad and the jitter error of the inner and outer axes shall each be less than 0.5 mrad. The inner axis must follow a command with an acceleration of 600 deg/sec^2 up to a velocity of 150 deg/sec, while the outer axis must follow accelerations of 400 deg/sec^2 up to a velocity of 100 deg/sec.

The directional servos' position must be sensed with an accuracy of better than 1 mrad and velocity with a linearity of 5% for recording purposes.

A RVDT will sense the inner and outer servo positions with an accuracy of 0.25 milliradians over the range required. This 0.25 milliradians is within the servo bias plus dynamic lag error budget of 0.7 mrad and the position recording accuracy of 1.0 mrad.

A tachometer is used with a feed-forward servo velocity command to reduce the servos' dynamic lag error. This tachometer will also be used to reduce the servos' error caused by friction and will sense velocity with a linearity of 5% for recording purposes.

The servos' compensation and open loop crossover frequency are selected to keep the servos' dynamic lag error plus the servo error caused by friction to less than 0.45 mrad.

In order to insure that the servos' settling time is less than the time it takes a position command to reach a velocity of 150 deg/sec (inner) and 100 deg/sec (outer) moving with an acceleration of 600 deg/sec^2 (inner) and 400 deg/sec^2 (outer), an open loop crossover frequency, ω_c, of 60 rad/sec is selected. Assuming a reasonable settling time, t_s, of one-third the time it takes to reach the 150 deg/sec (100 deg/sec) velocity, then it follows that $t_s = 1/3 \ (150/600) = 1/3 \ (100/400) = 1/12$ sec. The relation between crossover frequency and settling time is approximately $\omega_c = 5/t_s$ and, therefore, the directional servos' inner and outer axis crossover frequency is $\omega_c = (5) \ (12) = 60$ rad/sec.

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5.3.2.2.2 Component Definition

Limited angle brushless Aeroflex torque motor (TQ18-7, 20 in. oz) and Tachometer (TG18-14) are selected. An Inland 50A 50 watt amplifier will be used with this motor.

A Pickering RVDT (P-2350) with an accuracy of 0.25 mrad over a ±5.25 degree range is chosen as the position sensor.

The directional servos' inner and outer axis components (which are identical) are given in Figure 5-27.

5.3.2.2.3 Servo Amplifier Gains and Compensation Network Definition

The servo amplifier gains and compensation networks are given in Figure 5-27. The series compensation was chosen so that the open loop transfer function's crossover frequency is 60 rad/sec, as required, and the open loop gain (6000) is large enough to reduce the dynamic lag error below the 0.45 mrad required. The series compensation's lag-lead network $(S/20 + 1)/(S/0.2 + 1)$ is needed to reduce the open loop gain to 0 db at the 60 rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response.

The tachometer feedback loop acts to increase the motor mechanical pole from 2.2 rad/sec to 200 rad/sec.

The open loop transfer function can be determined from Figure 5-27 by first determining the closed tach loop transfer function,

$$\frac{G}{1 + GH} = \frac{1300}{S(S/200 + 1)(S/5000 + 1)} ,$$

and then multiplying all transfer functions. Neglecting the pole at 500 rad/sec, the open loop transfer function is:

$$GOL = \frac{6000\ (S/20 + 1)}{S(S/0.2 + 1)(S/200 + 1)}$$

5.3.2.2.4 Servo Performance

The directional servos' (inner and outer axis) peak torque disturbance response is about 80 mrad/in-oz. (see Figure 5-28). However, since brushless torque motors and tachometers are being used which have essentially zero friction torque, the servo jitter error will be less than 0.5 mrad. The low frequency torque disturbance response is less than 1 mrad/in-oz and, therefore, the servo bias error resulting from friction is negligible compared to the servo bias error resulting from the RVDT
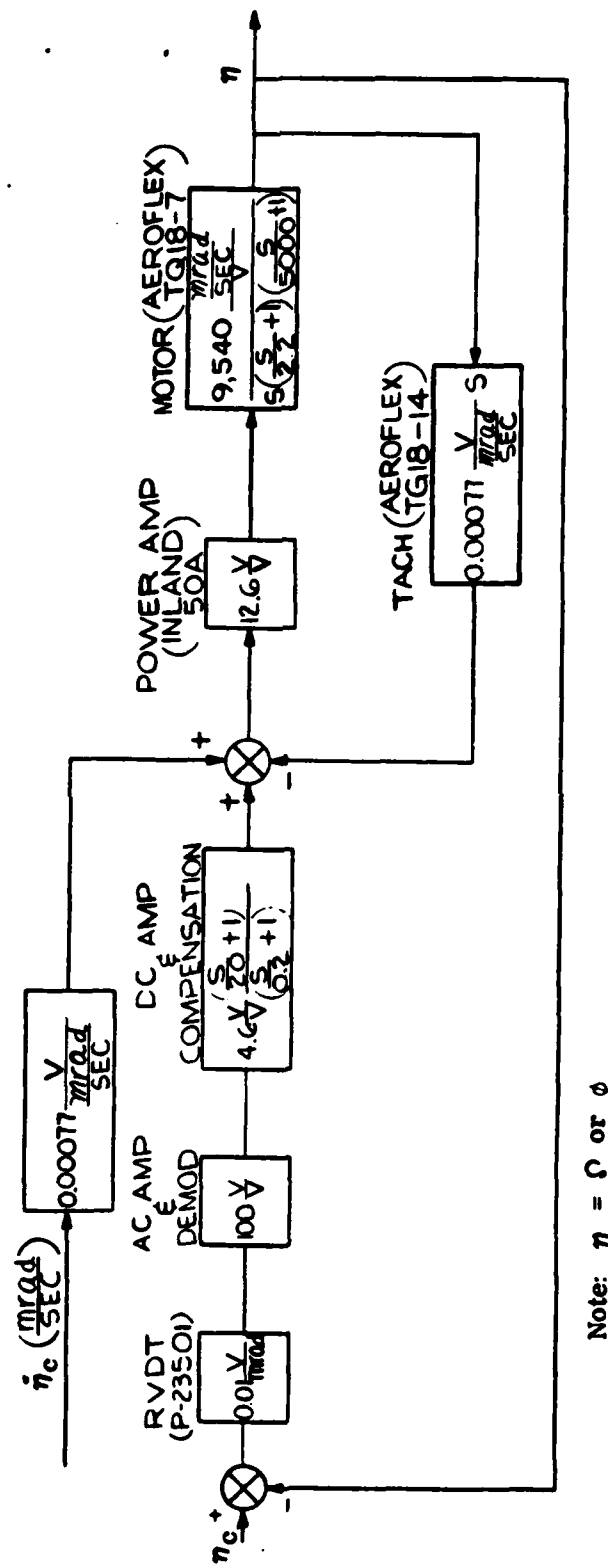
Figure 5-27. Directional Servo Block Diagram

Note: $\eta = \Omega$ or ϕ
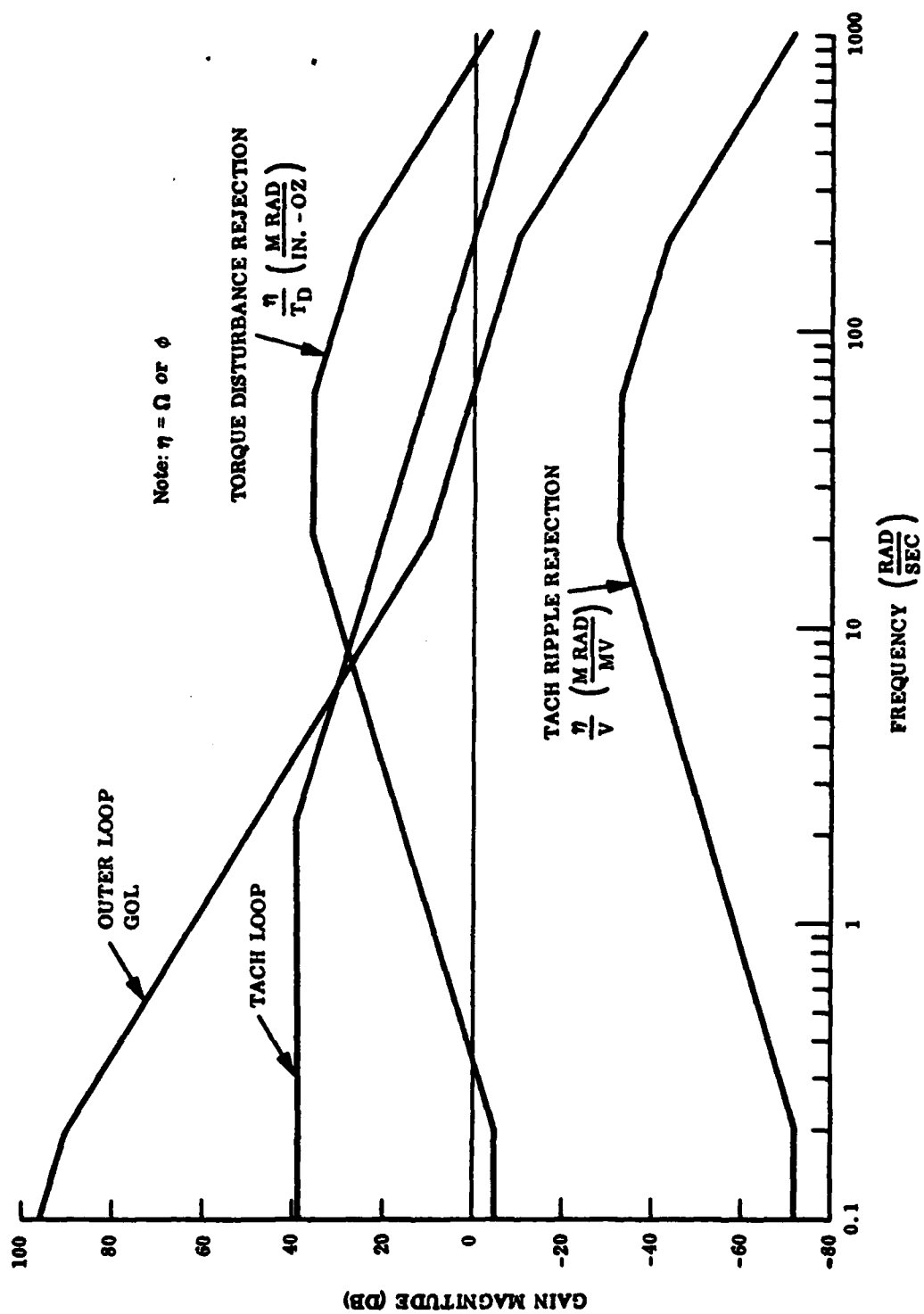
Figure 5-28. Directional Mirror Servo Bode Diagram

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position sensor accuracy (0.25 mrad). The dynamic lag error, E, for an open loop transfer function of the form K $(T_2 S + 1)/S (T_1 S + 1) (T_3 S + 1)$ (this is the form of the directional servo's open loop transfer function) is:

$$E = \frac{\dot{\eta}}{K} + \frac{K (T_1 + T_3 - T_2) - 1}{K^2} \ddot{\eta}$$

where η is the servo input command and $\dot{\eta}$ and $\ddot{\eta}$ are the velocity and acceleration of this command, respectively. The dynamic lag error with the addition of a velocity command fed to the tach loop is:

$$E = \frac{\dot{\eta} (1-C)}{K} + \frac{K (T_1 - T_2) - 1}{K^2} \ddot{\eta} (1-C) + \frac{T_3 \ddot{\eta}}{K}$$

where C is the amount of the true velocity command fed to the tach loop (a 5% velocity error means 95% true velocity and C = .95).

Substituting the directional servo parameters along with C = 0.95 into the dynamic lag error formula results in a dynamic lag error of 0.45 mrad for the inner axis and 0.30 mrad for the outer axis.

The bias plus dynamic lag error budget of 0.7 mrad is, therefore, met by both the inner and outer axes of the directional servos.

5.3.2.3 Target Positioning in the Display Field

5.3.2.3.1 Introduction

The approach selected for the target display subsystem of the IRSS is to slave the display window to the sensor, so that the two will move in unison within the display field. The display window is a 3.5 degree cone about the central axis of the display arm. The sensor field has the same central axis with a smaller cone angle.

The object of the target positioning subsystem is to place the target at a desired position within the display field. The target position may or may not be within the sensor field of view. The target is generated by reflecting a fixed light beam off a mirror supported in a two-axis gimbal. The light source and gimballed mirror are slaved to the display arm of the system.

The display arm may be located anywhere within an azimuth angle (ψ_A) of $\pm 90°$, and elevation angle (θ_A) of $\pm 30°$. The target may be placed anywhere within a 3.5° cone about the display arm central axis. The target position command is given in the form of two angles, ϵ_ψ and ϵ_θ, which represent the difference between the display arm position, ψ_A and θ_A, and the desired target position, ψ_T and θ_T (see Figure 5-29).

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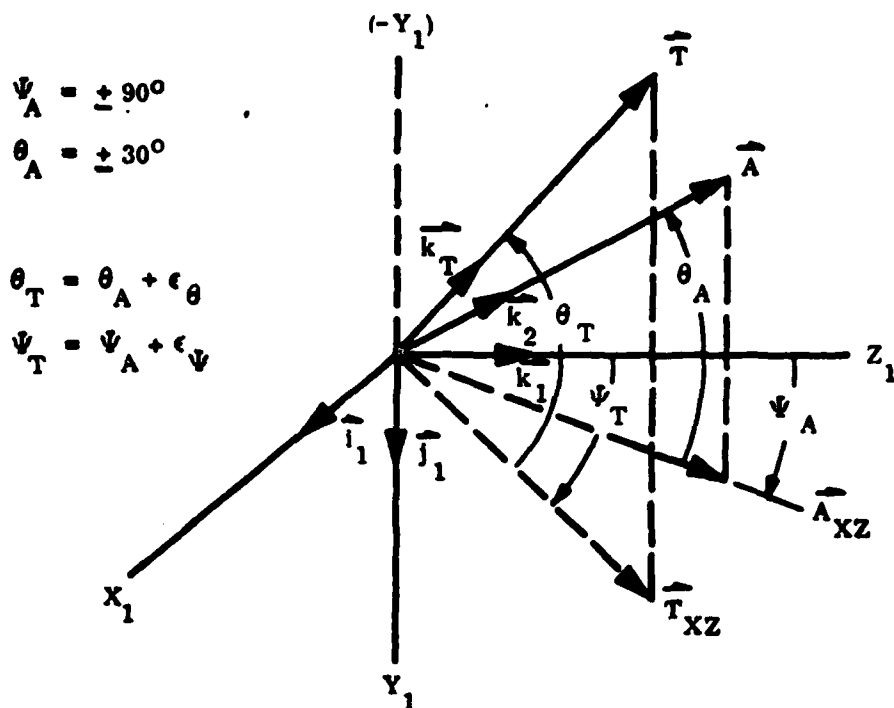
Figure 5-29. Display Arm Position and Target Position in Inertial
Reference Frame

The following analysis is carried out in order to determine the exact solution of the transformation equations relating the desired angular position of the target (ψ_T and θ_T) to the required angular position of the gimballed mirror (Ω and ϕ). Thus, knowing the display arm position (ψ_A and θ_A), and the delta input angles (ϵ_ψ and ϵ_θ) which define the desired target position, the transformation equations may be solved to determine the exact gimbal rotations (Ω, ϕ) which will position the target reflecting mirror such that the incident light beam will be reflected to the desired target position.

The transformation equations representing the exact relationship between target position and mirror position are very complicated. The hardware required to solve these equations, in particular the multipliers, is costly. Therefore, the exact solution equations will be reduced to approximate equations by standard approximation methods. The approximate equations, determined to an acceptable accuracy, will then be incorporated into the target generation subsystem.

The complete target generation subsystem consists of seven individual targets. However, since these are similar, this analysis is carried out for a single representative target.

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5.3.2.3.2 Definition of Display Arm Position (ψ_A, θ_A), and Target Position (ψ_T, θ_T)

The coordinate system (X_T, Y_T, Z_T) is affixed to the target vector, $\overrightarrow{T}$, and the (X_2, Y_2, Z_2) coordinate system is affixed to the display arm vector, $\overrightarrow{A}$. Both the target coordinate system and the display arm coordinate system are referenced to the inertial coordinate system (X_1, Y_1, Z_1) by two Euler rotations. Both the target vector and the display arm vector are defined as unit vectors along the Z axes of their respective coordinate systems. All three systems are initially coincident; the position of the display arm vector is then obtained by two Euler rotations, the first being ψ_A about the Y_2 axis (initially coincident with Y_1) and the second being θ_A about X_2. Likewise, the target position is described by ψ_T and θ_T.

The vectors and their Euler angles are shown in Figure 5-30. From the geometry of the figure and the definition of the angles, we see that: $\psi_T = \psi_A + \epsilon_\psi$ and $\theta_T = \theta_A + \epsilon_\theta$, where ϵ_ψ and ϵ_θ are the angular differences between display arm position and target position measured in the inertial reference frame.

In the physical positioning of the display arm, $\overrightarrow{A}$, the angle ψ_A corresponds to an azimuth angle, and θ_A to an elevation angle. The angles ϵ_ψ and ϵ_θ represent the difference between the desired position of the target, $\overrightarrow{T}$, and the actual position of the display arm as specified in the inertial coordinate system. However, the outer and inner gimbal rotations of the target positioning mirror correspond to Euler rotations in the coordinate system affixed to the display arm, the (X_2, Y_2, Z_2) reference frame. Therefore, for a known display arm position (ψ_A, θ_A), the desired target mirror position, defined by ϵ_ψ and ϵ_θ, must be transformed into two Euler rotations (Ω and ϕ) measured with respect to the display arm reference frame.

Defining the mirror position angles will be done in two steps: first - by defining the desired target position with respect to the display arm reference frame, and second - by determining the required mirror position (Ω and ϕ) which will direct the incident light beam to the desired target position, also in the display arm reference frame.

5.3.2.3.3 Target Position in Display Arm Reference Frame

The Euler angles between the target reference frame (X_T, Y_T, Z_T) and the display arm reference frame (X_2, Y_2, Z_2) are defined as: first a rotation, β, about the Y_T axis (initially coincident with Y_2), and second, a rotation, α, about the X_T axis. The two reference frames and rotating angles are shown in Figure 5-30.

The components of the target vector, $\overrightarrow{T}$, expressed in the display arm frame are:

$$\overrightarrow{T} = T_{X_2} \overrightarrow{i_2} + T_{Y_2} \overrightarrow{j_2} + T_{Z_2} \overrightarrow{k_2}$$

Figure 5-30. Target Position With Respect to the Display Arm Reference Frame

The values of these components in terms of the Euler angles α and β are:

$$T_{X_2} = |T| \cos \alpha \sin \beta$$

$$T_{Y_2} = -|T| \sin \alpha$$

$$T_{Z_2} = |T| \cos \alpha \cos \beta$$

The target vector may also be expressed in the inertial frame as:

$$\vec{T} = T_{X_1} \vec{i}_1 + T_{Y_1} \vec{j}_1 + T_{Z_1} \vec{k}_1$$

With the component values expressed in terms of the Euler angles ψ_T and θ_T (see Figure 5-29) we have:

$$T_{X_1} = |T| \cos \theta_T \sin \psi_T$$

$$T_{Y_1} = |T| \sin \theta_T$$

$$T_{Z_1} = |T| \cos \theta_T \cos \psi_T$$

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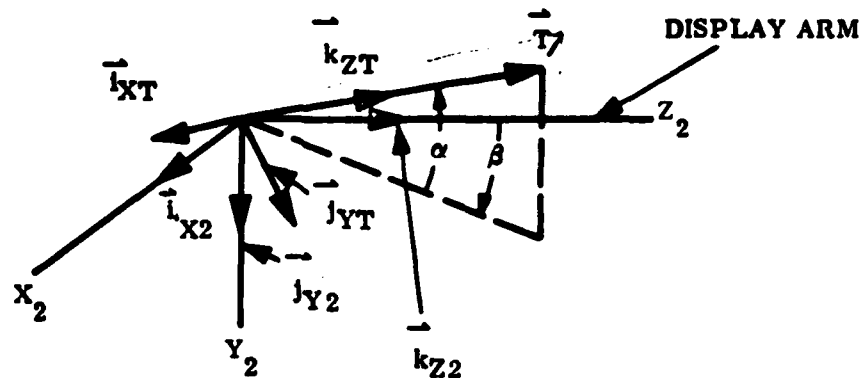
Figure 5-30. Target Position With Respect to the Display Arm Reference Frame

The values of these components in terms of the Euler angles α and β are:

$$T_{X_2} = |T| \cos \alpha \sin \beta$$

$$T_{Y_2} = -|T| \sin \alpha$$

$$T_{Z_2} = |T| \cos \alpha \cos \beta$$

The target vector may also be expressed in the inertial frame as:

$$\vec{T} = T_{X_1} \vec{i_1} + T_{Y_1} \vec{j_1} + T_{Z_1} \vec{k_1}$$

With the component values expressed in terms of the Euler angles ψ_T and θ_T (see Figure 5-29) we have:

$$T_{X_1} = |T| \cos \theta_T \sin \psi_T$$

$$T_{Y_1} = |T| \sin \theta_T$$

$$T_{Z_1} = |T| \cos \theta_T \cos \psi_T$$

As shown in Figure 5-29, the display arm reference frame can be related to the inertial reference frame by two Euler rotations, ψ_A and θ_A. If the matrices of these rotations are called, respectively, A and B, the relationship between the target vector components in the inertial frame and the display arm frame are:

$$\begin{bmatrix} T_{X_2} \\ T_{Y_2} \\ T_{Z_2} \end{bmatrix} = [B] \, [A] \begin{bmatrix} T_{X_1} \\ T_{Y_1} \\ T_{Z_1} \end{bmatrix}$$

where $|T| = 1$

$$A = \begin{bmatrix} \cos\psi_A & 0 & -\sin\psi_A \\ 0 & 1 & 0 \\ \sin\psi_A & 0 & \cos\psi_A \end{bmatrix} \qquad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_A & \sin\theta_A \\ 0 & -\sin\theta_A & \cos\theta_A \end{bmatrix}$$

Substituting the values for the components of $\vec{T}$ in their respective frames of reference we have:

$$\begin{bmatrix} \cos\alpha\sin\beta \\ -\sin\alpha \\ \cos\alpha\cos\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_A & \sin\theta_A \\ 0 & -\sin\theta_A & \cos\theta_A \end{bmatrix} \begin{bmatrix} \cos\psi_A & 0 & -\sin\psi_A \\ 0 & 1 & 0 \\ \sin\psi_A & 0 & \cos\psi_A \end{bmatrix} \begin{bmatrix} \cos\theta_T\sin\psi_T \\ -\sin\theta_T \\ \cos\theta_T\cos\psi_T \end{bmatrix}$$

Carrying out the multiplication:

$$\begin{bmatrix} \cos\alpha\sin\beta \\ -\sin\alpha \\ \cos\alpha\cos\beta \end{bmatrix} = \begin{bmatrix} \cos\psi_A\cos\theta_T\sin\psi_T - \sin\psi_A\cos\theta_T\cos\psi_T \\ \sin\theta_A\sin\psi_A\cos\theta_T\sin\psi_T - \cos\theta_A\sin\theta_T \\ + \sin\theta_A\cos\psi_A\cos\theta_T\cos\psi_T \\ \cos\theta_A\sin\psi_A\cos\theta_T\sin\psi_T + \sin\theta_A\sin\theta_T \\ + \cos\theta_A\cos\psi_A\cos\theta_T\cos\psi_T \end{bmatrix}$$

With the above three equations, combined with the relationships between the display arm position (ψ_A, θ_A), the target position (ψ_T, θ_T), and the difference angles $(\epsilon_\psi, \epsilon_\theta)$,

all in the inertial reference frame, we have defined the target position with respect to the display arm reference frame (i.e., β and α). These relationships are summarized below:

(1.) $\quad \theta_T = \theta_A + \epsilon_\theta$

(2.) $\quad \psi_T = \psi_A + \epsilon_\psi$

(3.) $\quad \sin \alpha = -[\sin \theta_A \sin \psi_A \cos \theta_T \sin \psi_T - \cos \theta_A \sin \theta_T + \sin \theta_A \cos \psi_A$
$$\cos \theta_T \cos \psi_T]$$

(4.) $\quad \cos \alpha \sin \beta = \cos \psi_A \cos \theta_T \sin \psi_T - \sin \psi_A \cos \theta_T \cos \psi_T$

(5.) $\quad \cos \alpha \cos \beta = [\cos \theta_A \sin \psi_A \cos \theta_T \sin \psi_T + \sin \theta_A \sin \theta_T$
$$+ \cos \theta_A \cos \psi_A \cos \theta_T \cos \psi_T]$$

5.3.2.3.4 Mirror Position (Ω, ϕ)

The light source which produces the target is incident to the mirror along the axis of the display arm coordinate system (Y_2). The positioning mirror is fixed to the display arm system, but may be set at two Euler angles with respect to it in order to achieve the desired target position. The mirror coordinate system is defined by its normal, $\vec{N}$, a unit vector perpendicular to the plane of the mirror. The orientation of the other two unit vectors in the plane of the mirror is not significant in this analysis.

For analysis purposes, assume that the normal to the mirror is, initially, along the Y_2 axis of the display arm. Its orientation will then be measured by two Euler rotations from this position. The first rotation, Ω, is about the Z_2 axis of the display arm coordinate system. This corresponds to an outer-gimbal rotation in the mirror positioning system. The second rotation, ϕ, is about an axis in the (X_2, Y_2) plane perpendicular to $\vec{N}$, such that $\vec{N}$ moves in a plane perpendicular to the (X_2, Y_2) plane of the display arm coordinate system. This movement corresponds to an inner-gimbal rotation in the mirror positioning system. The normal, positioning angles, and incident ray are shown in Figure 5-31.

From Figure 5-31 we can see that the components of $\vec{N}$ with respect to the display arm coordinate system are:

$$N_X = -|N| \cos \phi \sin \Omega$$

$$N_Y = |N| \cos \phi \cos \Omega$$

$$N_Z = |N| \sin \phi$$
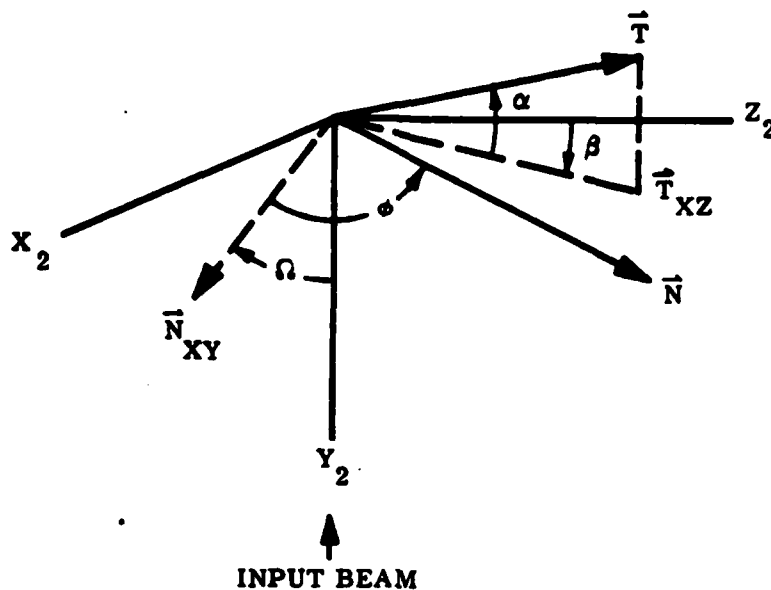
Figure 5-31. Mirror Position in Display Arm Reference Frame

and,

$$\vec{N} = N_X \vec{i}_2 + N_Y \vec{j}_2 + N_Z \vec{k}_2$$

As before, the target referenced to the display arm coordinate system is:

$$\vec{T} = T_x \vec{i}_2 + T_y \vec{j}_2 + T_z \vec{k}_2$$

and,

$$T_x = |T| \cos \alpha \sin \beta$$

$$T_y = -|T| \sin \alpha$$

$$T_z = |T| \cos \alpha \cos \beta$$

Also, from Figure 5-31 the incident ray, $\vec{I}$, in the display arm system is:

$$\vec{I} = -|I|\,\vec{j}_2$$

To determine the relationship between the position of the incident ray, $\vec{I}$, the normal to the mirror, $\vec{N}$, and the target position, $\vec{T}$ (which is also the output ray, O, from the mirror), we employ the physical relationship between the vector cross-product of the normal with each of the other two vectors. That is:

$$\vec{O} \times \vec{N} = \vec{N} \times \vec{I}$$

From this relationship:

$$\vec{O} \times \vec{N} = \vec{T} \times \vec{N} = (T_{Y_2} N_{Z_2} - T_{Z_2} N_{Y_2})\,\vec{i}_2 + (T_{X_2} N_{Z_2} + T_{Z_2} N_{X_2})\,\vec{j}_2$$

$$+ (T_{X_2} N_{Y_2} - T_{Y_2} N_{X_2})\,\vec{k}_2$$

$$\vec{N} \times \vec{I} = (-N_{Z_2}\,I)\,\vec{i}_2 + 0 \cdot \vec{j}_2 + (N_{X_2}\,I)\,\vec{k}_2$$

Equating like terms results in three equations

1. $T_Y N_Z - T_Z N_Y = -N_Z\,I$

2. $T_X N_Z - T_Z N_X = 0$

3. $T_X N_Y - T_Y N_X = N_X\,I$

By substitution it can be shown that the first and third equation are equivalent. Substituting the component values in the equations, and defining

$|I| = 1$, we have:

1.) $T_Y N_Z - T_Z N_Y = -N_Z$

or: $T_Z N_Y - T_Y N_Z = N_Z$

1. a) $(\cos \alpha \cos \beta) \cos \phi \cos \Omega - (-\sin \alpha) \sin \phi = \sin \phi$

2.) $T_X N_Z = T_Z N_X$

2. a) $(\cos \alpha \sin \beta) \sin \phi = -(\cos \alpha \cos \beta) \cos \phi \sin \Omega$

Let

$P = \sin \alpha$
$Q = \cos \alpha \cos \beta$
$R = -\cos \alpha \sin \beta$

The resultant equations are:

1. a) $Q \cos \phi \cos \Omega + P \sin \phi = \sin \phi$

2. a) $-R \sin \phi = -Q \cos \phi \sin \Omega$

Solving:

from 1. a) $Q \cos \phi \cos \Omega = (1-P) \sin \phi$

$$\frac{\sin \phi}{\cos \phi \cos \Omega} = \frac{Q}{1-P} , \text{ or } \tan \phi = \frac{Q}{1-P} \cos \Omega$$

from 2. a)

$$\frac{\sin \phi}{\cos \phi \sin \Omega} = \frac{Q}{R}$$

$$\tan \phi = \frac{Q}{R} \sin \Omega$$

combining 1.a) and 2.a),

$$\frac{Q}{R} \sin \Omega = \frac{Q}{1-P} \cos \Omega$$

$$\frac{\sin \Omega}{\cos \Omega} = \frac{R}{1-P}$$

$$\therefore \tan \Omega = \frac{R}{1-P} = \frac{-\cos \alpha \sin \beta}{1 - \sin \alpha}$$

from 1.a)

$$\therefore \tan \phi = (\cos \Omega) \frac{Q}{1-P} = (\cos \Omega) \frac{\cos \alpha \cos \beta}{1 - \sin \alpha}$$

The equation for Ω must be solved first, and the result employed in solving for ϕ.

If we now substitute in for α and β the expression relating them back to the display arm and target positions in the inertial frame, we get the desired result, namely, the display arm position (ψ_A and θ_A) and the desired angular differences between the display arm and target (ϵ_ψ and ϵ_θ), related to two rotations of the supporting gimbals of the target positioning mirror (Ω and ϕ). The relationships are:

$$(1) \quad \tan \Omega = \frac{-\cos \psi_A \cos \theta_T \sin \psi_T + \sin \psi_A \cos \theta_T \cos \psi_T}{(1 - \sin \theta_A \sin \psi_A \cos \theta_T \sin \psi_T + \cos \theta_A \sin \theta_T}$$
$$- \sin \theta_A \cos \psi_A \cos \theta_T \cos \psi_T)$$

$$(2) \quad \tan \phi = (\cos \Omega)(\cos \theta_A \sin \psi_A \cos \theta_T \sin \psi_T + \sin \theta_A \sin \theta_T$$
$$\frac{+ \cos \theta_A \cos \psi_A \cos \theta_T \cos \psi_T)}{(1 - \sin \theta_A \sin \psi_A \cos \theta_T \sin \psi_T + \cos \theta_A \sin \theta_T}$$
$$- \sin \theta_A \cos \psi_A \cos \theta_T \cos \psi_T)$$

Where ψ_T and θ_T are computed as previously:

$$(3) \quad \psi_T = \psi_A + \epsilon_\psi$$

$$(4) \quad \theta_T = \theta_A + \epsilon_\theta$$

In Table 5-7, the solutions of the exact equations, Ω and ϕ, along with the corresponding α and β, are listed as functions of θ_A, ϵ_ψ, and ϵ_θ. The mirror position angles, Ω and ϕ, are independent of the display arm azimuth angle, ψ_A, and, therefore, the value of ψ_A was left at $0.0°$ in generating these data.

5.3.2.3.5 Approximation Equations

The two mirror positioning equations are lengthy and complex. The large number of multiplications involved presents problems in the solution of these equations. The analog computer, to be used for target position computations, has a limited number of multipliers available, and additional multipliers are costly. Therefore, it is desirable to approximate the mirror positioning equations, preserving accuracy while minimizing the number of multiplications required.

Numerous data points were generated, via the exact mirror positioning equations, for solutions of Ω and ϕ over the range of θ_A, ϵ_θ, ψ_A, and ϵ_ψ. Approximation curves were fitted to these data points using least squares or equivalent methods.

The most accurate approximation equations determined thus far are:

$$\text{(outer gimbal)} \quad \Omega = -\epsilon_\psi \left[\cos \theta_\theta + .018 \, \epsilon_\theta - .004 \, \theta_A \, \epsilon_\theta \right]$$

$$\text{(inner gimbal)} \quad \phi = 0.5 \, \epsilon_\theta - .009 \, \epsilon_\psi^2 + .00014 \, \theta_A \, \epsilon_\psi$$

$$\phi = 0.5 \, \epsilon_\theta + \epsilon_\psi \left[-.009 \, \epsilon_\psi + .00014 \, \theta_A \right]$$

Table 5-8 shows the actual and approximate solutions, and the difference between them for both Ω and ϕ. The difference between actual and approximate values of Ω and ϕ has been limited to .2 m radian maximum. The Ω and ϕ values listed in Table 5-8 are the same as those generated in Table 5-7 so that they may be cross-referenced to determine the values of θ, ϵ_θ, and ϵ_ψ used in the approximate equations.

When ϵ_ψ and ϵ_θ are both $0.0°$, ϕ has a value of $45°.0$. Since this is an "initial condition" represented by a constant, it is subtracted from the original ϕ before the ϕ approximation is determined. Therefore, the ϕ approximation equation actually generates a value for (ϕ exact $- 45.0°$).

5.3.3 PROJECTOR DESIGN

5.3.3.1 Optical Design

5.3.3.1.1 Functional Description

The element projectors will all be basically conventional transparency projectors employing Abbe illumination as shown in Figure 5-32. The essential optical elements

TABLE 5-7. SOLUTIONS TO TARGET POSITIONING EQUATIONS

Θ_A							
0.	0.	0.	0.	0.	0.	0.	45.000
0.	0.	1.000	0.	1.000	0.	0.	45.500
0.	0.	2.000	0.	2.000	0.	0.	46.000
0.	0.	3.000	0.	3.000	0.	0.	46.500
0.	0.	0.	1.000	0.	1.000	-1.000	44.991
0.	0.	1.000	1.000	1.000	1.000	-1.017	45.491
0.	0.	2.000	1.000	2.000	1.000	-1.035	45.991
0.	0.	3.000	1.000	3.000	1.000	-1.054	46.491
0.	0.	0.	2.000	0.	2.000	-1.999	44.965
0.	0.	1.000	2.000	1.000	2.000	-2.034	45.465
0.	0.	2.000	2.000	2.000	2.000	-2.070	45.964
0.	0.	3.000	2.000	3.000	2.000	-2.106	46.463
0.	0.	0.	3.000	0.	3.000	-2.996	44.922
0.	0.	1.000	3.000	1.000	3.000	-3.049	45.420
0.	0.	2.000	3.000	2.000	3.000	-3.102	45.919
0.	0.	3.000	3.000	3.000	3.000	-3.157	46.417
10.0	0.	0.	0.	0.	0.	0.	45.000
10.0	0.	1.000	0.	1.000	0.	0.	45.500
10.0	0.	2.000	0.	2.000	0.	0.	46.000
10.0	0.	3.000	0.	3.000	0.	0.	46.500
10.0	0.	0.	1.000	0.001	0.985	-0.965	44.992
10.0	0.	1.000	1.000	1.001	0.982	-0.999	45.492
10.0	0.	2.000	1.000	2.001	0.979	-1.013	45.992
10.0	0.	3.000	1.000	3.001	0.976	-1.020	46.492
10.0	0.	0.	2.000	0.006	1.970	-1.969	44.969
10.0	0.	1.000	2.000	1.006	1.964	-1.997	45.469
10.0	0.	2.000	2.000	2.006	1.957	-2.026	45.968
10.0	0.	3.000	2.000	3.006	1.951	-2.055	46.468
10.0	0.	0.	3.000	0.013	2.954	-2.951	44.931
10.0	0.	1.000	3.000	1.013	2.945	-2.994	45.430
10.0	0.	2.000	3.000	2.013	2.936	-3.037	45.929
10.0	0.	3.000	3.000	3.013	2.927	-3.081	46.428
20.0	0.	0.	0.	0.000	0.	0.	45.000
20.0	0.	1.000	0.	1.000	0.	0.	45.500
20.0	0.	2.000	0.	2.000	0.	0.	46.000
20.0	0.	3.000	0.	3.000	0.	0.	46.500
20.0	0.	0.	1.000	0.003	0.946	-0.946	44.994
20.0	0.	1.000	1.000	1.003	0.934	-0.958	45.494
20.0	0.	2.000	1.000	2.003	0.928	-0.961	45.994
20.0	0.	3.000	1.000	3.003	0.922	-0.971	46.494
20.0	0.	0.	2.000	0.011	1.879	-1.879	44.975
20.0	0.	1.000	2.000	1.011	1.867	-1.900	45.475
20.0	0.	2.000	2.000	2.011	1.855	-1.921	45.974
20.0	0.	3.000	2.000	3.011	1.843	-1.942	46.474
20.0	0.	0.	3.000	0.025	2.819	-2.817	44.943
20.0	0.	1.000	3.000	1.025	2.801	-2.848	45.443
20.0	0.	2.000	3.000	2.025	2.783	-2.868	45.943
20.0	0.	3.000	3.000	3.025	2.765	-2.912	46.442
30.0	0.	0.	0.	0.000	0.	0.	45.000
30.0	0.	1.000	0.	1.000	0.	0.	45.500
30.0	0.	2.000	0.	2.000	0.	0.	46.000
30.0	0.	3.000	0.	3.000	0.	0.	46.500
30.0	0.	0.	1.000	0.004	0.866	-0.866	44.995
30.0	0.	1.000	1.000	1.004	0.857	-0.872	45.495
30.0	0.	2.000	1.000	2.004	0.849	-0.879	45.995
30.0	0.	3.000	1.000	3.004	0.840	-0.865	46.495
30.0	0.	0.	2.000	0.015	1.732	-1.732	44.981
30.0	0.	1.000	2.000	1.015	1.715	-1.744	45.481
30.0	0.	2.000	2.000	2.015	1.697	-1.757	45.961
30.0	0.	3.000	2.000	3.015	1.680	-1.770	46.481
30.0	0.	0.	3.000	0.034	2.598	-2.597	44.958
30.0	0.	1.000	3.000	1.034	2.572	-2.616	45.458
30.0	0.	2.000	3.000	2.033	2.545	-2.635	45.958
30.0	0.	3.000	3.000	3.033	2.519	-2.653	46.458

TABLE 5-8. COMPARISON OF EXACT AND APPROXIMATE SOLUTIONS FOR
MIRROR POSITIONING ANGLES

Ω	Ω_{ap}	$\Delta\Omega$	ϕ	$\phi-45°$	ϕ_{ap}	$\Delta\phi$
0.	0.	0.	45.000	0.000	0.	0.000
0.	0.	0.	45.500	0.500	0.500	0.000
0.	0.	0.	46.000	1.000	1.000	0.000
0.	0.	0.	46.500	1.500	1.500	0.000
-1.000	-1.000	0.000	44.991	-0.009	-0.009	0.000
-1.017	-1.018	0.001	45.491	0.491	0.491	0.000
-1.035	-1.036	0.001	45.991	0.991	0.991	0.000
-1.054	-1.054	0.000	46.491	1.491	1.491	-0.000
-1.999	-2.000	0.001	44.965	-0.035	-0.036	0.002
-2.034	-2.036	0.002	45.465	0.465	0.464	0.001
-2.070	-2.072	0.002	45.964	0.964	0.964	0.000
-2.106	-2.108	0.002	46.463	1.463	1.464	-0.000
-2.996	-3.000	0.004	44.922	-0.078	-0.082	0.003
-3.049	-3.054	0.005	45.420	0.420	0.418	0.002
-3.102	-3.108	0.006	45.919	0.919	0.918	0.001
-3.157	-3.162	0.005	46.417	1.417	1.418	-0.001
0.	0.	0.	45.000	0.000	0.	0.000
0.	0.	0.	45.500	0.500	0.500	0.000
0.	0.	0.	46.000	1.000	1.000	0.000
0.	0.	0.	46.500	1.500	1.500	0.000
-0.985	-0.985	0.000	44.992	-0.008	-0.008	0.000
-0.999	-0.999	-0.000	45.492	0.492	0.492	-0.000
-1.013	-1.013	-0.001	45.992	0.992	0.992	-0.000
-1.026	-1.027	-0.001	46.492	1.492	1.492	-0.000
-1.969	-1.970	0.001	44.969	-0.031	-0.031	-0.000
-1.997	-1.998	0.000	45.469	0.469	0.469	-0.000
-2.026	-2.026	-0.000	45.968	0.968	0.969	-0.001
-2.055	-2.054	-0.002	46.468	1.468	1.469	-0.001
-2.951	-2.954	0.003	44.931	-0.069	-0.069	-0.000
-2.994	-2.996	0.003	45.430	0.430	0.431	-0.001
-3.037	-3.038	0.001	45.929	0.929	0.931	-0.002
-3.081	-3.088	-0.000	46.425	1.425	1.431	-0.003
0.	0.	0.	45.000	0.000	0.	0.000
0.	0.	0.	45.500	0.500	0.500	0.000
0.	0.	0.	46.000	1.000	1.000	0.000
0.	0.	0.	46.500	1.500	1.500	0.000
-0.948	-0.948	0.000	44.994	-0.006	-0.006	0.000
-0.950	-0.950	-0.000	45.494	0.494	0.494	-0.000
-0.961	-0.960	-0.001	45.994	0.994	0.994	-0.000
-0.971	-0.970	-0.002	46.494	1.494	1.494	-0.000
-1.879	-1.879	0.001	44.975	-0.025	-0.025	0.000
-1.900	-1.899	-0.000	45.475	0.475	0.475	-0.000
-1.921	-1.919	-0.001	45.974	0.974	0.975	-0.000
-1.942	-1.939	-0.003	46.474	1.474	1.475	-0.001
-2.817	-2.817	0.002	44.943	-0.057	-0.057	0.000
-2.846	-2.849	0.001	45.443	0.443	0.443	-0.000
-2.880	-2.879	-0.001	45.943	0.943	0.943	-0.001
-2.912	-2.909	-0.002	46.442	1.442	1.443	-0.001
0.	0.	0.	45.000	0.000	0.	0.000
0.	0.	0.	45.500	0.500	0.500	0.000
0.	0.	0.	46.000	1.000	1.000	0.000
0.	0.	0.	46.500	1.500	1.500	0.000
-0.866	-0.866	0.000	44.995	-0.005	-0.005	0.000
-0.872	-0.872	-0.000	45.495	0.495	0.495	0.000
-0.879	-0.878	-0.001	45.995	0.995	0.995	0.000
-0.885	-0.884	-0.001	46.495	1.495	1.495	0.000
-1.732	-1.732	0.000	44.981	-0.019	-0.020	0.001
-1.744	-1.744	-0.000	45.481	0.481	0.480	0.001
-1.757	-1.756	-0.001	45.981	0.981	0.980	0.001
-1.770	-1.768	-0.001	46.481	1.481	1.480	0.001
-2.597	-2.598	0.001	44.958	-0.042	-0.044	0.002
-2.616	-2.616	0.000	45.458	0.458	0.456	0.002
-2.635	-2.634	-0.001	45.958	0.958	0.956	0.002
-2.653	-2.652	-0.001	46.458	1.458	1.456	0.002
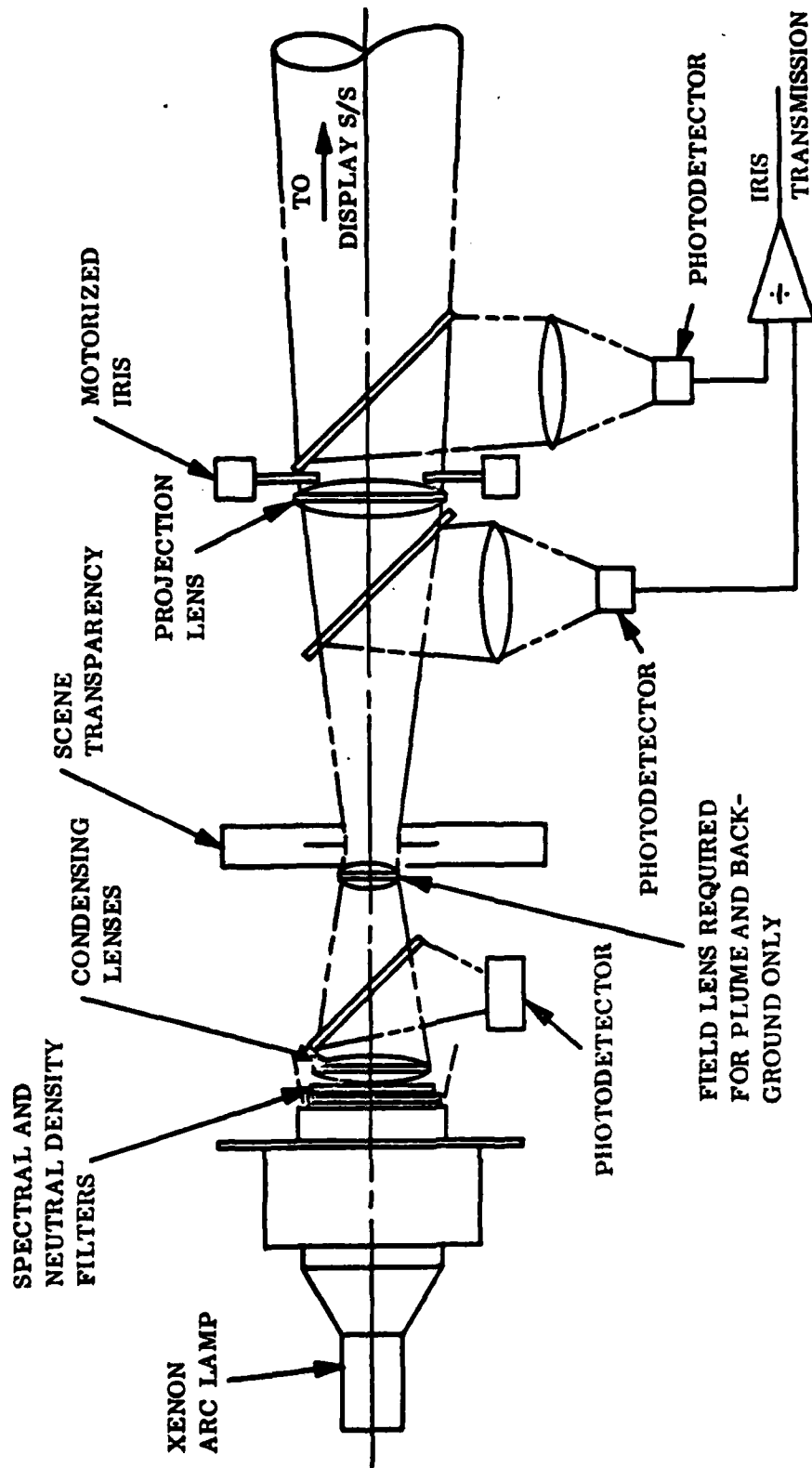
Figure 5-32. Single Purpose Infrared Projector

XENON
ARC LAMP

SPECTRAL AND
NEUTRAL DENSITY
FILTERS

CONDENSING
LENSES

SCENE
TRANSPARENCY

PHOTODETECTOR

FIELD LENS REQUIRED
FOR PLUME AND BACK-
GROUND ONLY

PHOTODETECTOR

PROJECTION
LENS

MOTORIZED
IRIS

TO
DISPLAY S/S

PHOTODETECTOR

IRIS
TRANSMISSION

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include (1) a source of radiation, (2) appropriate spectral and neutral density filters, (3) a condensing system to image the source onto the transparency plane, (4) a scene transparency, (5) a projection lens, and (6) the motorized iris. Also included are one photodetector to monitor, and provide the feedback for stabilization of source radiant intensity and two additional photodetectors to monitor the iris transmission factor and provide feedback to the iris controls. This type of projector will be used for the tailpipe, flare, plume, and infrared background. For the tailpipe, flare, and plume, the scene transparency will be a set of moving blades that control the apparent size of the target. In the background case, the transparency becomes a rotating cloud wheel producing a random background scene.

The dual purpose UV-Visible fuselage and background projector is somewhat more complex and is shown in Figure 5-33. The beam exiting from the first field lens is divided into two parts by a beamsplitter. Following the deviated path, the source is imaged on a cloud wheel transparency which is then imaged by a projection lens on the front surface of the highly polished transparency blades which act as an object to the main projection lens. Light passing through the hole produced by the blades is lost in the system, so that we have a background scene with a hole of variable size (i.e., the fuselage) in it. This hole is then filled by an image of the source whose brightness is less than that of the background scene, thereby producing the required fuselage/background contrast ratio of less than one.

5.3.3.1.2 Components Definition

Each of the seven infrared projection lenses will have a 5 inch focal length, a 1.75 inch diameter clear aperture, and be made of arsenic trisulfide and calcium fluoride. These projection lenses will exhibit less than 0.3 milliradian blur over a 1.15 degree field, with degrading performance up to the maximum seven degree field. The 1.15 degree field is required for a 1 meter tailpipe seen at 50 meters (minimum) range and demands sharp imagery. The plume and background, which occupy the larger field, are fuzzy in real life and, therefore, require no special performance levels from the projection lens.

The UV-Visible projector will use a doublet made of lithium fluoride and quartz as its projection lens. It has a 5-inch focal length, and a 1" diameter clear aperture. It must exhibit less than 0.3 milliradian blur over a seven degree field with poorer performance allowable from seven to 14 degrees.

5.3.3.1.3 Energy Source Selection

The selection criterion for evaluating sources for use in the projectors is their ability to achieve the required target radiance. The Infrared Simulation System is essentially

120
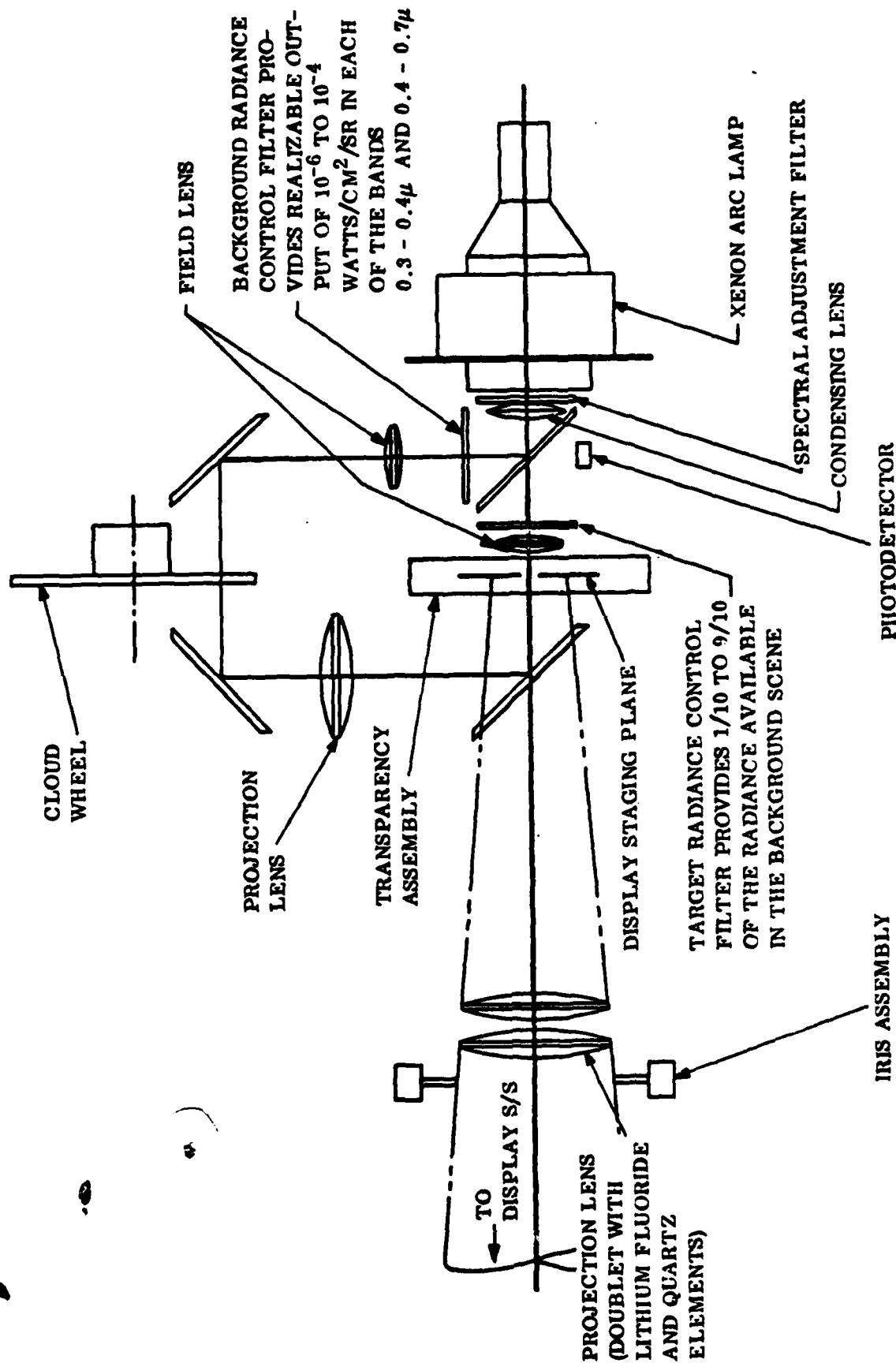
Figure 5-33. UV-Visible Background/Fuselage Projector

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specular, and in a specular optical system the image is as bright or as radiant as the source except for losses in transmission. The three sources of opacity in our system are:

(1) pupil expansion taking place in the display secondary

(2) reflection losses in the display mirrors

(3) transmission losses in the refractive elements of the projector.

As described in Section 5.2.3.4, the dimpled mirror is required to produce an exit beam 11.64 inches in diameter. The opacity due to this expansion is then:

$$0 = \frac{(11.64)^2}{D_P^2}$$

where D_P is the diameter of the projection lens exit pupil which varies according to the size of the field being projected. Each of the directional mirrors is 1.86 inches in diameter and has a path length of 3.6 inches from it to the projector pupil. This diameter then becomes:

$$D_P = 1.86 - (3.6)(2)(\tan \theta)$$

where θ is the half-field angle. The opacity traceable to all three sources is tabulated in Table 5-9.

Given the opacity of the mediating optics, it is possible to compare, for any given source, the required surface radiance with that available in the source. Such calculations, whose results are shown in Table 5-10, confirm that the Varian 150X8S Xenon Illuminator has the required capability to serve as a universal source. This lamp is a small, 5200°K solar simulator lamp with a sapphire window. The light emitted from the lamp is approximately collimated and spans the full spectral range of interest. Average working life is 1000 hrs.

5.3.3.1.4 Contingency Planning

Varian recently announced that production has temporarily been suspended because of seal problems. Therefore, a search for a second source was begun so that IRSS would not be delayed if Varian does not resume production in time. It was found the ILC Laboratories, Inc., also makes a Xenon short arc with a sapphire envelope. Its construction is more conventional, in that the envelope is tubular with no integral reflector. Its use, therefore, would require a slightly different condensing system. On the advice of Dr. John Emmett of the Naval Research Laboratories, the feasibility of using a Cesium (or Sodium) alkali-metal short arc lamp is also being investigated. The use of such a lamp in this application is a rather new development; however, the device has excellent properties in the 1 to 5 micron region. Quotations for a lamp

TABLE 5-9. SYSTEM OPACITY FOR VARIOUS TARGETS

	Pupil Expansion	Reflection 9 Mirrors	Transmission	System Opacity
Tailpipe & **Flare**	1.75" dia. projection lens $\varphi = \dfrac{(11.64)^2}{(1.75)^2}$ = 44.2	$\varphi_1 = \dfrac{1}{.98}$ = 1.02 $\varphi = \varphi_1^9$ = 1.12	2 lenses @ 1.25 3 windows @ 1.11 $\varphi = (1.25)^2 \times (1.11)^3$ = 2.14	106.0
Plume & **IR Background**	1.4" dia. projection lens $\varphi = \dfrac{(11.64)^2}{(1.4)^2}$ = 69.1	$\varphi_1 = \dfrac{1}{.98}$ = 1.02 $\varphi = \varphi_1^9$ = 1.12	3 lenses @ 1.25 3 windows @ 1.11 $\varphi = (1.25)^3 \times (1.11)^2$ = 2.67	206.0
Fuselage & **UV - Visible Background**	.91" dia. projection lens $\varphi = \dfrac{(11.64)^2}{(.91)^2}$ = 163.6	$\varphi_1 = \dfrac{1}{.86}$ = 1.163 $\varphi = \varphi_1^9$ = 3.88	4 lenses @ 1.25 1 beamsplitter @ 2 2 beamsplitters @ 3.3 2 windows @ 1.11 $\varphi = (1.25)^4 \times (2) \times (3.3)^2 \times (1.11)^2$ = 65.48	4.16×10^3

TABLE 5-10. RADIANCE REQUIREMENTS AND THE VARIAN 150X8S LAMP

Target	Spectral Band (μ)	Area (CM²)	Maximum Required Output	Apparent Target Radiance (Watts/CM²/SR)	System Opacity	Required Source Radiance (Watts/CM²/SR)	Available Source Radiance From Varian 150X8S Lamp (Watts/CM²/SR)
Tailpipe ◯ 1 Meter Dia.	1-3 }1-5 3-5	7.9×10^3	1000 Watts/SR	.13	106	15.8 128	440
Plume △ 1 Meter x 5 Meters	3-5	2.5×10^4	500 Watts/SR	.02	206	4.2	28
UV Background & Fuselage ▭ 3 Meters x 20 Meters	0.3-0.4 0.4-0.7	6.0×10^5	10^{-4} Watts/CM²/SR 10^{-4} Watts/CM²/SR	⟶ Same ⟶ Same	4.2×10^3	.42 .42	85 410
Flare ◯ 1 Meter Dia.		7.9×10^3	Up to 10 Times Any Target (2000K Profile)	$1.05 (1-3)$ $0.25 (3-5)$	106	111 26.5	440 30
Infrared Background	1-3 3-5	—	5.4×10^{-3} Watts/CM²/SR 1.4×10^{-4} Watts/CM²/SR	⟶ Same ⟶ Same	208	1.1 .29	440 30

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of this kind have been solicited from Holobeam, Inc., ILC Laboratories, Inc., and the Electro-Optical Systems Division of the Xerox Corporation. GE Drawing No. SK56205-914 shows the projector layouts and a layout of the projection subsystem (see Appendix C).

5.3.3.2 Transparency Design

5.3.3.2.1 Mechanical Design

All information with respect to size, shape, and aspect of the target is introduced through motion of the transparency mechanism. Three basic shapes are required: (1) a uniform circle (tailpipe and flare), (2) a rectangle of varying aspect (fuselage), and (3) a triangle of varying aspect (plume). Figure 5-34 shows how sliding metal vanes are used to synthesize these shapes and how the size is related to target range.

At the lower limit (i.e., a .05 meter radius flare at 5000 meters), the vane opening would need to be 5×10^{-5} inches, a clearly impractical limit for any electro-mechanical system. A more meaningful limit is obtained by limiting the minimum opening to a value commensurate with the resolution capabilities of the projection lens (which was described previously as 3×10^{-4} radians). This criterion would then limit the minimum vane opening to a more manageable 7.5×10^{-4} inches. In doing this, however, we introduce the problem of correct simulation of target radiance once the vanes have hit their stops. This can be accomplished easily by the additional refinement of engaging a servo-controlled iris at the transition point as illustrated graphically in Figures 5-35, 5-36, and 5-37. There the transparency vane position and iris transmission requirements are shown for the tailpipe/flare, plume, and fuselage. The mechanical and servo design of the iris will be discussed in Section 5.3.3.3.

Figure 5-38 illustrates the mechanical design concept and identifies the major components of one channel (i.e., 2 vanes) of a two-channel tailpipe/flare transparency. The drive mechanism uses preloaded (i.e., zero backlash) ball nuts to transform rotary motion to linear motion. The screw has a ground thread with a cumulative lead accuracy of .0005 in/ft. The running friction is typically 10% of the running torque with a 1% friction ripple. The screw lead (i.e., .0625 in) is sized to require something close to a full rotation of the screw (i.e., 288°) for full linear travel. Use of this technique, and the very high accuracy of the screw lead, permit a single turn potentiometer to be used as the position transducer after initial calibration.

The fuselage and plume transparencies will use the same concept but the screw lead will be .333 in. and the vanes will be shaped differently. Detailed layouts of the three transparency mechanisms are included in Appendix C (GE Drawings 47R196993, 47E193825, and 47R196994).

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UNIFORM CIRCLE

RECTANGLE OF
VARIABLE ASPECT

TRIANGLE OF
VARIABLE ASPECT
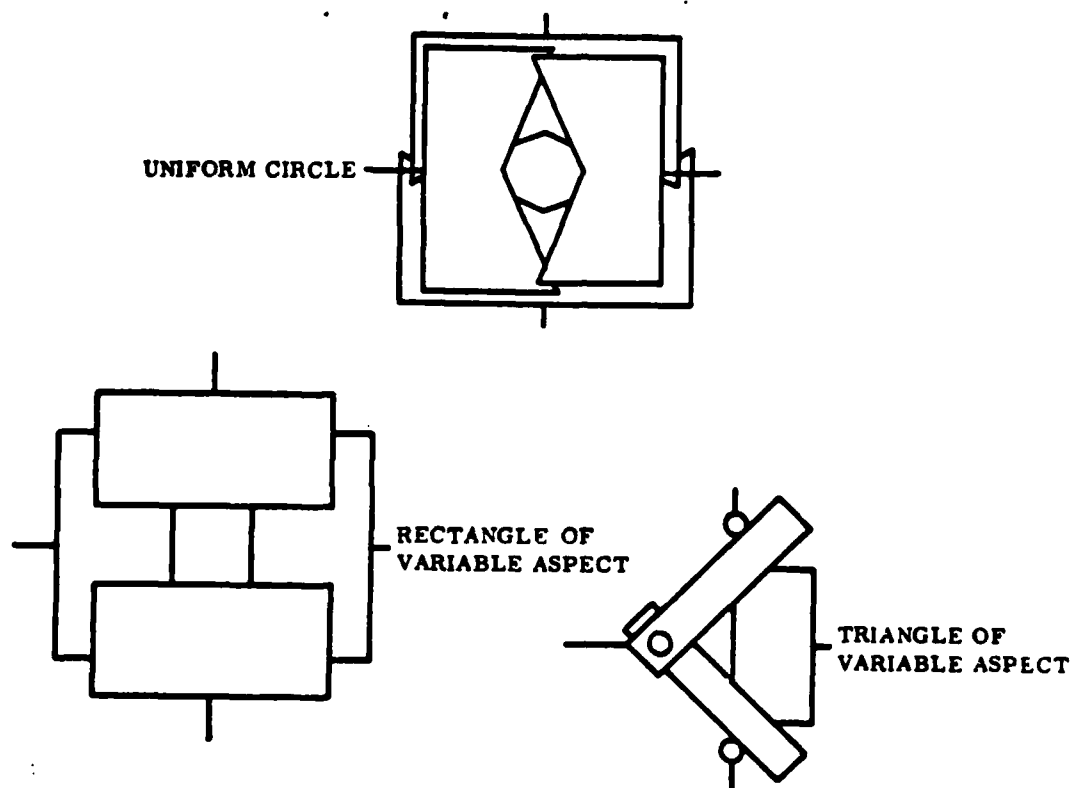
Synthesis of Target Shapes with Sliding Blades

VANE
DISPLACEMENT
(X)

PROJECTION
LENS

TARGET
RADIUS
(r)

FOCAL LENGTH (f)

TARGET RANGE R

$$X = \frac{rf}{R}$$

$$\dot{X} = -\frac{rf}{R^2}\ \dot{R}$$

$$\ddot{X} = \frac{2rf}{R^3}\ \dot{R}^2 - \frac{rf}{R^2}\ \ddot{R} \quad \nearrow \quad 0,\ \text{since } \ddot{R} = 0$$
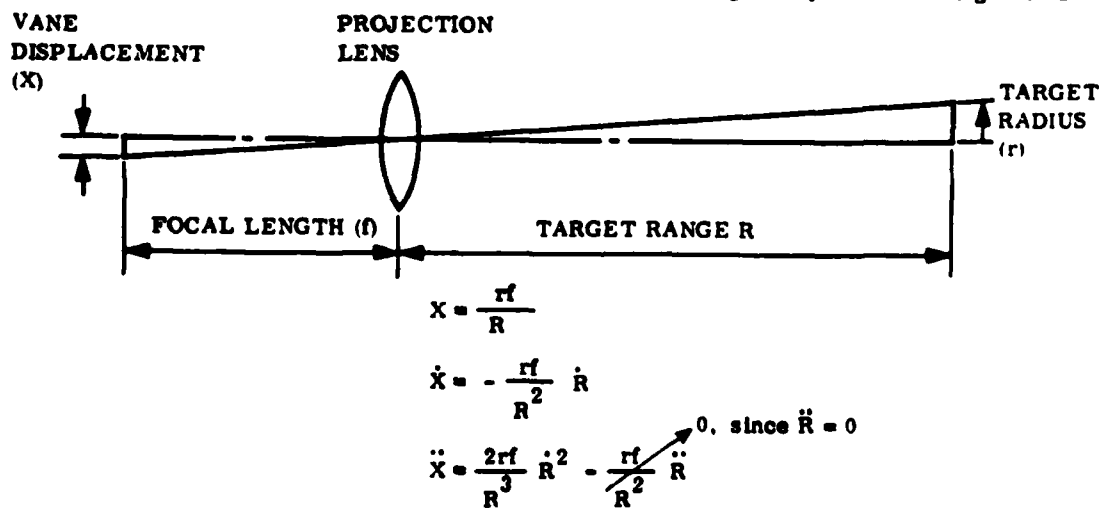
Figure 5-34.   Target Size and Shape Synthesis
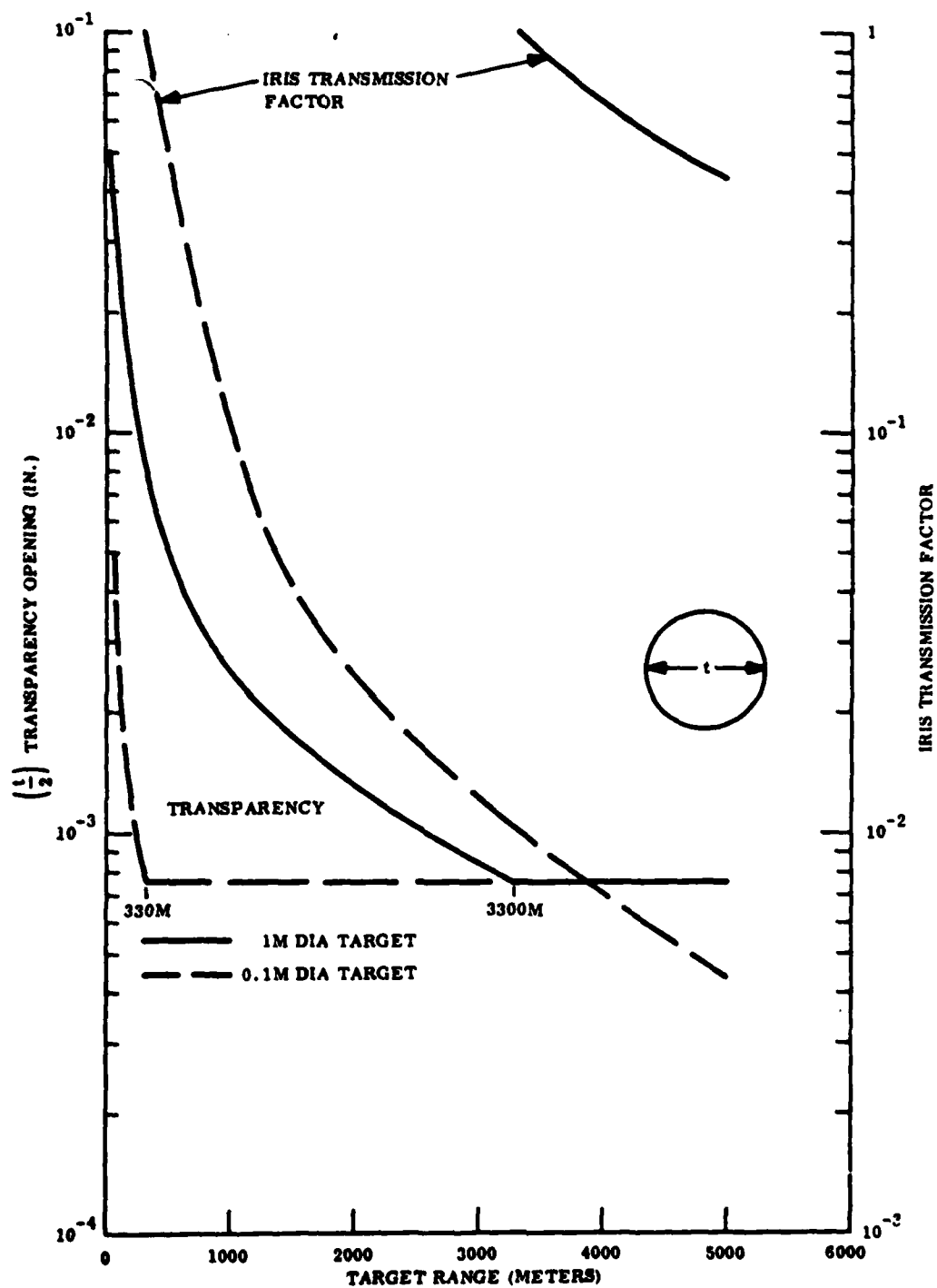
Figure 5-35. Tailpipe and Flare Transparency Vane Opening and Iris Transmission
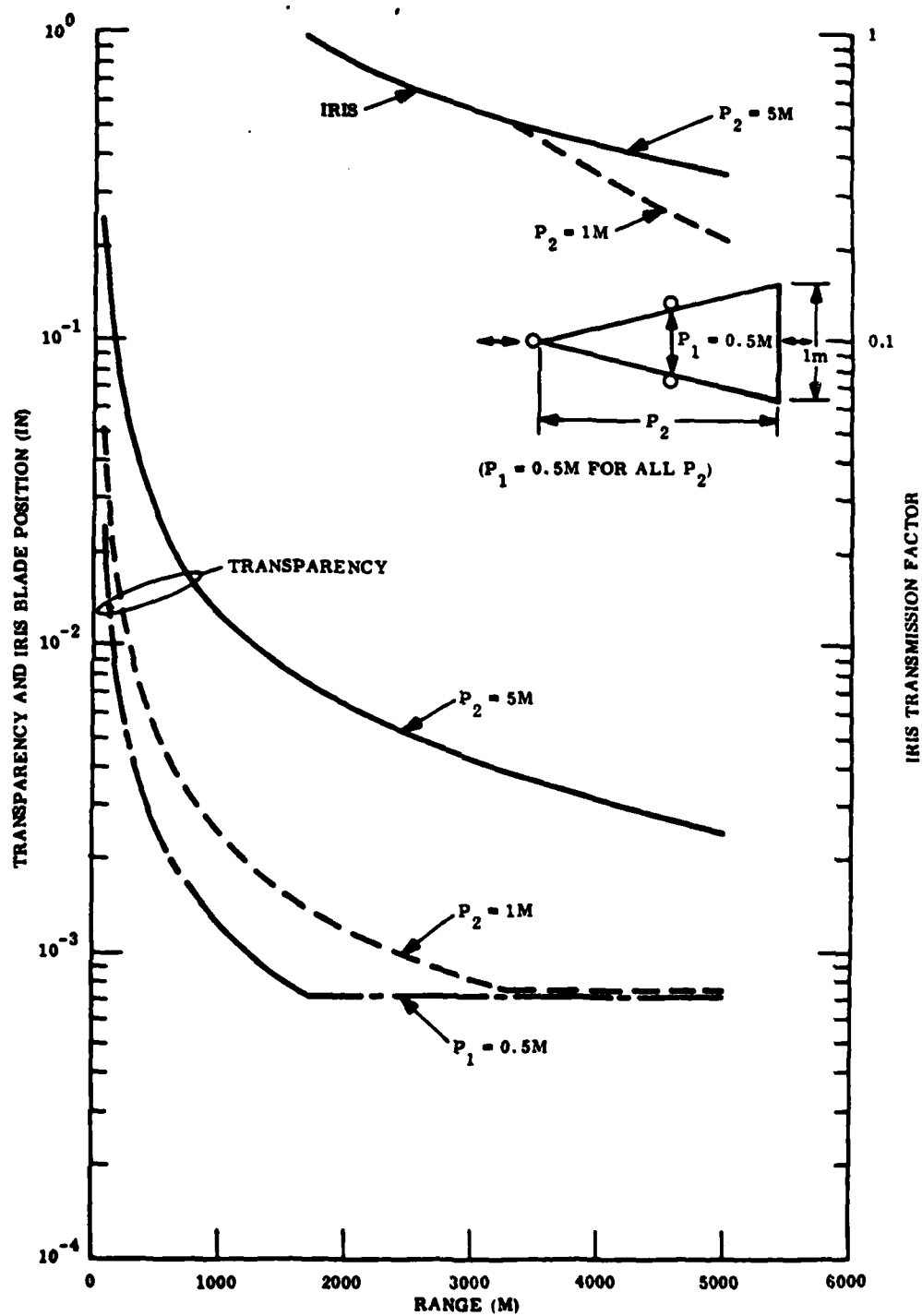
Figure 5-36. Plume Transparency Vane Opening and Iris Transmission
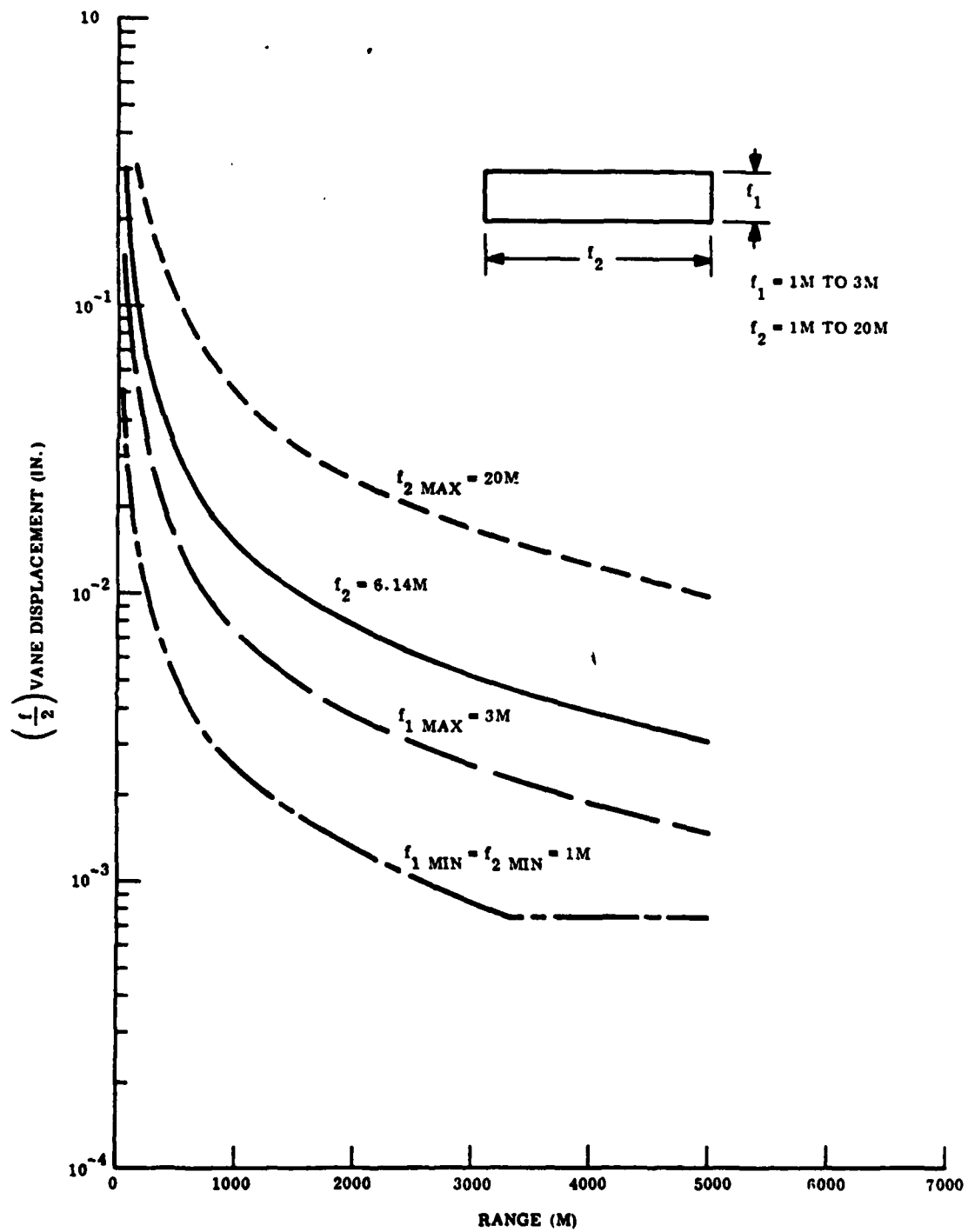
Figure 5-37. Fuselage Vane Opening for Transparency
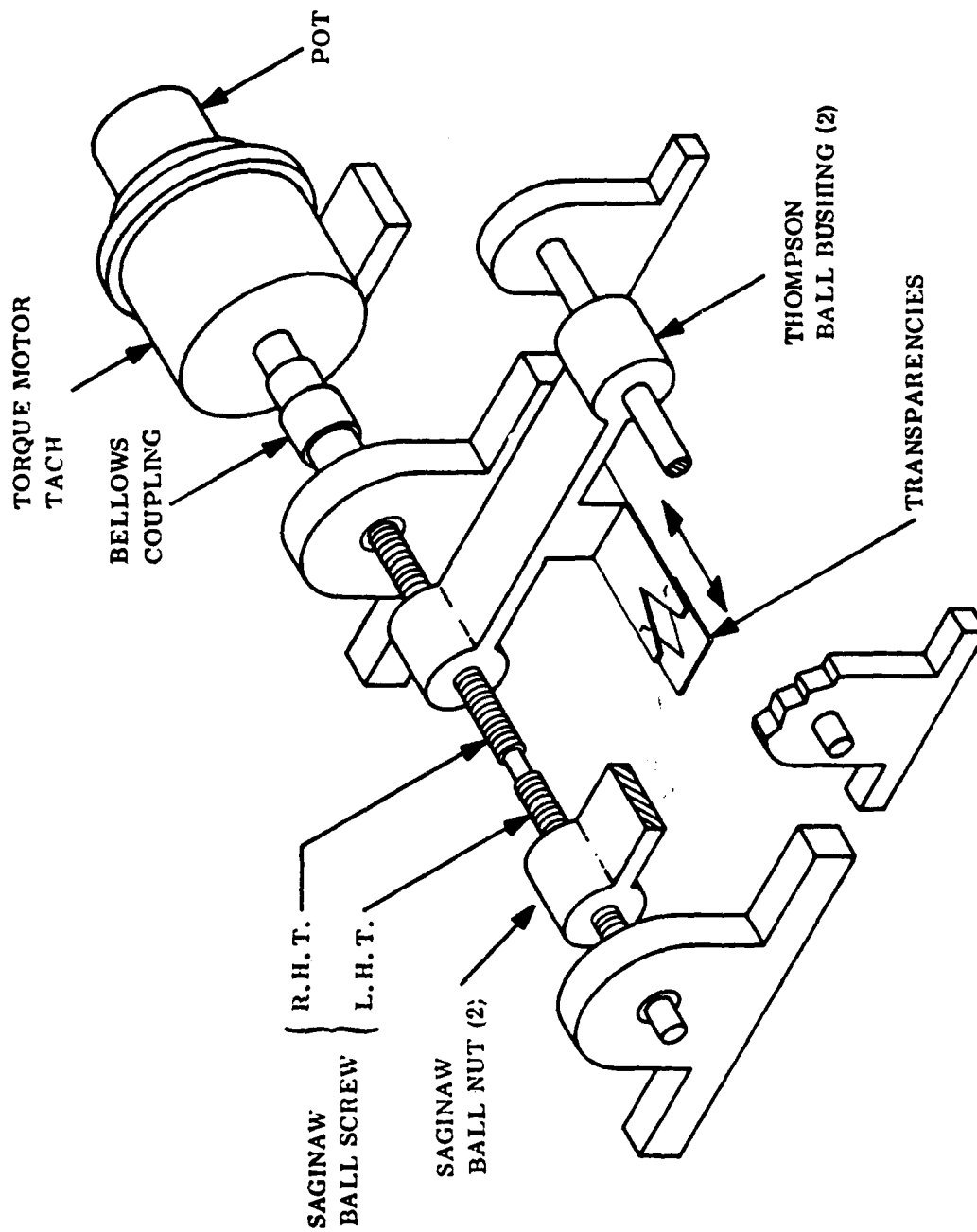
Figure 5-38. Transparency Mechanism (One Channel)

5.3.3.2.2 Servo Analysis

5.3.3.2.2.1 Tailpipe and Flare Servo

a) <u>Requirements and Design Rationale.</u> - The tailpipe and flare servos' position range is 5.0×10^{-2} inches. The bias error shall be less than 1.88×10^{-5} inches, and the repeatability error shall be less than 3.8×10^{-6} inches at the smallest opening. The dynamic lag error shall be less than 1.25×10^{-4} inches at the maximum velocity and acceleration. The servo must follow position commands that move with an acceleration of 90 inches/sec^2 up to a velocity of 1.5 inches/sec.

Since maximum positional accuracy is required only at minimum vane openings, the position potentiometer will likewise be required to maintain the specified .025% accuracy specification only over a relatively small band, and may be allowed to degrade as the opening increases. To this end, the potentiometer will be custom compensated to meet the .025% linearity over a small rotational sector at the low end of its travel.

A tachometer is used with a feedforward servo velocity command to the tach loop to reduce the servos' dynamic lag error. This tachometer will also be used to reduce the servo error caused by friction.

The servos' compensation and open loop crossover frequency are selected to keep the servos' dynamic lag error to less than 1.25×10^{-4} inches and errors caused by static friction to less than the 3.8×10^{-6} inches repeatability error.

In order to insure that the servos' settling time is less than the time it takes its position command to reach a velocity of 1.4 inches/sec moving with an acceleration of 90 in/sec^2, an open loop crossover frequency, ω_c, of 900 rad/sec is used. Assuming a reasonable settling time, t_s, of one-third the time it takes to reach the 1.5 in/sec velocity, then it follows that $t_s = 1/3(1.5/90) = 1/180$ sec. The relation between crossover frequency and settling time is approximately $\omega_c = 5/t_s$ and, therefore, the tailpipe and flare servos' crossover frequency is $\omega_c = (5)(180) = 900$ rad/sec.

b) <u>Component Definition.</u> - The tailpipe and flare motor load inertia is 0.023 oz-in.sec^2. The motor is required to accelerate the load to 9000 rad/sec^2 (90 in/sec^2 through a 16 turns/inch ball screw), to a velocity of 150 rad/sec (1.5 in/sec through a 16 turns/inch ball screw). A PMI (U12M4) motor, which can generate the required torque (250 in-oz) at this high velocity of 150 rad/sec, is used.

A Magtech (2375-06) tachometer which has a maximum operating speed of 180 rad/sec is the rate pack-off component selected.

The custom compensated potentiometer described previously will be used for position sensing.

The tailpipe and flare servo components are given in Figure 5-39.

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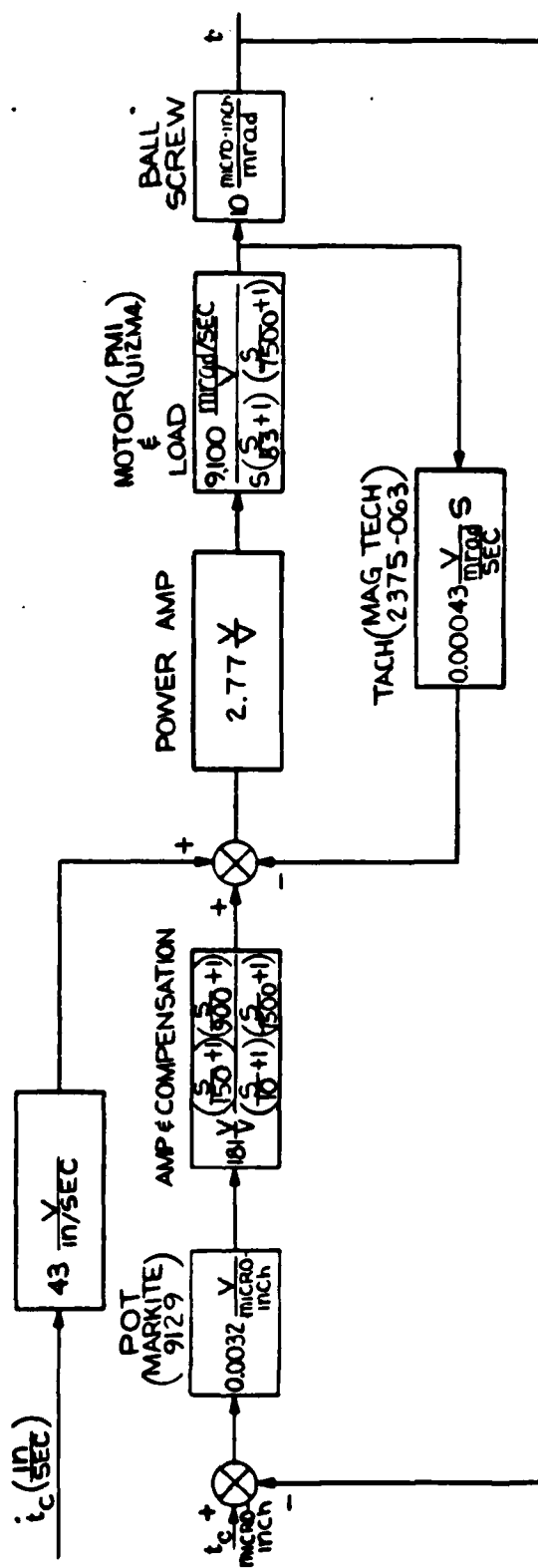
Figure 5-39. Tailpipe and Flare Servo Block Diagram

c) <u>Servo Amplifier Gains and Compensation Network Definition.</u> - The servo ampli-
fier gains and compensation networks are given in Figure 5-39. The series com-
pensation was chosen so that the open loop transfer function's crossover frequency
is 70 rad/sec, as required, and the open loop gain (13,500) is large enough to reduce
the dynamic lag error below the 1.25×10^{-4} inches required. The series compen-
sation's lag-lead network (S/150 + 1)/(S/10 +1) is needed to reduce the open loop gain
to 0 db at the 900 rad/sec crossover frequency and still provide the lead needed for
a well-damped servo transient response. The compensation's lead network (S/900 + 1)/
(S/7500 + 1) cancels the closed tach loop transfer function pole at 900 rad/sec and
replaces it with a pole at 7500 rad/sec.

The tachometer feedback loop acts to increase the motor mechanical pole from
83 rad/sec to 900 rad/sec.

The open loop transfer function can be determined from Figure 5-39 by first determin-
ing the closed tach loop transfer function

$$\frac{G}{1 + GH} = \frac{2,320}{S(S/900 + 1)\,(S/7500 + 1)}$$

and then multiplying all transfer functions. The open loop transfer function is:

$$GOL = \frac{1350\,(S/150 + 1)}{S(S/10 + 1)\,(S/7500 + 1)^2}$$

d) <u>Servo Performance.</u> - The low frequency torque disturbance response is less than
1/30 microinch/in-oz. (see Figure 5-40) and, therefore, with even 10 in-ozs. of
static friction torque, the resulting error is much less than the allowed servo repeata-
bility error of 3.8 microinches. The servo repeatability error will, therefore, be
determined by the pot repeatability and this corresponds to less than 2 microinches.
The servo bias error is determined by the pot accuracy (assuming a linear and zero
backlash ball screw) and this corresponds to less than the 1.88×10^{-5} inches required.

The dynamic lag error, E, for the tailpipe and flare servo with a velocity command
fed to the tach loop is:

$$E = \frac{\dot{t}\,(1 - C)}{K} + \frac{\left[K\,(\tau_1 - \tau_2) - 1\right]}{K^2}\,\ddot{t}\,(1 - C)$$

where $\tau_1 = 1/10$ sec, $\tau_2 = 1/150$ sec, $K = 13.5 \times 10^3$ sec^{-1}, $\dot{t} = 1.5$ in/sec, $\ddot{t} =$
90 in/sec^2, and C is the amount of true velocity command fed to the tach loop (a 10%
velocity error means 90% true velocity and C = 0.90).
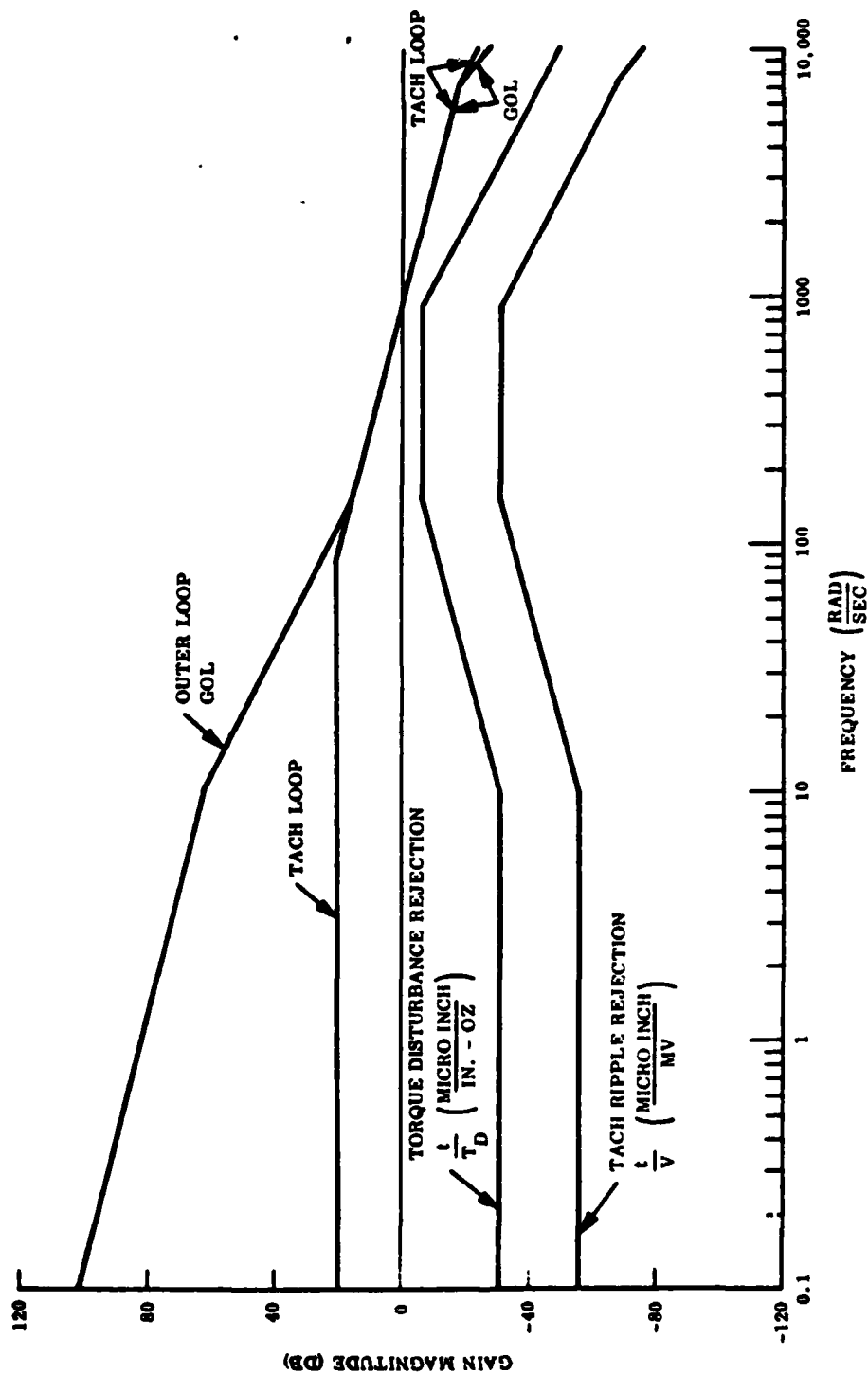
Figure 5-40. Tailpipe and Flare Servo Bode Diagram

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Substituting these tailpipe and flare servo parameters along with C = 0.90 (a velocity command with a 10% error can easily be generated) into the dynamic lag error formula results in a dynamic lag error of 0.845 x 10^{-4} inches and this is less than the 1.25 x 10^{-4} inches allowed.

The repeatability, bias, and dynamic lag error budgets are, therefore, all met by the tailpipe and flare servo.

5.3.3.2.2.2 <u>Plume "P_1" Servo.</u> - The Plume "P_1" servo requirements justify this servo being the same as the tailpipe and flare servo. The plume "P_1" servos position range is 2.5 x 10^{-2} inches (one-half of that of the tailpipe and flares servo). The bias error shall be less than 1.88 x 10^{-5} inches and the repeatability error shall be less than 3.8 x 10^{-6} inches (both the same as those of the tailpipe and flare servo). The plume "P_1" servo must follow position commands that move with an acceleration of 45 in/sec^2 up to a velocity of 0.75 in/sec. These commands are both one-half of those of the tailpipe and flare servo; however, the settling time (t_s = 1/3 (0.75/45) = 1/180 sec) and hence, the open loop crossover frequency (ω_c = 5/t_s = 900 rad/sec) of the plume "P_1" servo are required to be equal to those of the tailpipe and flare servo.

The Plume "P_1" servos amplifier gains, compensation networks, and components are the same as those of the tailpipe and flare servos and are given in Figure 5-39.

The Plume "P_1" servos Bode diagram torque rejection and tach ripple rejection are the same as those of the tailpipe and flare servos and are given in Figure 5-40.

Since the Plume "P_1" servo requirements are equal or less than those of the tailpipe and flare servos, this servo's repeatability, bias, and dynamic lag error budgets are, therefore, all met.

5.3.3.2.2.3 <u>Plume "P_2" Servo</u>

a) <u>Requirements and Design Rationale.</u> - The plume "P_2" servos position range is 0.25 inches. The bias error shall be less than 4.25 x 10^{-5} inches and the repeatability error shall be less than 0.85 x 10^{-5} inches at minimum opening. The dynamic lag error shall be less than 1.25 x 10^{-3} inches at maximum velocity and acceleration. The servo must follow position commands that move with an acceleration of 450 inches/sec^2 up to a velocity of 4.5 inches/sec.

A high accuracy potentiometer will sense motor shaft angle with an accuracy corresponding to better than 4.25 x 10^{-5} inches at the plume vane (motor shaft drives the vane through a zero backlash 3 turns/inch ball screw).

A tachometer is used with a feedforward servo velocity command to the tach loop to reduce the servo's dynamic lag error. This tachometer will also be used to reduce the servo error caused by friction.

The servo's compensation and open loop crossover frequency are selected to keep its dynamic lag error to less than 4.25×10^{-5} inches and errors caused by static friction to less than 0.85×10^{-5} inches repeatability error.

In order to insure that the servo's settling time is less than the time it takes its position command to reach a velocity of 4.5 inches/sec moving with an acceleration of 270 inches/sec^2, an open loop crossover frequency, ω_c, of 900 rad/sec is used. Assuming a reasonable settling time, t_s, of one-third the time it takes to reach the 4.5 inches/sec velocity, then it follows that $t_s = 1/3 \, (4.5/270) = 1/180$ sec. The relation between crossover frequency and settling time is approximately $\omega_c = 5/t_s$ and, therefore, the Plume "P$_2$" servo's crossover frequency is $\omega_c = (5) (180) =$ 900 rad/sec.

b) Component Definition. - The plume "P$_2$" servo motor load inertia is 0.023 oz-in sec^2. The motor is required to accelerate the load to 8,500 rad/sec^2 (450 in/sec^2 through a 3 turns/inch ball screw) to a velocity of 142 rad/sec (7.5 in/sec also through a 3 turns/inch ball screw). A PMI (U12M4) motor which can generate the required torque (240 in-oz) at this high velocity of 142 rad/sec is used.

A Magtech (2375-06) tachometer which has a maximum operating speed of 180 rad/sec. is the rate device selected.

The custom compensated potentiometer described in paragraph 5.3.3.2.2.1 will be used here also but its accuracy at the low end must be increased to .01%.

The tailpipe and flare servo components are given in Figure 5-41.

c) Servo Amplifier Gains and Compensation Network Definition. - The servo amplifier gains and compensation networks are given in Figure 5-41. The series compensation was chosen so that the open loop transfer function's crossover frequency is 70 rad/sec, as required, and the open loop gain (13,500) is large enough to reduce the dynamic lag error below the 1.25 inches required. The series compensation's lag-lead network $(S/150 + 1)/(S/10 + 1)$ is needed to reduce the open loop gain to 0 db at the 90° rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response. The compensation's lead network $(S/900 + 1)/$ $(S/7500 + 1)$ cancels the closed tach loop transfer function pole at 900 rad/sec and replaces it with a pole at 7500 rad/sec.

The tachometer feedback loop acts to increase the motor mechanical pole from 83 rad/sec to 900 rad/sec.

The open-loop transfer function can be determined from Figure 41 by first determining the closed tach loop transfer function

$$\frac{G}{1 + GH} = \frac{2,320}{S(S/900 + 1)\,(S/7500 + 1)}$$
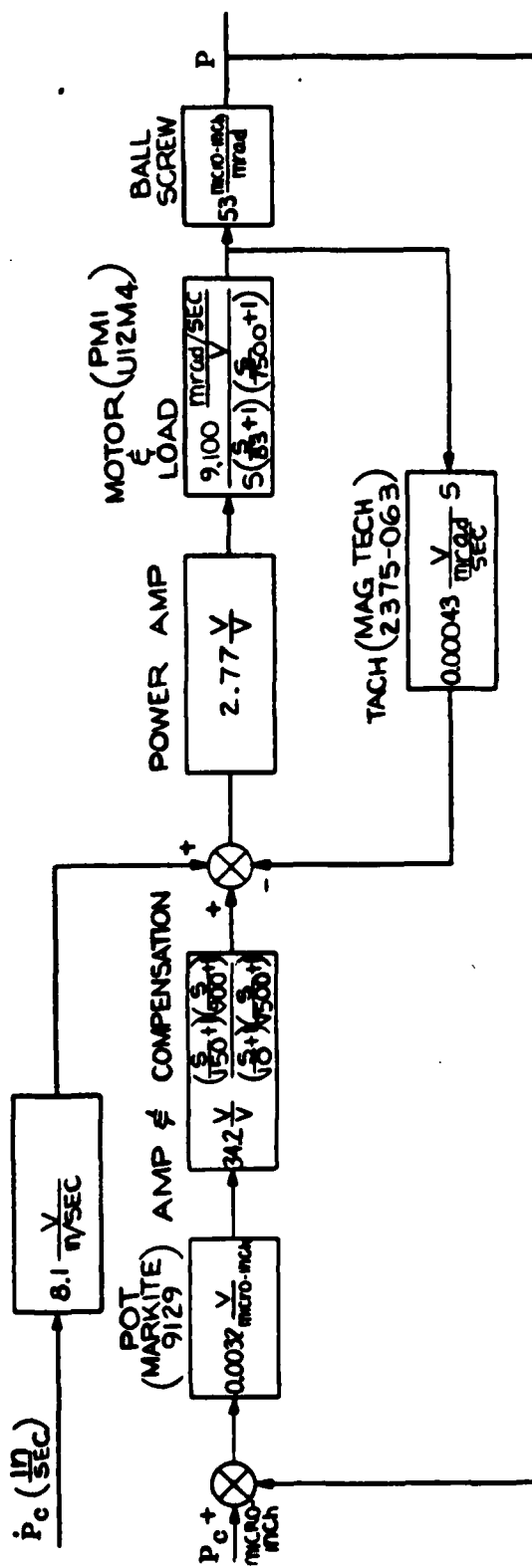
Figure 5-41. Plume "P_2" Servo Block Diagram

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and then multiplying all transfer functions. Neglecting the poles at .7500 rad/sec, the open loop transfer function is:

$$GOL = \frac{1350 \ (S/150 + 1)}{S \ (S/10 + 1) \ (S/7500 + 1)^2}$$

d) **Servo Performance.** - The low frequency torque disturbance response is less than 1/6 microinch/in-oz (see Figure 5-42) and, therefore, even with 10 in-ozs of static friction torque, the resulting error is much less than the allowed servo repeatability error of 8 microinches. The servo repeatability error will, therefore, be determined by the pot repeatability and this corresponds to less than 7 microinches. The servo bias error is determined by the pot accuracy (assuming a linear and zero backlash ball screw) and this corresponds to less than the 6.75×10^{-5} inches required.

The dynamic lag error, E, for the plume "P_2" servo with a velocity command fed to the tach loop is:

$$E = \frac{\dot{P} \ (1 - C)}{K} + \frac{\left[K \ (\tau_1 - \tau_2) - 1 \right] \ \ddot{P} \ (1 - C)}{K^2}$$

where $\tau_1 = 1/10$ sec, $\tau_2 = 1/150$ sec, $K = 13.5 \times 10^3 \text{sec}^{-1}$, $\dot{P} = 7.5$ in/sec, $\ddot{P} = 450 \ \text{in/sec}^2$ and C is the amount of true velocity command fed to the tach loop (a 10% velocity error means 90% true velocity and $C = 0.90$).

Substituting these plume "P_2" servo parameters along with $C = 0.90$ (a velocity command with a 10% error can easily be generated) into the dynamic lag error formula results in a dynamic lag error of 0.423×10^{-3} inches, which is less than the 1.25×10^{-3} inches allowed.

The repeatability, bias, and dynamic lag error budgets are therefore all met by the plume "P_2" servo.

5.3.3.2.2.4 **Fuselage "f_1" Servo.** - The fuselage "f_1" servo requirements justify this servo being the same as the plume "P_2" servo. The fuselage "f_1" servo's position range is 0.15 inches (80% of that of the plume "P_2" servo). The bias error shall be less than 4.25×10^{-5} inches and the repeatability error shall be less than 8.5×10^{-6} inches (the same as the P_2 servo). The fuselage "f_1" servo must follow position commands that move with an acceleration of 270 in/sec^2 up to a velocity of 4.5 in/sec. These commands are both 60% of those of the plume "P_2" servo, however, the settling time ($t_s = 1/3 \ (4.5/270) = 1/180$ sec) and, hence, the open loop crossover frequency ($\omega_c = 5/t_s = 900$ rad/sec) of the fuselage "f_1" servo is required to be equal to those of the plume "P_2" servo.

The fuselage "f_1" servos amplifier gains, compensation networks, and components are the same as those of the plume "P_2" servos and are given in Figure 5-41.

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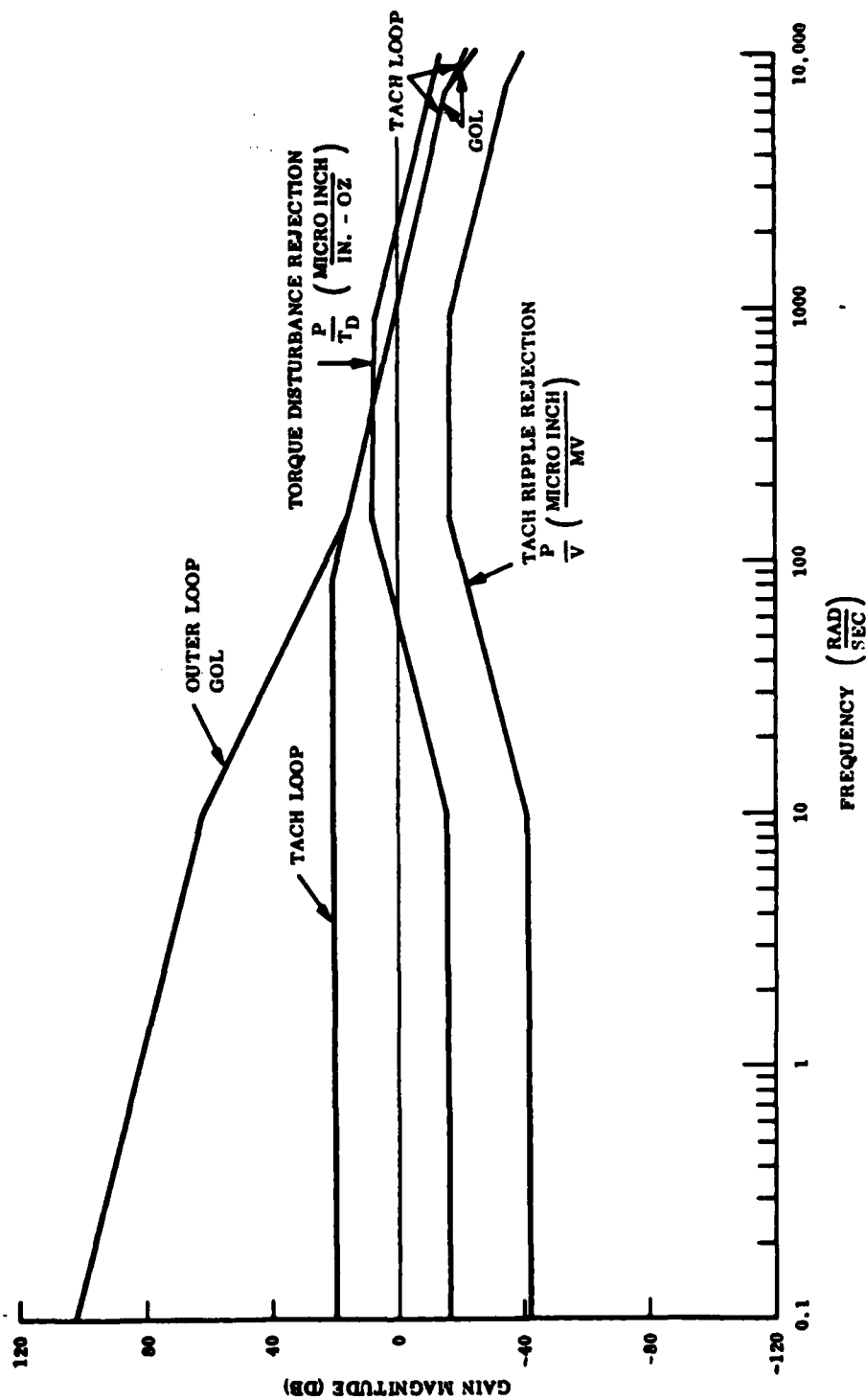
Figure 5-42. Plume "P$_2$" Servo Bode Diagram

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The fuselage "f_1" servo's Bode diagram, torque rejection, and tach ripple rejection are the same as those of the plume "P_2" servos and are given in Figure 4-42.

Since the fuselage "f_1" servo requirements are equal to or less than those of the plume "P_2" servos, the fuselage "f_1" servos repeatability, bias, and dynamic lag error budgets are, therefore, all met.

5.3.3.2.2.5 Fuselage "f_2" Servo. - The fuselage "f_2" servo requirements justify this servo being the same as the plume "P_2" servo. The fuselage "f_2" servo's position range is .3 inches (120% of that of the plume "P_2" servo). The bias error shall be less than 4.25×10^{-5} inches and the repeatability error shall be less than 8.5×10^{-6} inches (the same as the P_2 servo). The fuselage "f_2" servo must follow position commands that move with an acceleration of 550 in/sec^2 up to a velocity of 90 in/sec.

These commands are only 20% higher than the plume "P_2" servo and these higher rates and accelerations are within the capability of the "P_2" servo. Furthermore, the dynamic lag error resulting from these higher commands is $.51 \times 10^{-3}$ inches (20% higher than "P_2" servo dynamic lag error of $.423 \times 10^{-3}$ inches) and this is less than the 1.25×10^{-3} inches allowed.

The settling time ($t_s = 1/3 \ (9.2/530) = 1/180$ sec), and, hence, the open loop crossover frequency $\omega_c = 5/t_s = 900$ rad/sec) of the fuselage "f_2" servo, is required to be equal to those of the plume "P_2" servo.

The fuselage "f_2" servos amplifier gains, compensation networks, and components are the same as those of the plume "P_2" servos and are given in Figure 5-41.

The fuselage "f_2" servos Bode diagram, torque rejection, and tach ripple rejection are the same as those of the plume "P_2" servos and are given in Figure 5-42.

The fuselage "f_2" servos repeatability, bias, and dynamic lag error budgets are, therefore, all met.

5.3.3.3 Iris Design

5.3.3.3.1 Requirements

The iris transmission requirements are given in Figures 5-35 and 5-36 for the tailpipe/flare and plume, respectively. Rather than inferring the transmission factor from the diameter of the opening for these projectors, it has been decided to use two photodetectors and to take the ratio of their outputs as a direct measurement of transmission.

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This step is necessary for two reasons: (1) the illumination across the aperture is not expected to be perfectly uniform, and (2) the apparent target radiance must be controlled to 5%.

For the fuselage/UV-Visible projector and the infrared background projector, the object radiance need not be varied during an intercept. It is, therefore, satisfactory to use a potentiometer as a feedback element. Once the projector output has been calibrated, any desired value of object radiance may be obtained by setting the iris diameter with a potentiometer in the control console.

5.3.3.3.2 Design Details

The mechanism uses a commercially available 20-leaf iris driven by a DC torque motor through a 2:1 gear train as shown in GE Drawing #SK56205-903, which is included in Appendix C.

The iris transmission factor (T) is given by:

$$T = \frac{d^2}{(44)^2}$$

where d is the diameter of the instantaneous iris opening in millimeters and 44 millimeters is the diameter of the maximum opening. The most severe iris requirements occur when a .1 meter diameter flare is being simulated (see Figure 5-33). Since the range accuracy requirements extend only to 1500 meters, this corresponds to a minimum transmission value of .04 or a diameter of 8.8 mm. Since it is the area of the aperture that must be controlled to 5%, the instantaneous diameter must be accurate to 2.25% or .2 mm.

5.3.3.3.3 Iris Servo Analysis

a) Requirements and Design Rationale. - The iris servo's position (iris diameter) range is 44mm. The servo's bias error shall be less than 0.20mm at minimum opening. The servo's dynamic lag error shall be less than 1mm at maximum opening. The servo must follow position commands that move with an acceleration of 1650 mm/sec^2 up to a velocity of 180 mm/sec.

An iris transmission sensor detects radiation transmission through the iris with an accuracy corresponding to better than 0.20 mm at the iris. Since the transmission sensor's gain is nonlinear, a linearizing function generator is placed at the output of this sensor so as to maintain a linear open loop servo gain.

A tachometer is used to reduce the servo error caused by friction.

The servo's compensation and open loop crossover frequency are selected to keep the servo's dynamic lag error to less than 1 mm and errors caused by static friction to much less than 0.20 mm.

In order to insure that the servo's settling time is less than the time it takes the servo's position command to reach a velocity of 180 mm/sec moving with an acceleration of 1650 mm/sec^2, the open loop crossover frequency, ω_c, of 150 rad/sec is used. Assuming a reasonable settling time, t_s, of one-third the time it takes to reach the 180 mm/sec. velocity, then it follows that $t_s = 1/3$ (180/1650) = 1/30 sec. The relation between crossover frequency and settling time is approximately $\omega_c = 5/t_s$ and, therefore, the iris servo's crossover frequency is ω_c = (5) (30) = 150 rad/sec.

b) <u>Component Definition</u>. - The iris servos' motor load inertia is 0.015 oz-in-sec^2. The motor is required to accelerate the load to 82 rad/sec^2 (1650 mm/sec^2 through a 18.2 mm/rad iris opening mechanism). It is the Inland (T-1352) 20 in-oz. motor. An Inland 50A 50 watt amplifier is used with this motor.

A Magtech (2375-06) tachometer is used. The iris servo's components are given in Figure 5-43.

c) <u>Servo Amplifier Gains and Compensation Network Definition.</u> - The servo amplifier gains and compensation networks are given in Figure 1. The series compensation was chosen so that the open loop transfer function's crossover frequency is 150 rad/sec, as required, and the open loop gain (4,500) is large enough to reduce the dynamic lag error below the 0.22 mm required. The series compensation's lag-lead network (S/30 + 1)/(S/1 + 1) is needed to reduce the open loop gain to 0 db at the 150 rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response. The compensation's lead network (S/150 + 1)/(S/1500 - 1) cancels the closed tach loop transfer function pole at 150 rad/sec and replaces it with a pole at 1500 rad/sec. This pole only adds 6 degrees of phase shift at the 150 rad/sec crossover frequency.

The tachometer feedback loop acts to increase the motor mechanical pole from 3 rad/sec. to 150 rad/sec.

The open-loop transfer function can be determined from Figure 5-43 by first determining the closed tach loop transfer function

$$\frac{G}{1 + GH} = \frac{2,300}{S(S/70 - 1)(S/3,333 + 1)}$$

and then multiplying all transfer functions. Neglecting the pole at 2500 rad/sec, the open loop transfer function is:

$$GOL = \frac{4,500 \ (S/30 + 1)}{S \ (S/1 + 1) \ (S/1500 + 1)}$$

d) <u>Servo Performance.</u> - The low frequency torque disturbance rejection (see Figure 5-44) is about 1/900 mm/in-oz. and, therefore, even with 10 in-ozs of static
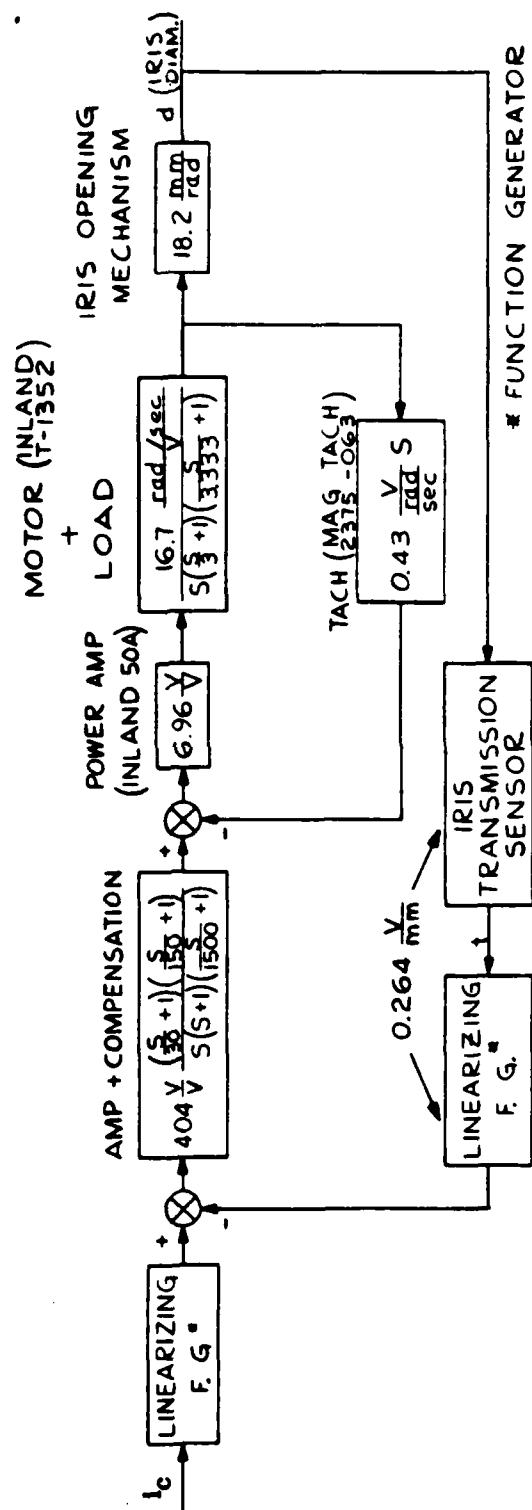
Figure 5-43. Iris Servo Block Diagram
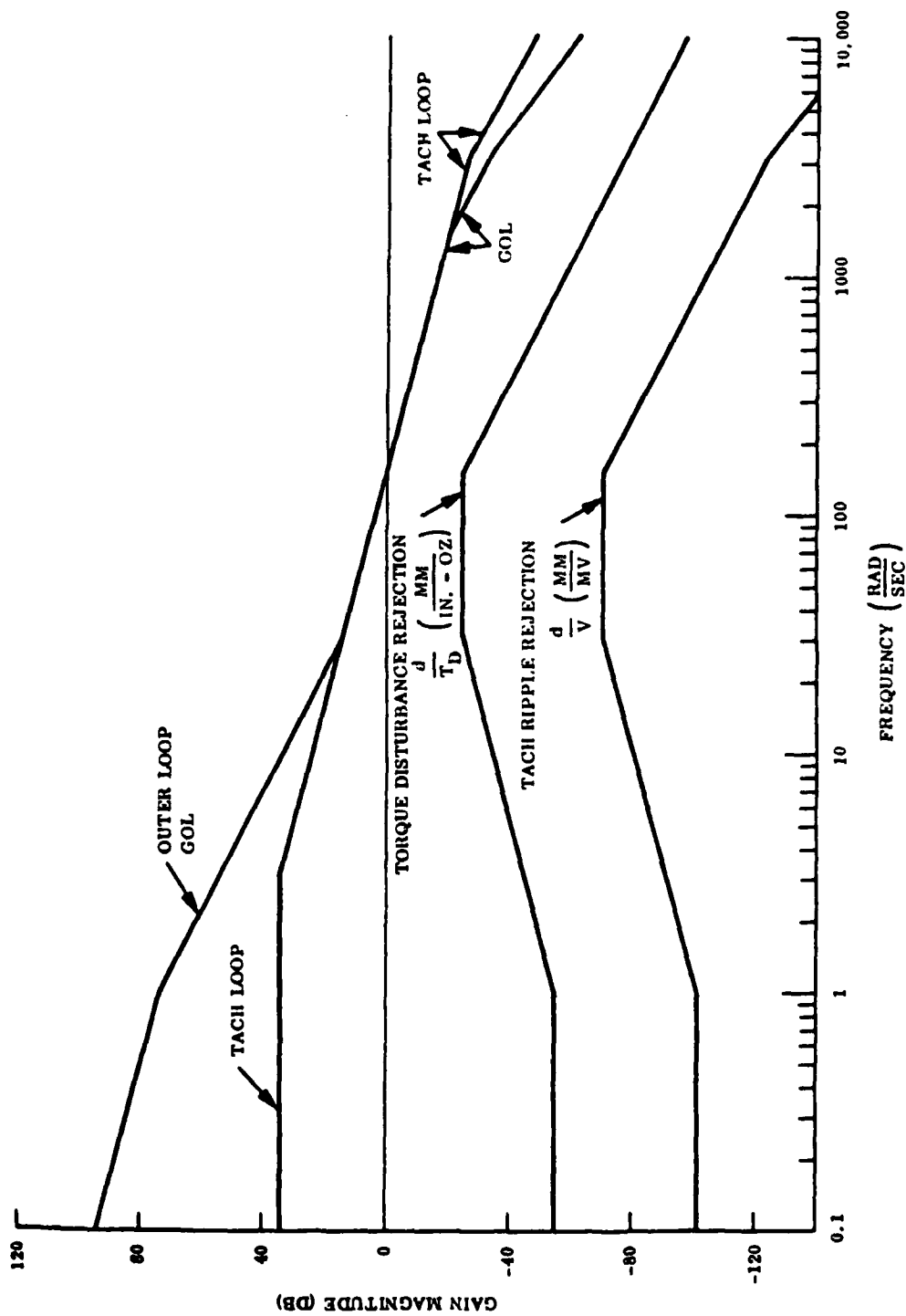
Figure 5-44. Iris Servo Bode Diagram

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friction torque, the resulting servo error is much less than the allowed servo bias error of 0.20 mm. The servo bias error will, therefore, be determined by the iris transmission sensor accuracy and this corresponds to less than 0.20 mm at the iris.

The dynamic lag error, E, for this iris servo is:

$$E = \frac{\dot{d}}{K} + \frac{\ddot{d} \, K (\tau_1 + \tau_3 - \tau_2) - 1}{K^2}$$

where $\tau_1 = 1$ sec, $\tau_2 = 1/30$ sec, $\tau_3 = 1/1500$ sec, $K = 4,5000$ sec^{-1}, $\dot{d} = 180$ mm/sec, and $\ddot{d} = 1650$ mm/sec^2.

Substituting these iris servo parameters into the dynamic lag error formula results in a dynamic lag error of 0.4 mm and this is less than the 1 mm allowed.

The bias and dynamic lag error budgets are therefore both met by the iris servo.

5.3.3.4 Cloud Wheel Design

5.3.3.4.1 Mechanical Design

The cloud wheel is a circular disc with interference filters of variable size, spaced randomly around its periphery to simulate clouds. Since cloud wheel rates were not specified it was assumed this rate should be equal to the instantaneous angular rate of the display window in the field. The cloud wheel rate is given by

$$\dot{\varphi} = \frac{5}{2} \, \dot{\theta}, \text{ where}$$

5 is the focal length of the projection lens, 2 is the radius of the wheel and $\dot{\theta}$ is the display arm rate. Therefore,

$$\ddot{\varphi} = \frac{5}{2} \, \ddot{\theta}.$$

A range of motion adequate for the simulation was determined to be $\dot{\omega} = 1°$/sec to 250°/sec with an accuracy of ±10%; maximum acceleration is 1000°/sec^2 since that of the display arm is 400°/sec^2.

5.3.3.4.2 Cloud Wheel Rate Servo Analysis

a) Requirements and Design Rationale. - The cloud wheel rate servo's rate range is 1 deg/sec to 250 deg/sec. Wheel acceleration is 1000 deg/sec^2. Velocity accuracy of ±10% is satisfactory.

A tach with a voltage output at 1 deg/sec well above servo amplifier noise is used. The servo's compensation and open loop crossover frequency are selected to keep the servo's rate bias error caused by static friction and the servo's rate jitter error caused by running friction to less than 1 deg/sec.

b) Component Definition. - An Inland motor (T-1352, 20 in-oz) is used. This motor can easily accelerate the 0.08 in-oz-sec load to 1000 deg/sec^2 (17.5 rad/sec^2) and overcome static friction of not more than 5 in-oz. An Inland (50A) 50 watt power amplifier is used with this motor.

An Inland (TG 2138) tach with a gradient of 2.2 v/rad/sec and a maximum rate of 28 rad/sec is used.

The cloud wheel rate servos components are given in Figure 5-45.

c) Servo Amplifier Gains and Compensation Network Definition. - The servo amplifiers gains and compensation networks are given in Figure 5-45. The series compensation was chosen so that: (1) the open loop transfer functions crossover frequency is 300 rad/sec, which, is required to keep the servo's high frequency jitter error below 1 deg/sec; and (2) the open loop gain is large enough to keep the servos' rate bias error caused by static friction to less than 1 deg/sec. The series compensation's lag-lead network (S/60 + 1)/(S/0.6 + 1) is needed to reduce the open loop gain to 0 db at the 300 rad/sec crossover frequency and still provide the lead needed for a well-damped servo transient response.

d) Servo Performance. - The low frequency torque disturbance rejection (see Figure 5-46) is 0.4mrad/sec/in-oz and, therefore, with 5 in-oz of static friction torque, which is about the maximum expected, the rate bias error is only 0.1 deg/sec. The high frequency peak torque disturbance rejection is about 40 mrad/sec/in-oz and therefore running friction torque variations can be as high as 0.5 in-oz, which is much higher than expected, before a 1 deg/sec jitter error is exceeded.

The tach output at 1 deg/sec is 40 millivolts and this is well above the expected servo amplifier noise.

5.3.3.5 Target Rotation

In order to maintain proper orientation of the non-circular targets (i.e., plume and fuselage) as they maneuver through the display field, rolling about the line of sight axis, it is required to rotate these two transparencies.

The transparency mechanisms will be mounted on a pair of preloaded angular contact bearings designed to limit axial travel to .0005 inches and prevent defocusing. Angular position accuracy need not be high (= 5 degrees should be quite adequate). The rates and accelerations have not been defined yet but a D.C. torque motor with a timing belt drive will probably be used.
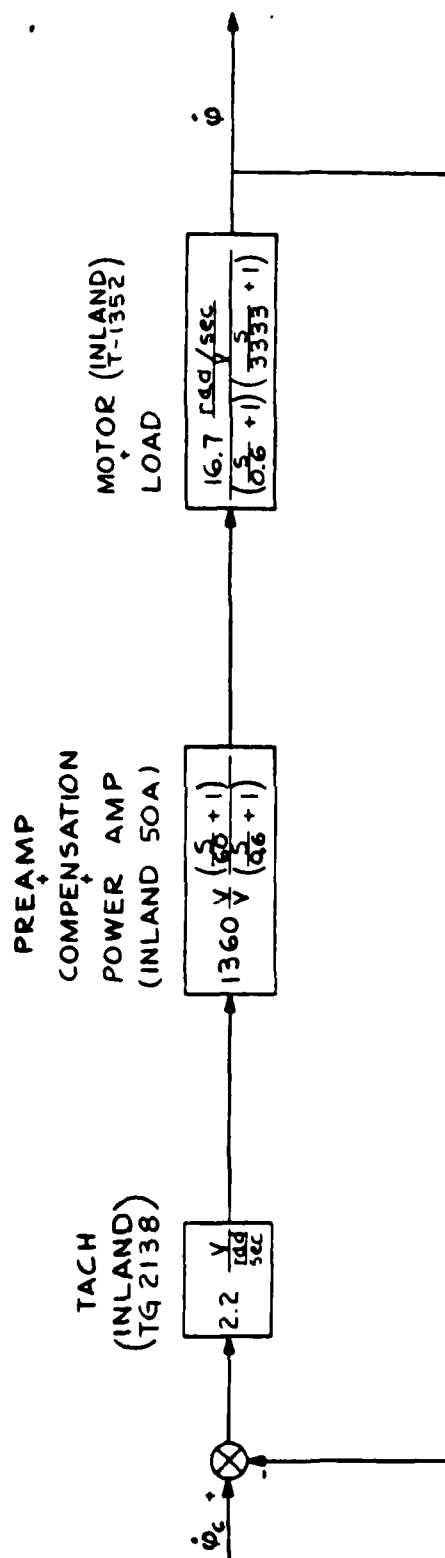
Figure 5-45. Cloud Wheel Rate Servo Block Diagram
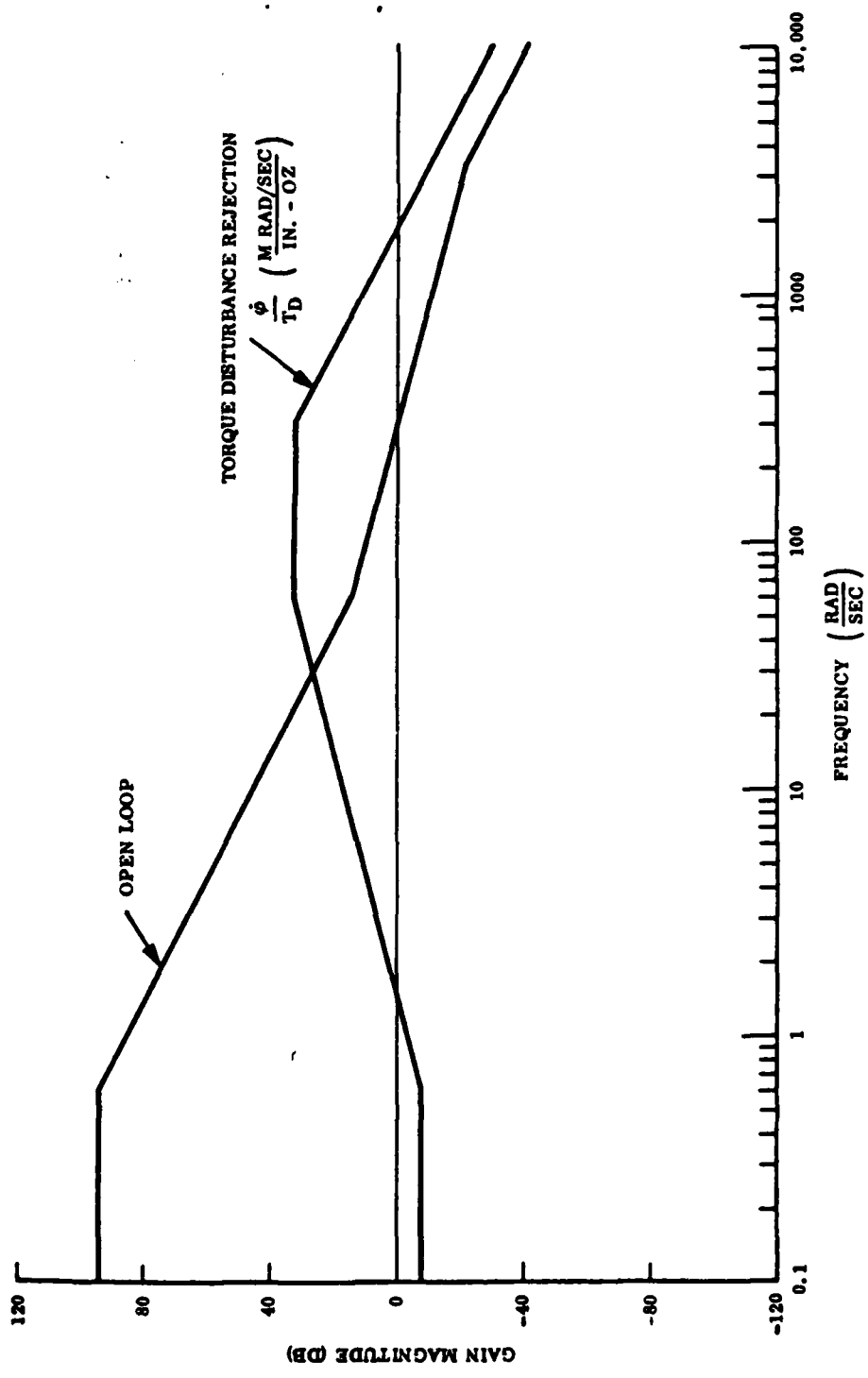
Figure 5-46. Cloud Wheel Rate Servo Bode Diagram

5.3.4 PROJECTOR AZIMUTH TABLE

The projector azimuth table is a high-performance, single-axis table on which the projector assembly is mounted. The table must accept a digital command from the display arm's 16 bit azimuth shaft encoder and follow this command with a maximum dynamic lag error of .1 mrad. It must follow a 100°/sec maximum velocity and a 400°/sec^2 maximum acceleration. A table manufactured by the Fecker Systems Division of Owens Illinois Corporation will meet these requirements and has tentatively been selected to fill this need.

5.4 SUPPORT STRUCTURE DESIGN

5.4.1 SUMMARY

Selection of a support structure design was dictated by the optical requirements of the system. These requirements (summarized in Table 5-11) are given in terms of the allowable deflections and the natural frequency of the system. The initial design approach taken was to design a structure with a minimum natural frequency of 100 Hz. Because of the size of the system, it was realized that this was impractical and would require a massive structure. A more realistic approach was then taken by assuming a damped system and looking at deflections caused by dynamic excitation and static load. As a result, a preliminary support structure design was made which meets the optical requirements as given in Table 5-11.

5.4.2 DESIGN ANALYSIS (Second Level)

The support structure up to the 2nd level (i.e., dimpled and folding mirrors) consists of four square tube columns with cross members. The remaining structure consists of four angles with cross members extending from the 2nd level to the 3rd level (i.e., collimating) mirrors. Both levels of mirrors will have a stiff structural frame acting as a girder.

The structural adequacy of the support structure was examined. The first step was to determine its stiffness and assume a realistic damping coefficient of the structure. From

TABLE 5-11. STRUCTURAL DEFLECTION REQUIREMENTS AS DETERMINED BY OVERALL OPTICAL PATH ACCURACY REQUIREMENTS

DEFLECTIONS		
	2nd Level Mirrors	3rd Level Mirrors
Maximum Horizontal Deflections	±.05 inch (δ_1)	±.1 inch (δ_2)
Maximum Vertical Deflections	±.025 inch (δ_3)	±.025 inch (δ_4)

FREQUENCIES VS. ANGULAR DEFLECTIONS

2nd Level Mirrors

Frequency	Angular Deflections
100 Hz	---
---	.0001 rad.

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this the amplification and magnification factors were calculated for resonant excitations. The deflection for calculated dynamic loading at resonance was then found. The total allowable static load on the system was also evaluated to ascertain the adequacy of the design.

A computer analysis of the support structure (described previously) was made to determine its stiffness and angular deflection under lateral load. The stiffness (h) of the system up to the second level was calculated to be 1.1×10^6 lbs/in.

The angular deflection of the second level with a lateral load applied at the second level was found to be 2.3×10^{-10} rad/lb. From Table 5-11, the allowable angular deflection of the second level mirrors is 10^{-4} rad. Thus, the allowable lateral load that may be applied to the structure, based on angular deflection, is

$$P = \frac{1 \times 10^{-4} \text{ rad}}{2.3 \times 10^{-10} \text{ rad/lb.}}$$

$$P = 435,000 \text{ lbs.}$$

From Table 1, the allowable horizontal deflection (δ_1) of the second level mirrors is ±.05 inches. Assuming that the mirrors are rigidly attached laterally to the structure, the allowable load that may be applied to the structure, as governed by horizontal deflection, is

$$P = h \delta_1$$

$$P = 1.1 \times 10^6 \text{ lbs/in} \times .05 \text{ in.}$$

$$P = 55,000 \text{ lbs.}$$

Consequently, horizontal deflection governs the allowable lateral load.

The magnitude of lateral load actually applied to the structure was assumed to be that produced by the motion of the display arm. The resulting load used in the analysis is the centrifugal force which is given by:

$$P = \frac{I}{K} \omega^2,$$

where

K = Display arm radius of gyration (2 ft.)

I = Display arm azimuthal inertia (22 slug ft^2)

ω = Display arm maximum angular rate (1.75 rad/sec)

$$P = \frac{(22 \text{ slug-ft}^2)(1.75^2 \text{ rad}^2/\text{sec}^2)}{2 \text{ ft.}}$$

$$P = 34 \text{ lbs.}$$

The support structure will be a welded and bolted construction. Consequently, the damping factor (C/C_c) of the system will be approximately

$$\frac{C}{C_c} = .03$$

Under dynamic excitation a magnification $H(\omega)$ of the applied load will occur.

$$H(\omega) = \frac{1}{\left[\left[1 - \frac{\omega}{\omega_n}\right]^2 + 4\left[\frac{C}{C_c}\frac{\omega}{\omega_n}\right]^2\right]^{1/2}}$$

When the frequency of excitation equals the natural frequency of the system, the greatest magnification of load occurs and

$$H(\omega_n) = \frac{1}{2C/C_c} = \frac{1}{2(.03)} = 17$$

At the natural frequency ω_n, the amplification, $M(\omega)$, of base vibrations in the structure will be at a maximum and be equal to $H(\omega_n)$: $M(\omega_n) = H(\omega_n) = 17$.

Therefore, the equivalent static load caused by dynamic excitation can reasonably be expected to range around

$$P = H(\omega_n) \times 34 \text{ lbs.} = 580 \text{ lbs.}$$

Since this is 2 orders of magnitude less than the allowable static load, the structural design appears to be entirely adequate.

Step inputs caused by the sudden starts and stops of the motor may produce loads greater than that obtained by the steady state dynamic loading analyzed previously. But a step response is very unlikely to produce a load above the allowable static load of 55,000 lbs.

5.4.3 DESIGN ANALYSIS (Third Level)

Horizontal deflection of the 3rd level mirrors was the critical deflection governing their support structure. The stiffness of the support structure from the 2nd level to the 3rd level was calculated to be 14,700 lbs/in. Deflection of the 3rd level mirrors

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caused by a resonant excitation at the second level will be approximately 17 times the amplitude of vibration of the 2nd level. A typical value of amplitude of vibration will be that produced by the centrifugal force of the display arm calculated previously.

$$\delta = \frac{P}{h} = \frac{580}{1.1 \times 10^6} = 5.27 \times 10^{-4} \text{ in.}$$

Therefore, assuming a resonant excitation of the 2nd level with the above amplitude, the third level will deflect approximately

$$\delta_{2(calc)} = 17 \times 5.27 \times 10^{-4} \text{ in.} = .01 \text{ in.}$$

Since this deflection is only one tenth of the maximum allowable (see Table 5-11), the structural design is judged to be safely adequate at this level also.

In other words, the support structure from the 2nd level to the 3rd level is capable of withstanding resonant loads 10 times as large as those which may be produced by the centrifugal acceleration of the display arm.

5.4.4 MOUNTING BASE

It is important that the support structure, Guidance Unit Mount, and projector azimuth table be mounted to a base that is stiff enough to prevent relative angular displacements greater than 0.05 mrad. It is also important that the base provide enough damping to prevent the transmission of unacceptable vibrations to these elements. A detailed vibration analysis, to be carried out in Phase II, and based on MICOM's environment specifications, will determine if the existing floor is adequate and, if not, what kind isolation system is required. The performance of several conventional isolation systems that may need to be employed is shown in Figure 5-47.
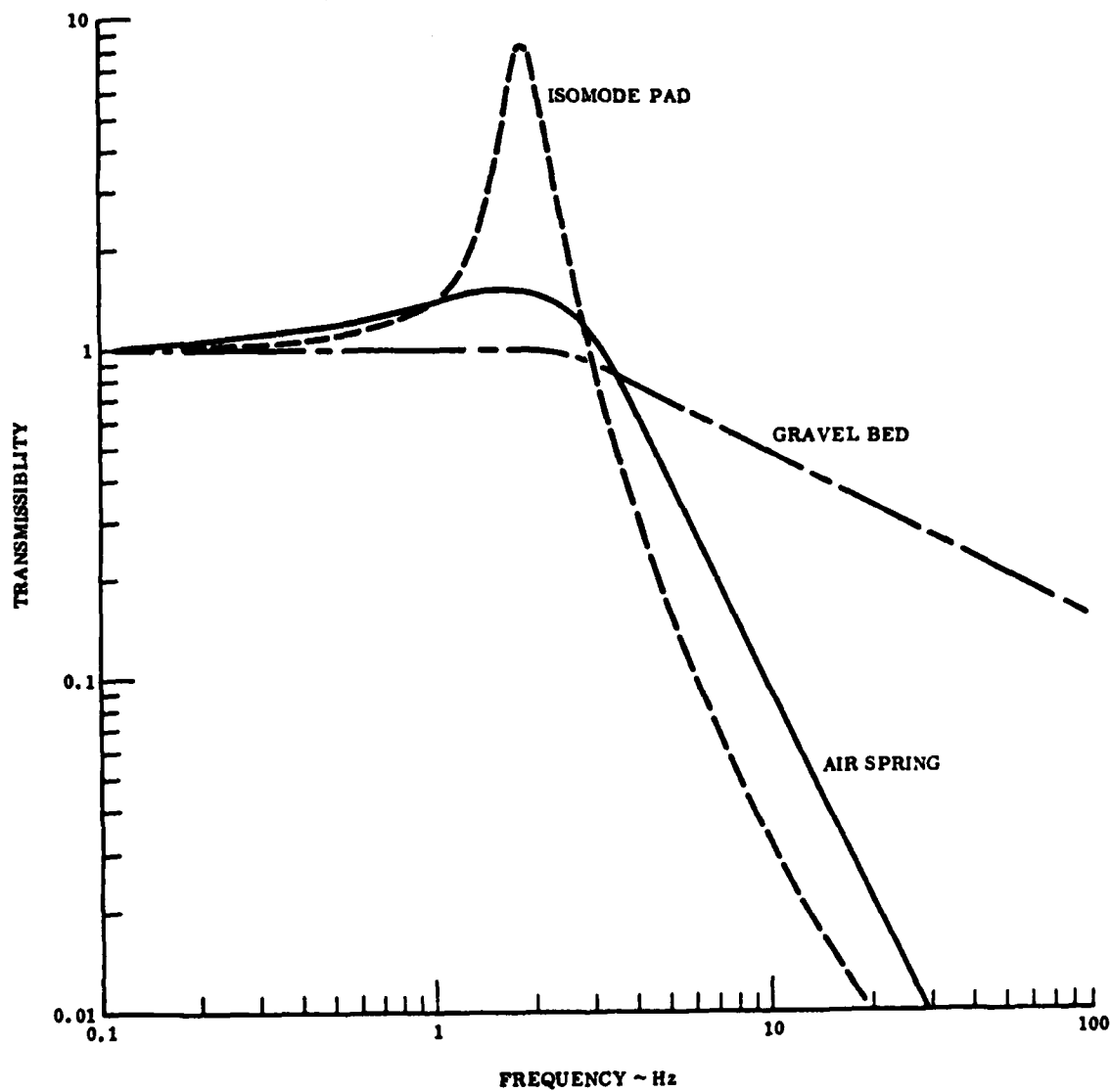
Figure 5-47. IRSS Seismic Block Isolation Systems

5.5 CONTROL CONSOLE AND COMPUTER INTERFACE SUBSYSTEM

5.5.1 INTRODUCTION

The control console includes, broadly, all of the electronic equipment necessary for operation of the Infrared Simulation System including operator controls and interface equipment. A plan view of the proposed operator's area is shown in Figure 5-48 and includes the following major assemblies:

1. Operator Console

2. Terminet Console

3. Digital Processor & Peripherals

4. Control Electronics, Motor Drivers, and Lamp Supplies

5. Guidance Unit Mount Electronics

6. Analog Processor (GFE: EAI 680)

5.5.2 ORGANIZATION

The functional organization of the IRSS electronics is shown in Figure 5-49. The function of each of the major components is described briefly below, and in more detail in succeeding paragraphs.

(a) Control Electronics includes all of the servo and control loop electronic equipment necessary for operation of the 8-channel projector and display arm.

(b) Command and Data Management includes the analog and digital equipment necessary for interfacing of command and performance data with the MICOM hybrid computer facility and the various IRSS subsystems, and provides the means to conduct open loop testing by generation of precision function programs. The focal point of this section is a GE-PAC 30 process controller which enables wide flexibility in system usage through the various software routines planned for the IRSS.

(c) Operator Controls and Displays provide the means to operate and monitor the IRS System. The operator console will include the following:

1. System Power Control and Lock

2. Display Arm Controls

3. Projector Controls

4. Guidance Unit Mount Control Panel

5. Emergency Shutdown
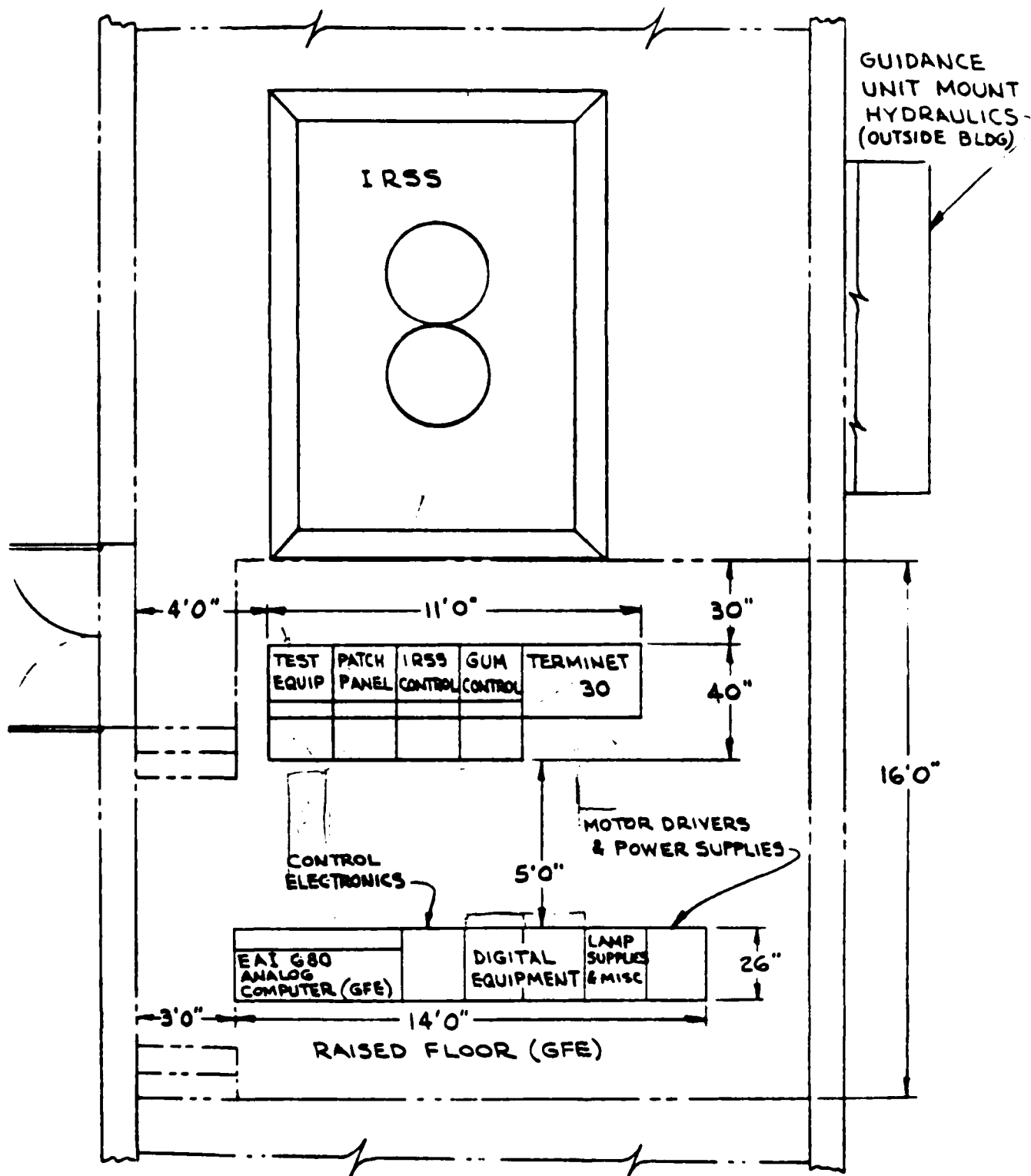
Figure 5-48. Layout of IRSS Operator Area
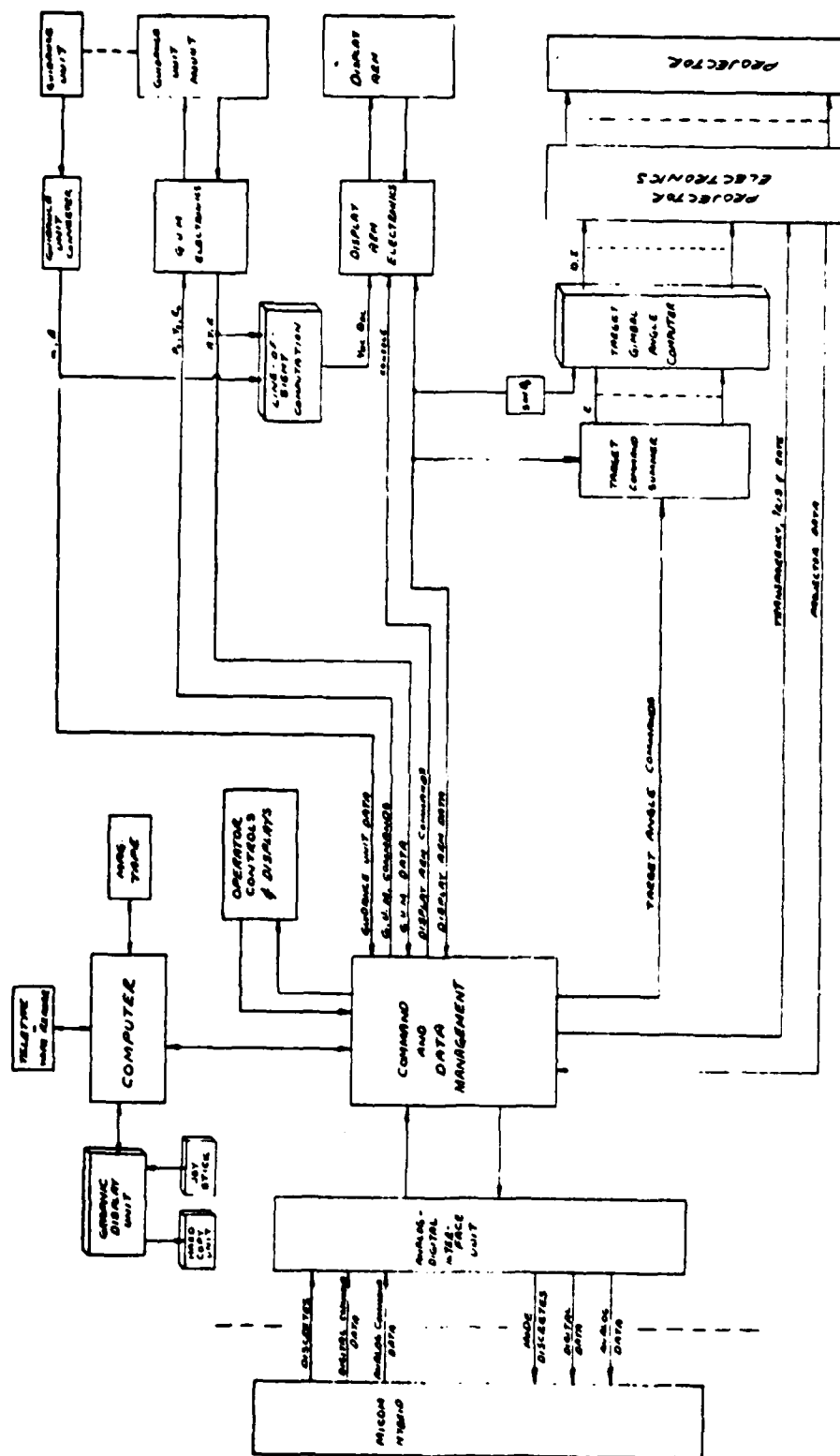
Figure 5-49. IRSS Functional Organization

6. Operational Mode Selection

7. Manual (locking 10-turn potentiometer) input to each control loop

8. External (patching) input to each control loop

9. System Status Display

10. Data Monitor Jack Panel

11. System Test Equipment including:

    Dual Beam Storage Oscilloscope

    Function Generator

    Digital Voltmeter

12. Teletype & Tape Reader/Punch Console (Terminet)

(d) <u>Line-of-Sight and Directional Mirror Gimbal Angle Computation</u>-These computations are required to provide the display arm commands as a function of the Guidance Unit and Guidance Unit Mount position data; and to generate seven sets of directional mirror gimbal commands as a function of target commands and display arm position. The necessity of performing these complex computations in real time to a high degree of accuracy dictates the use of an analog computer for this service.

(e) <u>Guidance Unit Converter</u> - The converter processes the guidance unit output signal into the α and β spherical coordinates required for IRSS operation. This unit will also contain the electronics for a single axis autopilot to provide yaw command signals to the guidance unit mount during open loop testing. Since the requirements of this converter are unique for each type of test specimen, this unit must be provided by the using organization. An interface connector will be included at the operator console which will provide access to the required signal sources and command inputs. Access to regulated supply voltages will also be available at the interface connnector as a user convenience.

5.5.3 CONTROL ELECTRONICS

5.5.3.1 Function and Operation

The control electronics will implement the servo and control loops shown in Figures 5-50 to 5-56 and also the target rotation and iris transmission control loops not included here. Type A transparencies are for tailpipe and plume p_1; Type B are plume p_2 and fuselages, f_1 and f_2.

Figure 5-50. Block Diagram – Display Arm Azimuth Control

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Figure 5-51. Block Diagram – Display Arm Elevation Control

Figure 5-52. Block Diagram – Display Arm Vertical Drive Control

Figure 5-53. Block Diagram – Type A Transparency Control

Figure 5-54. Block Diagram – Type B Transparency Control

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Figure 5-55. Block Diagram – Directional Mirror Control

Figure 5-56. Block Diagram – Cloud Wheel Control

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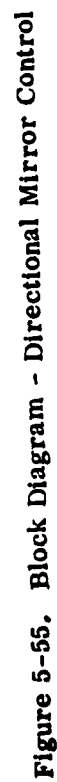
Each loop will consist of one or more printed circuit cards containing the circuits necessary to provide the required control functions.

Command inputs from the various sources will be switched by function relays on the board to minimize noise and common mode errors. Relays will be commanded by logic signals to set up the required operating modes.

Analog command inputs from the MICOM hybrid computer will be interfaced by means of differential analog receivers which will provide the necessary common mode rejection and differential-to-single-ended transition.

Manual commands (operator console potentiometer) will be received via follower amplifiers in order to eliminate loading effects. This precaution is not necessary for the external commands (operator console jack) where the command level may generally be monitored directly at the source. However, three non-committed buffer amplifiers (accessible at the console) will be provided for use with high impedance sources.

5.5.3.2 Self-Checking and Diagnostic Capability

As part of the diagnostic and self-check capability, the error signal at the output of each primary mode summer (e.g., position error in a position mode servo) will be continuously monitored for recording and display. The error signal for each servo will be thresholded against a fixed level based on the servo design error budget. Error signals exceeding the pre-determined allowance will be used to set a bit in a recycling error message word and will also set a visual flag on the operator console. This scheme will allow an instant determination to be made of system performance during a test run and will allow the time and location of off-normal errors to be easily identified. The suspect circuit can then be evaluated in detail by means of the system diagnostic data recorded during the run.

5.5.3.3 Equipment Safety

The control electronics will also contain the necessary equipment safety provisions intended to prevent damage to the display arm and/or Guidance Unit Mount in the event of system malfunction. These circuits, operating on such parameters as position error, relative position, actual and derived rates, etc., will sense off-normal parameters and switch into rate limiting or shutdown modes that will prevent equipment damage. These will, of course, be interlocking between the display arm and Guidance Unit Mount such that both units will be shut-down if malfunction is sensed in either one.

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5.5.4 COMMAND AND DATA MANAGEMENT SYSTEM (CDMS)

5.5.4.1 Description

The CDMS includes the analog and digital equipment necessary for interfacing and management of commands and performance data among the IRSS subsystems and provides the means to conduct open-loop testing by generation of precision programmed functions as target commands.

While functionally part of the CDMS, the analog receivers and output data buffers will generally be integrated into the control loop or function being served. This section will thus primarily concern the digital constituent of the CDMS.

5.5.4.2 Digital Equipment

Digital equipment is required to (1) interface whole word and discrete commands and data with the MICOM hybrid facility, (2) multiplex the commands to the separate output channels for transmission to the control electronics, (3) convert and multiplex performance and diagnostic data for transmission to the MICOM Hybrid Computer Laboratory for recording and evaluation, (4) provide program generation and recording for open-loop testing, (5) provide for subtraction of display arm position from target commands as a step in the directional mirror command sequence, and (6) provide a self-check capability for the entire IRS system.

Trade-off studies between special purpose digital equipment and a general purpose process controller to satisfy these needs point heavily to the latter as the more cost-effective and flexible design solution. The GE-PAC 30-2 process controller has been selected for this application.

The GE-PAC 30-2 is a 16 bit device with a 2 microsecond memory cycle time. The I/O Multiplexer channel can service 256 devices at a 20K byte/second rate. A block transfer can be made at 150K bytes/second. Additionally, selector channel outputs are available at 500K bytes/second and a direct memory access (DMA) channel at 900K bytes/second. An extensive list of peripheral equipment as well as both analog and digital I/O interfaces are available. A real-time multiprogramming operating system and a Fortran compiler are software packages supplied as part of the system.

A block diagram of the proposed system is shown in Figure 5-57. This diagram depicts the baseline digital system plus several optional items (within the broken lines) which are considered logical for future growth and expansion.

Block Diagram – Command and Data Management System (Digital Section)

PARAMETER	TERM MADE IN	(BYTES) DIGITAL DEMAND OUT	(HERTZ?) RATE
Ψ		1	150
P	2	1	200
R	2	1	250
θ	7	7	150
I	7	7	150
Ψ_T	USED TO GENERATE θ5I		150
θ̇		7	150
ψ̇		7	10
f	10	5	1000
P	2	2	1000
γ	3	3	1000
α	8	8	150
β	1	1	150
Ψ_D		2	150
θ_D		2	150
ψ_P		2	90
ψ_DC	1	1	150
θ			150
TOTAL	41 CHAN	12 BYTES (96 BITS) 49/35 CHAN	

OPEN LOOP ONLY
OPEN LOOP ONLY

I/O MUX BUS

MAG TAPE UNIT D3-202 D3-301

MAG TAPE CONTROLLER D3-103

SELECTOR CHANNEL D1-102

DRUM CONTROLLER D4-101

32 MK DRUM D4-203

OPTIONAL

MEMORY BUS CONTROLLER D1-101

GE-PAC 30-IE 16/64K CORE POWER FAIL DETECT / AUTO RESTART A5-204

DIRECT MEMORY ACCESS CHAN

OPERATOR CONTROLS

TERMINET 300 ASR E2-201

TERMINET INTERFACE E2-101

TEKTRONIX T4002A GRAPHIC TERMINAL

TERMINAL INTERFACE

OPTIONAL

PRECISION CLOCK F4-102

INTERFACE CIRCUITS   CONTROL

INTERFACE CIRCUITS   DATA

(DC COMPUTER)

A TO D CONVERTER & CONTROLLER G1-213   12 BIT

16 CHAN MUX G1-304

16 CHAN MUX G1-304

16 CHAN MUX G1-304

(47) ANALOG INPUTS FROM CONTROL ELECTR

DIGITAL I/O MUX CONTR. F3-101 F3-104

128 BIT INPUT MOD F3-102

128 BIT INPUT MOD F3-103

(6) DIGITAL INPUTS FROM CONTROL ELECTR.

F3-103   F3-103   F3-103   F3-103

OPEN LOOP ONLY F3-103

OPEN LOOP ONLY F3-103

(49) D TO A CONVERTERS

ANALOG OUTPUTS TO CONTROL ELECTR.

Figure 5-57. Block Diagram – Command and Data Management System (Digital Section)

5.5.4.3 Directions of Growth

The first expansion block is the addition of a drum memory. The drum will provide the memory capability to program all targets at maximum rates for a full ten-second (estimated) or loop test engagement. By comparison, the baseline system is memory limited and unable to provide full command/command rate capability. In addition, since the memory will also be used for interim storage of performance and diagnostic data during the test (followed by transfer to magnetic tape for permanent storage), the drum also increases the data recording capability of the system.

The second expansion group is the graphic display terminal which can serve as a powerful tool for test evaluation, data reduction, and many other tasks.

5.5.4.4 Command and Data Interface (Closed-Loop Testing)

5.5.4.4.1 Description

Digital interfacing with the MICOM hybrid computer facility (CDC 6600) during closed-loop testing will be implemented via the direct memory access channel (DMAC) in the GE-PAC 30-2. This approach allows data to be read into and out of memory independent of the central processor and permits a significant improvement in data transfer rate.

5.5.4.4.2 Data Requirements

The DMAC has sixteen data lines and eleven control lines. Seven of these control lines will be used for CDC interface lines. The CDC controlled lines are Read, Write, Data In, Data Out, Address In, and Address Out. A DMAC Busy signal will be monitored by the CDC. Data flow within the CDMS is shown in Figure 5-58. Figure 5-59 shows a full list of both analog and digital data requirements.

5.5.4.4.3 Data Transmission

The table in figure 5-57 includes the parameter data rates. The rates have been classified as high (1000 Hertz) or low (250 Hertz or lower) in order to form a reasonable format. There are ten CDC input high rate parameters and twenty-five low rate parameters. These have been put into a format in which the ten high rate parameters and seven of the twenty-five low rate parameters are sent in groups. Each group contains new values of all the high rate parameters and values for seven different low rate parameters. After four groups have been transmitted, the cycle is complete, since all the low rate channels have been sent once while the high rate channels have been sent four times. Figure 5-60 lists the high and low rate parameters and illustrates the format sequence. Data transfer can be accomplished in either a real time mode or a block transfer mode. In the real time mode each group (17 words)

Figure 5-58. Data Management Data Flow

Figure 5-59. Data Requirement Matrix

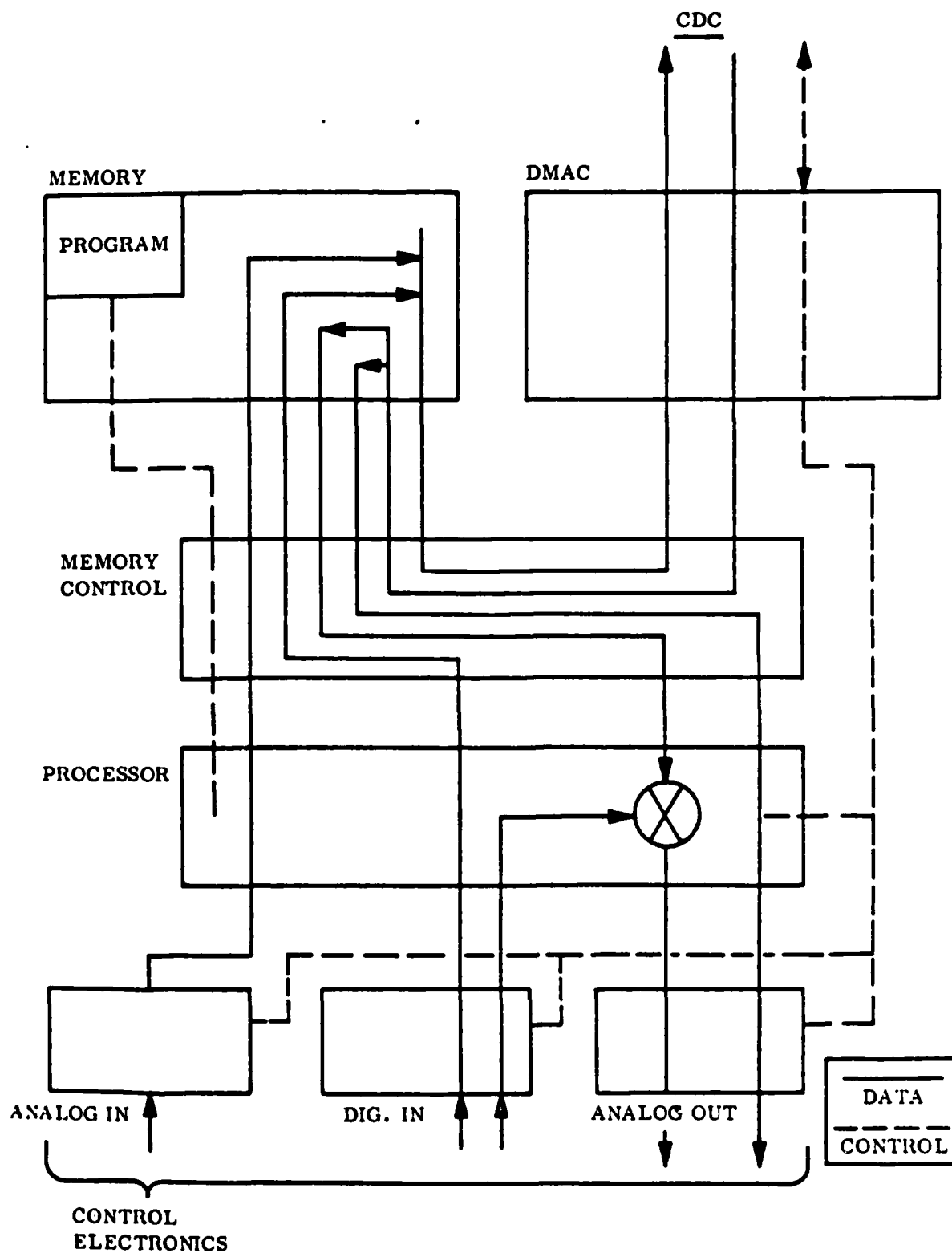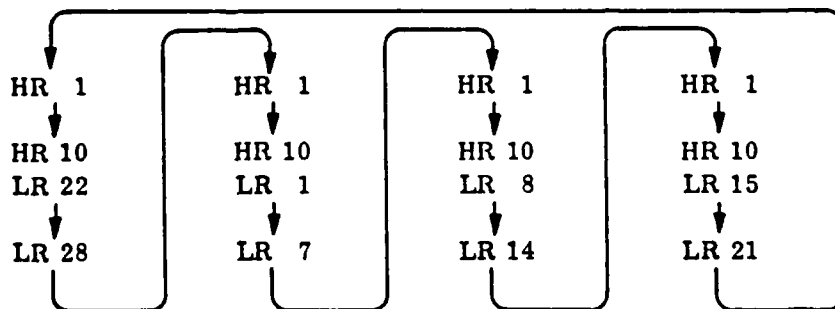| Parameter	Symbol	Quantity	Open Loop Command	Closed Loop Hybrid Interface (Command)	Open Loop Record	Closed Loop Hybrid Interface (Record)	Command Signal Required Accuracy	Command Signal Range	Maximum Velocity	Maximum Acceleration	Required Number of Increments	Required Word Size	Command Signal Accuracy	Rate of Least Significant Bit at Max. Velocity	Servo Bandwidth (Hz)	Sampling Rate for Command and Record (Hz)	Transducer
1. G.U.M. Yaw Angle	Y	1		X_D	X	$X_{A\&D}$	2.5×10^{-4} rad	3.14 rad	1.75 rad/sec	17.5 rad/sec²	12,600	14	1.93×10^{-4} rad	9,100	15	150	15 Bit Encoder
2. G.U.M. Pitch Angle	P	1		X_D		$X_{A\&D}$	2.0×10^{-4} rad	2.6 rad	1.75 rad/sec	17.5 rad/sec²	14,000	14	1.93×10^{-4} rad	9,100	20	200	15 Bit Encoder
3. G.U.M. Roll Angle	R	1		X_D		$X_{A\&D}$	2.5×10^{-4} rad	6.28 rad	31.4 rad/sec	125.6 rad/sec²	25,200	15	1.93×10^{-4} rad	163,000	25	250	15 Bit Encoder
4. Directional Mirror Outer	O	7		X_D	X	X_D	1×10^{-4} rad	.12 rad	1.75 rad/sec	7.0 rad/sec²	1,200	11	9.7×10^{-6} rad	18,000	10	150	RVDT (Analog)
5. Directional Mirror Inner	I	7		X_D	X	X_D	1×10^{-4} rad	.18 rad	1.75 rad/sec	7.0 rad/sec²	1,800	11	9.7×10^{-5} rad	18,000	10	150	RVDT (Analog)
6. Target Angle Azimuth	ψ_T	7	X	X_D			1×10^{-4} rad	3.14 rad	1.75 rad/sec	7.0 rad/sec²	31,400	16	9.7×10^{-5} rad	18,000	10	150	—
7. Target Angle Elevation	θ_T	7	X	Y_D			1×10^{-4} rad	1.05 rad	1.75 rad/sec	7.0 rad/sec²	10,500	14	9.7×10^{-5} rad	18,000	10	150	—
8. Target Angle Rate Azimuth	$\dot\psi_T$	7	X	X_A			.016 rad/sec	1.75 rad/sec	7 rad/sec²	—	110	7			—	10	
9. Target Angle Rate Elevation	$\dot\theta_T$	7	X	X_A			.016 rad/sec	1.75 rad/sec	7 rad/sec²	—	110	7			—	10	
10. Tailpipe/Flare Transparency		5	X	X_D	Qty = 10 X	Qty = 10 X_D	1.9×10^{-5} in.	5×10^{-2} in.	1.5 in/sec	90 in/sec²	2,660	12	1.22×10^{-5} in.	123,000	150	1,000	Pot. (Analog)
11. Fuselage Trans. (Short Side)	f_1	1	X	X_D	X	X_D	6.75×10^{-5} in.	1.5×10^{-1} in.	4.5 in/sec	270 in/sec²	2,200	12	3.65×10^{-5} in.	123,000	150	1,000	Pot. (Analog)
12. Fuselage Trans. (Long Side)	f_2	1	X	X_D	X	X_D	4.25×10^{-5} in.	3×10^{-1} in.	9.2 in/sec	560 in/sec²	7,100	12	7.30×10^{-5} in.	126,000	150	1,000	Pot. (Analog)
13. Plume Trans. (Base)	P_1	1	X	X_D	X	X_D	1.9×10^{-5} in.	2.5×10^{-2} in.	7.5×10^{-1} in/sec	45 in/sec²	1,330	11	1.22×10^{-5} in.	61,500	150	1,000	Pot. (Analog)
14. Plume Trans. (Height)	P_2	2	X	X_D	X	X_D	4.25×10^{-5} in.	2.5×10^{-1} in.	7.5 in/sec	450 in/sec²	5,900	12	6.10×10^{-5} in.	123,500	150	1,000	Pot. (Analog)
15. IRIS Transmission	I	2	X C	X_D	X	X_D	2.1×10^{-3} ratio	1.0 ratio	—	—	480	9	2.0×10^{-3} ratio		10	150	Pot. (Analog)
16. Cloud Wheel Rate	W	2	X	X_A	X	X_A	.1°/sec	250°/sec	1000°/sec²	—	2,500	9	.12°/sec	9,200	—	10	Tach (Analog)
17. Target Rotation	TR	2	X	X_A	X	X_A	5 deg.	360°	—	—	72	7	2.5°	—	—	10	Pot. (Analog)
18. G.U.M. Yaw Rate	$\dot Y$	1		X_A	X	X_A	5×10^{-2} deg/sec	100 deg/sec	4,400°/sec²	—	2,000	11	3.05×10^{-4}°/sec	1.44×10	25	250	Tach (Analog)
19. G.U.M. Pitch Rate	$\dot P$	1		X_A	X	X_A	5×10^{-2} deg/sec	100 deg/sec	7,900°/sec²	—	2,000	11	3.05×10^{-4}°/sec	2.6×10	25	250	Tach (Analog)
20. G.U.M. Roll Rate	$\dot R$	1		X_A		X_A	3.6×10^{-2} deg/sec	7,200 deg/sec	12,300°/sec²	—	20,000	15	2.2×10^{-2}°/sec	5.6×10	25	250	Tach (Analog)
21. Guidance Unit Angle	α,β	2			X	$X_{A\&D}$	.1 deg	100 deg	30°/sec	—	1,400	10	.06°			150	Analog
22. Display Arm Azimuth Angle	ψ_D	1			X	X_D	1×10^{-4} rad	3.14 rad	1.75 rad/sec	7.0 rad/sec²	31,400	15	9.7×10^{-5}	18,000 rad	10	150	16 Bit Encoder
23. Display Arm Elevation Angle	θ_D	1			X	X_D	1×10^{-4} rad	1.05 rad	1.75 rad/sec	7.0 rad/sec²	10,500	14	9.7×10^{-5}	18,000 rad	10	150	16 Bit Encoder
24. Display Arm Azimuth Rate	$\dot\psi_D$	1				X_A						—			—		D.C. Tach
25. Display Arm Elevation Rate	$\dot\theta_D$	1				X_A						—			—		D.C. Tach
26. Projector Azimuth Table	ψ_P	1			X	X_D	1×10^{-4} rad	3.14 rad	1.75 rad/sec	7.0 rad/sec²	31,400	15	9.7×10^{-5}	18,000 rad	10	150	16 Bit Encoder
27. Directional Mirror Rates	$\dot O$	14				X_A						—			—		D.C. Tach.
28. Display Arm Azimuth Command	ψ_{DC}	1				X_D	1.75×10^{-3} rad	3.14 rad	1.75 rad/sec	7.0 rad/sec²	31,400	11	1.53×10^{-3}	1,400 rad	10	150	
29. Display Arm Elevation Command	θ_{DC}	1				X_D	1.75×10^{-3} rad	1.05 rad	1.75 rad/sec	7.0 rad/sec²	10,500	10	1.03×10^{-3}	400 rad	10	150	

DIGITAL IN FROM CDC

PARAMETER	(1000 Hz) HIGH RATE	($\bar{\bar{\leqslant}}$ 250 Hz) LOW RATE
Y		1
P		1
R		1
O		7
I		7
t	5	
f	2	
P	3	
i		8
TOTAL	**10**	**25**

```
   ┌──────────────┬──────────────┬──────────────┐
   ↓              ↓              ↓              ↓
HR  1          HR  1          HR  1          HR  1
   ↓              ↓              ↓              ↓
HR 10          HR 10          HR 10          HR 10
LR 22          LR  1          LR  8          LR 15
   ↓              ↓              ↓              ↓
LR 28          LR  7          LR 14          LR 21
   └──────────────┘  └──────────┘  └──────────┘
```

HR = HIGH RATE
LR = LOW RATE (INCLUDES 3 SPARES)

Figure 5-60. Data In Format

would be computed by the hybrid facility every millisecond and transmitted via the CDC interface. In a block transfer mode a number of groups may be computed at the hybrid facility and transmitted less frequently. This mode would not allow the control precision of the real time mode but would ease the timing and computation problems which might well occur at the hybrid facility. Data transmission to the hybrid facility will be handled similarly. In this case, there are fifteen high-speed channels and thirty-two low speed channels. This results in a twenty-three channel group (15 HR channels + 32/4 LR channels).

5.5.4.5 Function Program Generation for Open-Loop Testing

Operation of the IRSS digital electronics in conducting an open-loop simulation is illustrated in Figure 5-61 and consists of four sub-operations as described below:

1. Program Preparation may be accomplished by operator inputs via graphic input terminal and teletype. The computer core capability is sufficient to contain a Fortran compiler so that this aid can be made available to the operator. In the baseline configuration, the graphic terminal is not available, however, programs may still be generated from the teletype. Programs may, of course, also be generated on any suitable digital or hybrid facility.

2. After preparation, the stored program is then loaded into the IRSS magnetic drum as shown in (B). In the baseline system, which does not provide drum storage, the program will be loaded directly into the computer core memory. The core storage capability is limited compared to that available with a drum.

3. The system is now ready for real time testing. Stored program data are processed and sent to the control electronics. In turn, performance and diagnostic data will be obtained from the system during test and stored in the same drum for post-test data reduction.

4. Post-test data reduction can be accomplished using the configuration shown in (D). Data reduction in the ultimate system can include rapid investigation of suspected anomalies, graphic display of sensor and/or system performance with hard copy potential, and report generation support. After the data have been obtained, pertinent data may be transferred to magnetic tape for permanent storage.

5.5.5 OPERATOR CONSC ⁚

5.5.5.1 Description

The operator console will contain the centralized controls, displays, and readouts necessary for operation of the IRS System. A low-profile console will be used to permit visual observation of the Guidance Unit Mount and display arm by a seated

MAGNETIC
TAPE

INTERACTIVE
GRAPHICS

COMPUTER
(FORTRAN)

TELETYPE

A) PROGRAM PREPARATION

DRUM

MAGNETIC
TAPE

COMPUTER

TELETYPE

B) PROGRAM INSERTION

DRUM

COMM   RECORD

COMPUTER

D/A

A - D

DIGITAL
OUTPUTS

DIGITAL
INPUTS

CDC
INTERFACE

CONTROL ELECTRONICS

LOCAL
RECORDING

C) REAL-TIME TEST

DRUM

MAGNETIC
TAPE

PERMANENT
RECORD

GRAPHIC
DISPLAY

COMPUTER

TELETYPE

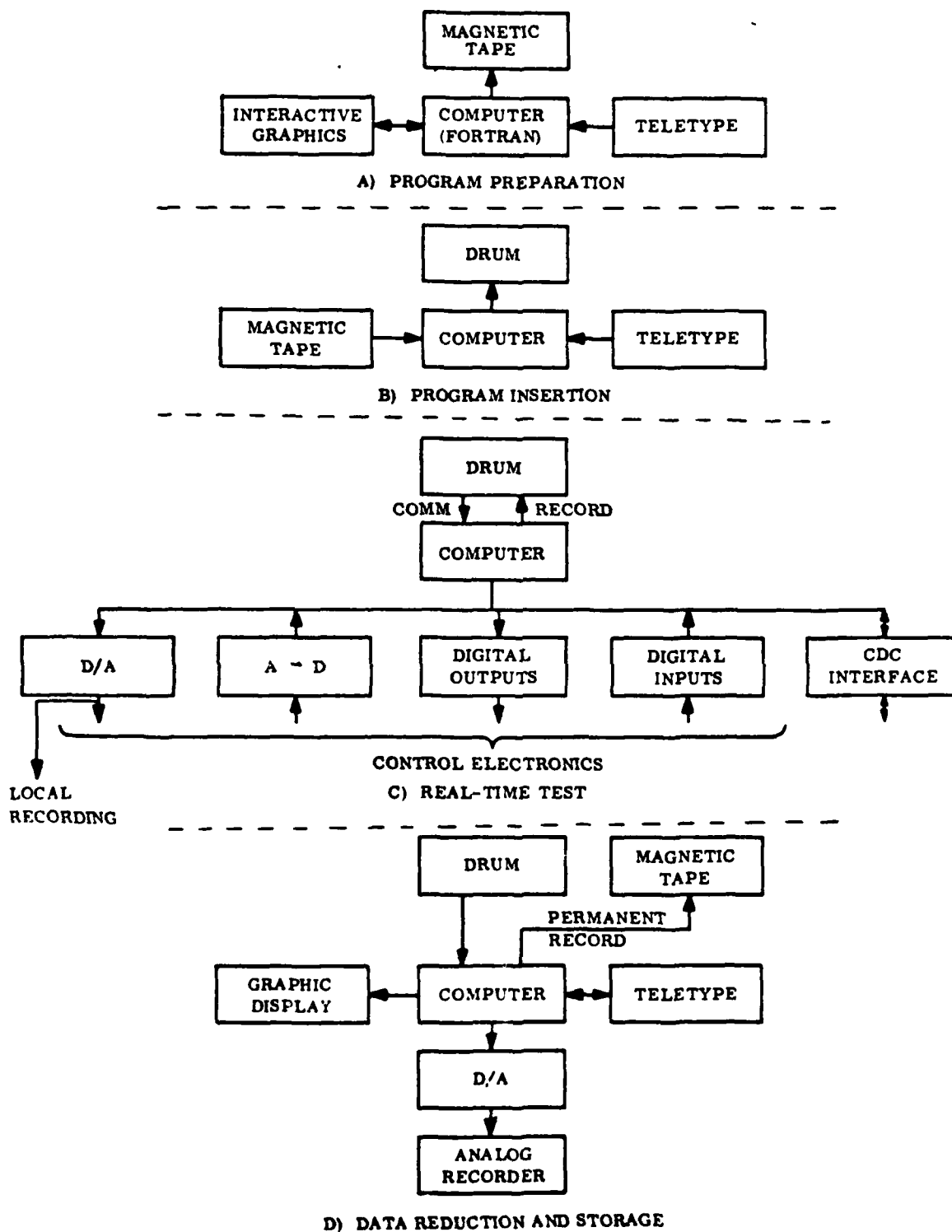D/A

ANALOG
RECORDER

D) DATA REDUCTION AND STORAGE

Figure 5-61. Digital Electronics Operation For Open Loop Simulation

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operator. It will include a full width writing surface. Adjacent to the main operator console will be the Terminet console containing the teletype and high speed tape reader/punch for communication with the GE-PAC-30 controller.

The operator console will contain the controls necessary to power-up and initialize the Guidance Unit Mount, display arm, and projector subsystems. The master power switch will be lockable to restrict unauthorized operation of the system. A guarded emergency shut-down switch will also be provided to allow the operator rapidly to shut down the entire system.

5.5.5.2 Inputting

Manual inputs to the control loops will originate from ten-turn locking precision potentiometers on the console. These potentiometers will be buffered by follower stages to eliminate loading effects and can thus be set directly without compensation to the precision afforded by the dial. If necessary, the console digital voltmeter can be employed to improve setting precision.

The "external" input to each control loop is intended for use with an external dynamic signal source such as a function generator. The majority of these instruments provides sufficiently low output impedance that buffering is generally not necessary. For the few instances where impedance buffering is needed, three non-committed follower amplifiers will be provided at a console patch panel for insertion between a signal source and the external input. Switching of the various input sources will be accomplished using low level relays. While not as desirable as solid state switching from a reliability standpoint, they do provide optimum characteristics in other areas. Contact resistances and thermal EMF's are low and sufficiently stable so as not to affect the gain accuracy at the summing input; there is no common mode limit; and isolation is excellent. The relatively slow response time and contact bounce will not have any effect in this application. The primary candidate relay, GE type 3 SCV, has a demonstrated life of 10^8 operations at low level conditions. The block contacts of each relay will be used to provide a positive console indication of all active inputs to each control loop, thus verifying that the IRSS is in the proper operational mode prior to running a test problem.

5.5.5.3 Displays

Display of the various classes of system data will be structured to enable the operator to observe quickly and ascertain system status and normalcy with a minimum of effort and ambiguity. For example, discrete signal lights (LED devices) will be used to indicate that a particular control loop has exceeded a preset limit, or which input modes are enabled. Continuous display of variables data will be limited to those instances where a judgment factor is advantageous or necessary. This will allow the operator to devote his primary attention to test operations rather than system

housekeeping. Actual variables data will, of course, be available at the console jack
panel for direct measurement using the built-in digital voltmeter and oscilloscope or
other diagnostic equipment.

5.5.6 LINE-OF-SIGHT (LOS) AND DIRECTIONAL MIRROR GIMBAL (DMG) ANGLE COMPUTATION

5.5.6.1 Definition

The LOS computation is required to derive azimuth and elevation commands for the
display arm as a position function of the Guidance Unit (α and β), and the Guidance Unit
Mount (P, Y, and R). The DMG computation involves a similar, although simpler,
calculation to be performed on the target commands after subtraction of the display
arm position data. The exact nature of the equations to be solved is discussed in
Section 5.2.5.1 of this report.

5.5.6.2 Implementation Alternatives

Several methods of performing the line-of-sight computations have been considered.
These calculations involve rectangular conversion of the Guidance Unit and G.U. Mount
polar data, operating on the resulting sine and cosine data, and then finally converting
to polar form for use as display arm commands.

Four methods have been considered:

1. Use of the MICOM hybrid computer facilities to perform the necessary con-
versions and arithmetics. This method is unattractive from the standpoint
that the IRSS would have no stand-alone capability and would always need
hybrid support for all but the very simplest test programs.

2. Use of a resolver computer chain - Discussions were held with Singer-
Kearfott Division on this approach. The results are that the best available
resolvers (1 minute) would not be able to achieve the desired 6 minute re-
sultant accuracy. Moreover, this method would have limited flexibility and
growth potential since it would be designed explicitly to operate with a two-
gimbal seeker head and could not be readily restructured for other possible
systems.

3. Use of a digital computer - The serial nature of a digital machine virtually
precludes doing this computation digitally at the required real time rates.

4. Use of Analog Computing Equipment - The L-O-S equations have been implemented
using 30 millivolt (static error) multipliers at the GE-RESD computer facility.
The results obtained were well within the desired error limit over the entire
angular range and demonstrate the suitability of analog solution.

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Discussions have been held with personnel of Electronic Associates, Inc., (EAI) of Long Branch, New Jersey, concerning the most effective means (both from a technical and cost viewpoint) of performing these computations as part of the IRSS.

5.5.6.3 Suggested Approach

Considering the large number of multipliers and electronic resolvers needed for the L-O-S calculation, and an even larger number of multipliers (plus one resolver) needed to compute the directional mirror gimbal angle commands, the use of a standard basic analog computer console outfitted with the required complement of multiplier and resolver trays appears to be the most efficient solution. Although the machine would be dedicated to L-O-S and D-M-G service by means of an immobilized patchboard, this patchboard could be removed and the analog machine used to supplement the digital in off-line preparation of function programs for open loop testing. It also provides the desired flexibility and growth potential to support alternate L-O-S computations that might arise due to future seeker head gimbal configurations. Future growth potential is also possible by expanding the standard console to its full capability of integrators and summing amplifiers and using this expanded equipment to solve on-line aerodynamic and guidance equations during simpler closed loop testing.

From the point of view of economics, the choice of a standard production machine virtually eliminates non-recurring engineering charges and minimizes maintenance program problems.

In the EAI line, both the model 7800 (100 volt) and the model 680 (10 volts) could provide the desired accuracy. However, even a fully expanded 680 console cannot support the required number of multipliers and additional equipment would be needed to perform all seven sets of DMG calculations. This problem does not occur in the larger 7800.

The use of the EAI 680 analog computer, which is available as GFE, will require some restructuring of the proposed Line-of-Sight and Directional Mirror Gimbal Command computational organization. Since a fully expanded 680 is not sufficient to handle the entire problem, various methods of achieving an acceptable solution have been investigated. These include:

1. Alternate ways to solve the required equations that will provide a closer match to the equipment in 680 No. 262. EAI has provided an inventory list of this machine that indicates the machine is not fully expanded. Additional data are needed to continue this effort early in Phase II.

2. Split responsibility between the IRSS - 680 and the MICOM hybrid. For example, use the 680 to do the L-O-S and two to three targets during closed loop simulation, with the Hybrid doing the rest. Then, for open loop testing, re-program the 680 to do the simplified (GUM pitch and roll constant) L-O-S and possibly five targets. The optimum split will depend on the make-up of the 680.

3. Expansion of the 680 capability by acquisition of additional multiplier and resolver trays plus necessary power supplies. This approach will probably be the most convenient and cost effective way to achieve the desired stand-alone capability.

4. In spite of possible procurement problems, trading-up from a 680 to a 7800 should not be overlooked.

Because of its critical function in the system, it is considered very desirable that the EAI 680 computer be made available to GE during the Philadelphia assembly, integration, and test phases.

5.5.7 ELECTROMAGNETIC COMPATIBILITY

Good EMI design practices will be followed throughout the design of the control console and related equipments. These practices will insure that the IRSS will not be susceptible to interference generated by nearby electrical/electronic equipment, and will, also, not be a source of interference to other sensitive equipment within the ACDF facility.

Particular attention will be paid to grounding, shielding, and interconnection techniques in order to minimize noise and offset errors introduced through common mode and pickup coupling. Adequate bypassing and the use of suitably low circuit impedances will be followed as a general design philosophy. Where necessary, physical isolation and separation will be maintained between high noise level harness lines and sensitive signal lines to supplement normal cable shielding. Interfacing of the IRSS to the MICOM hybrid computers and other signal sources will employ differential analog and digital receivers to insure rejection of common mode and induced error and noise sources.

As a final precaution, the design will be reviewed at progressive stages by GE-RESD EMC consultants to insure satisfactory performance of the completed design with respect to existing electromagnetic interference standards.

5.5.8 MAINTAINABILITY

Maintainability of the IRSS electronic equipment has been considered as one of the fundamental design considerations during the Phase I effort and will continue to be emphasized during the remaining design activity. Although high quality commercial grade components, adequately derated, are being specified throughout, random part failures are to be expected during the service life of the IRSS. To enable location and repair of these failed parts in a reasonably expedient and painless manner, the following philosophies are being followed:

1. Plug-in card construction will be employed.

2. Test points will be provided at key points and card extenders will be supplied for troubleshooting purposes.

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3. Consistent with meeting performance requirements, selection of active and passive components will be restricted to a controlled list of parts having an established history of performance and a high potential of long term availability on the replacement market.

4. A high degree of commonality among the various sub-assemblies will be maintained in order to obtain maximum usefulness from any spare parts stocking.

5. Documentation to be supplied will be sufficiently detailed to permit straight-forward logical troubleshooting.

6. The diagnostic self-checks planned as a software package will allow defective areas to be isolated quickly.

6.0 GROWTH POTENTIAL

It is a matter of major concern that the Infrared Simulation System not only be adequate to meet recognizable immediate needs, but have sufficient flexibility to assure its usefulness in the future in as yet undefined applications. Consequently, room for growth and modification must be built into the system from the beginning. There are four logical directions for such future growth to take: extension of optical capabilities, extension of dynamic capabilities, expansion of the command and data management system for open loop testing, and new applications.

6.1 EXTENSION OF OPTICAL CAPABILITIES

The optical capabilities of the Infrared Simulation System are defined in terms of the spatial complexity possible in the generated scene, the spectral range and complexity possible, the radiant power available, the optical resolution, and the field of view. In our design approach, all these features are capable of extension without major redesign, with the largest potential existing in the areas of image complexity (signatures as well as scenes).

The principle of compound projection is not limited to the single-stage compounding built into the present design. Each projector in the array can be made to project a target subassembly which itself is the product of compounding. The principle is illustrated in Figure 6-1. Extremely complex scenes can be synthesized in this way. The reserve of radiance available in the presently specified sources is adequate to allow two-stage compounding at least through the 0.3-to 3-micron region.

The source in each projector can also be made compound, thereby allowing the practical synthesis of complex spectra. Examples include the addition of line radiation to an otherwise continuous plume, or the synthesis of a two-component infrared terrain background.

In Table 5-10, it was shown that the radiance available with presently specified sources is adequate to exceed all specified requirements by varying degrees, except for flares in the 3-to-5-micron region, which just meet the requirements. By projection of multiple, superposed images, however, superradiant flares up to 600 percent higher than specified can be generated.

The optical resolution of the system was computed to be .7 mrad. This might be increased slightly by using a better projection lens but is primarily limited by the display subsystem performance.

The present display window subtends 7 degrees, adequate to ensure filling a 6-degree sensor field at all times. Although the display is not inherently limited to 7 degrees, the mechanical design limits expansion to 8 or 9 degrees without major redesign of the display arm.

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Figure 6-1. Extension to 2-State Compound Projection

6.2 EXTENSION OF DYNAMIC CAPABILITIES

Dynamic requirements affect the Guidance Unit Mount, the target positioning apparatus, and the target range control mechanisms.

The principal point to be noted here is that to a large extent this extension of dynamic capabilities has already been achieved in the IRSS design because the Supplemental Specification guidelines provided to GE-RESD by MICOM on 2 February 1971 have been incorporated to the fullest extent possible in the dynamic design requirements of the various subsystems, and particularly of the Guidance Unit Mount.

Target rates could be increased further, possibly with some sacrifice of accuracy, but other major changes probably would involve significant redesign effort.

6.3 EXPANSION OF THE COMMAND AND DATA MANAGEMENT SYSTEM CAPABILITY FOR OPEN-LOOP TESTING

In its present configuration, the command and data management system does not have the capacity to provide arbitrary complex function generation for all of the servo loops in the system for the nominal 10 second engagement. However, by trading off program complexity, program length, and number of targets, the IRSS will be more than adequate for present open loop testing needs. If in the future these needs increase, however, a drum storage unit may be added to the present system which will increase system capacity tremendously.

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Another growth item, providing increased system capability, is a graphic display unit. This would greatly simplify off-line program generation while adding the capability for real time visual monitoring of the engagement.

6.4 FUTURE ALTERNATIVE USES

The immediate application of the Infrared Simulation System will be to Army ground-to-air missiles employing passive infrared and electro-optical homing sensors. Other, future applications might include Army ground-to-ground and air-to-ground missiles employing laser semi-active or command-to-line-of-sight guidance. The IRSS design concept is easily adapted to tests of either of these forms of guidance.

To test missiles employing laser semi-active guidance (target designator systems), it is only necessary to substitute the laser for the presently specified Varian collimated arc source (possibly with a beam expander), employ a flare transparency, and with neutral density filters and the dynamic iris control the apparent radiance of the spot at the target. Jitter is readily introduced at the projector controls. If sensors fixed to the missile are involved, the display window will, of course, be slaved to the guidance unit mount.

Command-to-line-of-sight guidance usually involved two electro-optical systems, both of which can be tested in this apparatus. In a typical system of this type, the command unit held by the gunner observes the target and the receding missile and, based on a comparison of missile position and line of sight, transmits an up, down, left, or right command to the missile via modulation of the command beam. The missile, on the other hand, observes a receding source whose position in the field varies (if an imaging sensor) and whose signal is changing. Both ends of the command link can be tested in this simulator. The missile can be mounted tail first and presented with an image of a receding source whose modulation changes as its computer-directed relative position changes. Such a test can evaluate the optical capabilities of the sensor when working against realistic backgrounds, and the dynamic response of the missile. Next, the command unit can be mounted in the Guidance Unit Mount and presented with an image of the receding missile to test its ability to track and generate the proper commands. The command modulation can be picked up at the projector assembly by a missile receiver (it travels backward through the simulator) and used to control apparent missile position, employing the dynamic characteristics derived in the first part of the test.

APPENDIX B

4 June 1971   <u>MINUTES OF MEETING</u>

To: R. Hollman, Subcontract Specialist
        Rm. 2534 Chestnut St.

Subject: <u>Management Review Board Meeting for the IRSS Subcontractors</u>

Date of Meeting: May 25, 1971

Attendees: G. Hammett, Chairman Management Review Board
               R. F. Hall, Manager, Development S/C Bus. Mgmt.
               R. Baessler, Project Engineer
               T. Pauley, Technical Staff
               R. Hollman, Subcontract Specialist
               J. Donato, Finance

     This Management Review Board was convened by the Chairman for the purpose of selecting a proposed subcontractor for the Guidance Unit Mount (GUM) for the IRSS Program and for providing guidance in accordance with PPI 4.8.

     Mr. Hollman presented the background for the four (4) companies that were sent RFP's. Two (2) proposals were received and the technical and financial evaluations of these proposals from Carco and Owens-Illinois (Fecker Systems Division) were reviewed. Technical Evaluations per PPI 3.11 had been performed and, following financial evaluations, recommendations were prepared by Mr. Hollman and his team. The Board complimented the team on the professionalism displayed.

     The enclosures to these minutes contain the details of the evaluations.

     The over all technical ratings were as follows based on a 5 point rating system. Selection was made on the basis of nominal system requirements. "Nominal" requirements are those which meet the contract requirements. On this basis comparison is as follows:

	CARCO	OWENS-ILLINOIS
Technical	295	315
Financial	$238,004 FFP	$221,132 FFP

     The customer has expressed a desire (in conference) for a capability beyond that expressed in the contract. Recognizing this as a potential requirement the buyer solicitated and his team reviewed proposed compliance with the "high performance" requirements. Significantly, Owens-Illinois (Fecker Systems) was the more able of the two and the difference was so significant as to overcome the pricing factor. (See next page)

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Financial	$238,516	$257,419

The Board concurred with a recommendation for selection and award to Owens-Illinois (Fecker). Inasmuch as the price had been arrived at competively, there was no apparent reason for obtaining formalized cost or pricing data or certification under PL87-653. The team was, however, charged to perform fact finding and negotiation with Fecker to the extent necessary to insure a mutual understanding of technical requirements and to insure that pricing is accordingly proper. In the event of any significant technical or pricing changes (changes which would cast doubt on the validity of the competition or cause an increase in price of more than 5%) the team must return to the Board for further guidance. Otherwise the award may proceed.

George E. Hammett, Jr.
Chairman

Attachments:

1.   Preliminary Engineering Evaluation of GUM Proposals
2.   Team Presentation Charts

* THIS IS "NOMINAL" OR CONTRACT REQUIREMENTS

PRELIMINARY ENGINEERING EVALUATION OF GUM PROPOSALS

I.   2.1 & 2.2 Mechanical & Electrical Requirements (Common)

Requirement	Carco	Fecker	Comments	Weight Rating	Carco Rating	Carco Weighted Rating	Fecker Rating	Fecker Weighted Rating
2.1.1 Configuration Supply "L" & "D" Dm.	Yes	Yes		1				
2.1.2 Orthogonality ± 0.1 read	.15	.1	Carco will attempt .1 as design goal.	1	3	3	5	5
2.1.3 Axes Intersection .005"	.010"	.005" / .010" when fully loaded	Carco will attempt .005 but guarantees .010".	1	3	3	5	5
2.1.4 Mechanical Displacement Yaw ±90° Pitch ±80° Roll - continuous	±120° ±80° continuous	+90° ±80° continuous	Fecker could also produce ±120 in yaw if asked so this should not be considered a plus for Carco.	5	5	25	5	25
2.1.5 Angular Readout Mechanical Device accurate to .5°	±.1°		Insignificant	.1	5	5	1	1
2.1.7 Test Item Mount Universal Mount	Flat Plate	Cylinder	Carco's would require different hold down brackets for each test item - minor inconvenience.	3	5	15	5	15

Weighting: Importance
1 - Low
3 - Medium
5 - High

Rating:
1 - Fails to Meet
3 - Nearly Meets
5 - Meets

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I.   2.1 & 2.2   Mechanical & Electrical Requirements (Common)   (Continued)

Requirement	Carco	Fecker	Comments	Weight	Carco		Fecker	
					Rating	Weighted Rating	Rating	Weighted Rating
2.1.8 Gimbal Resonances Shall not be excited during normal operation	Outer-48 Middle-59.3	Outer-190hz Middle-174hz Inner-not shown	Large + for Fecker Fecker's mechanical design much heavier & stiffer than Carco's.	3	3	9	5	15
2.1.9 Guidance Unit Cooling Cryogenic	Bottle	Rotating Joint Controlled Leakage	Carco not interested in rotating joint. Fecker has built joints	5	1	5	5	25
High Pressure	Bottle	Rotating Joint Positive Seal						
2.1.10 Leveling Screws 10 arc seconds	10	10		1	5	5	5	5
2.2.1 Electrical Connection to Payload 86 wires	86	88		1	5	5	5	5
2.2.2 Limit Switches	Will Provide	Will Provide		1	5	5	5	5
2.2.3 Fail Safe Provisions	Yes	Yes		3	5	15	5	15
2.2.5 EMI	Will Comply	Will Design But Not Test For Conform-		3	5	15	3	9

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

II. PERFORMANCE REQUIREMENTS

Requirement	Carco	Fecker	Comments	Weight	Carco Rating	Carco Weighted Rating	Pecker Rating	Pecker Weighted Rating
2.3.1.1 Acceleration Yaw - 1000°/sec² Pitch-1000 " Roll -3600 "	6000°/sec² 6000 " 7200 "	1000°/sec² 1000 " 7200 "		5	5	25	5	25
2.3.1.2 Velocity Yaw - 100°/sec Pitch - 100 " Roll - 1800 "	150°/sec 150 " 1800 "	100°/sec 100 " 7200 "		5	5	25	5	25
2.3.1.3 Position Range Yaw 0-±90° Pitch 0-±80° Roll 0-±360°	Yes Yes Require Digital	Yes Yes Require Digital		5	5	25	5	25
2.3.1.4 Position Accuracy Yaw ±.25 mrad Pitch ±.20 " Roll ±.25	Analog: 1mrad, 1mrad, 1mrad but only to ±350°	Analog: .5, .5, 1mrad Digital: .25, .20, .25	**Digital** Fecker 15 bit Encoder (.2mrad) Carco - 720 pole inductosyn (.02mrad) **Analog** Fecker .5 mrad (implies geared .01% linearity pot but they do not mention gearing).	3	5	15	5	15

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II. **PERFORMANCE REQUIREMENTS** (Continued)

Requirement	Cargo	Pecker	Comments	Weight	Cargo		Pecker	
					factor	Weighted Rating	factor	Weighted Rating
2.3.1.3 Position Repeatability								
Yaw ± .1 mrad	.1 ⎫With	.1 ⎫With						
Pitch ± .1 mrad	.1 ⎬Pot	.1 ⎬Pot		5	5	15	5	15
Roll ± .1 mrad	.1 ⎭	.1 ⎭						
2.3.2 Rate Mode (Roll)								
Acceleration 7200°/sec.	7200	7200		5	5	25	5	25
Range 0 - ±7200	7200	7200		5	5	25	5	25
2.3.3.1 Position Readout	Analog	Analog	Both require digital system to meet requirements.					
Yaw ± .25 mr	± 1	± .5		5	5	15	5	15
Pitch ± .2 "	± 1	± .5						
Roll ± .25 "	± 1	± 1						
2.3.3.2 Rate Readout			Pecker - Tach Ripple <2% on Roll <1% on Pitch & Yaw					
1% Linearity	1%	1%	Cargo - Tach Ripple <4% Roll <3% Pitch & Yaw	5	5	15	5	15

III. PERFORMANCE GOALS

Requirement	Cargo	Pecker	Comments	Weight	Cargo Factor	Cargo Weighted Rating	Pecker Factor	Pecker Weighted Rating
2.4.1.1 Acceleration Consistent with Bandwidth Roll 12,337 deg/sec² Pitch 7,896 " Yaw 4,441 "	7200 °/sec² 6000 " 4000 "	12,300 °/sec² 7,830 " 4,420 "		5	3	15	5	25
2.4.1.2 Velocity	Same as 2.3.1.2	Same as 2.3.1.2		5	5	25	5	25
2.4.1.3 Position Range	Same as 2.3.3	Same as 2.3.3		5	5	25	5	25
2.4.1.4 Position Accuracy	Same as 2.3.1.4	Same as 2.3.1.4		3	5	15	5	15
2.4.1.5 Position Repeatability	Same as 2.3.1.5	Same as 2.3.1.5		3	5	15	5	15
2.4.1.6 Min. Smooth Velocity Yaw .0002°/sec. Pitch .0002°/sec. Roll .0035°/sec	.0004 .0004 .04		Pecker specifies as ± .2° roll, .01° pitch, and .005° yaw position error.	3	3	9	3	9
2.4.1.7 Bandwidth Roll 35 Hz Pitch 20Hz Yaw 15Hz	15Hz 9Hz 6Hz	25Hz 20Hz 15Hz	Cargo limited by Actuator Frequency Response.	5	3	15	5	25

III. PERFORMANCE GOALS (Continued)

Requirement	Cargo	Pecker	Comments	Weight	Cargo Rating	Cargo Weighted Rating	Pecker Rating	Pecker Weighted Rating
2.6.2.1 Acceleration Yaw 1,560°/sec² Pitch 1,560°/sec² Roll 3,940°/sec	4,000°/sec² 6,000 " 7,200 "	4,420°/sec² 7,830 " 12,300 "		5	5	25	5	25
2.6.2.2 Rate Range Yaw ± 100°/sec Pitch ± 100°/sec Roll ± 7200°/sec	150°/sec 150 " 7,200°/sec	100°/sec 100 " 7,200 "		5	5	25	5	25
2.6.2.3 Rate Accuracy Yaw 5% Pitch 5% Roll 5%	5% 5% 5%	5% 5% 5%		3	5	15	5	15
2.6.2.4 Rate Ripple Yaw 2% Pitch 2% Roll 2%	2% 2% 2%	1% 1% 2%		3	5	15	5	15
2.6.2.5 Minimum Smooth Velocity Yaw .01°/sec. Pitch .01°/sec. Roll .72°/sec.	.02 .02 .72	.01 .01 .72		3	3	9	5	15
2.6.2.6 Bandwidth Yaw 25Hz Pitch 25Hz Roll 25Hz	9 12 21	15 20 25		5	1	5	3.	15

IV. PRELIMINARY EVALUATION SUMMARY

	CARCO	FECKER
MECHANICAL & ELECTRICAL REQUIREMENTS	110	130
PERFORMANCE REQUIREMENTS	185	185
NOMINAL SYSTEM	295	315
MECHANICAL & ELECTRICAL REQUIREMENTS	110	130
PERFORMANCE GOALS	213	249
HIGH PERFORMANCE SYSTEM	323	379

PROGRAM: INFRARED SIMULATION SYSTEM

CUSTOMER: U.S. ARMY MISSILE COMMAND
                REDSTONE ARSENAL, ALABAMA

PRIME CONTRACT: DAAH01-71-C-0571

REQUEST FOR PROPOSAL: RE-A 4110

ITEM TO BE PURCHASED:

   3 AXIS GIMBAL TYPE GUIDANCE UNIT MOUNT
   FOR FLIGHT MOTION SIMULATOR

COMPANIES SOLICITED:

   AEROFLEX LABORATORIES
   CARCO ELECTRONICS
   GOERZ OPTICAL COMPANY
   FECKER SYSTEMS DIV. OF OWENS-ILLINOIS

5/11/71
RBH

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COST PROPOSALS RECEIVED:

NOMINAL SPECIFICATIONS:

FECKER SYSTEMS DIV.	$ 221,132	FFP
CARCO ELECTRONICS	$ 238,004	FFP
CARCO (ALTERNATE)	$ 180,090	FFP

HIGH PERFORMANCE SPECIFICATIONS:

FECKER SYSTEMS DIV.	$ 257,419	FFP
CARCO ELECTRONICS	$ 238,516	FFP
CARCO (ALTERNATE)	$ 180,602	FFP

PRICES INCLUDE DIGITAL/ANALOG
CONVERTER-ENCODER

NOMINAL SPECIFICATIONS MEET OUR CUSTOMER'S
REQUIREMENTS

COMPANIES FACT FOUND:

FECKER SYSTEMS DIV. OF OWENS-ILLINOIS

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5/11/71
RBH

ENGINEERING EVALUATION:

RATED ON 34 TECHNICAL REQUIREMENTS

RATING	FECKER SYS	CARCO
5 MEETS SPECS.	30	25
3 NEARLY MEETS	3	7
1 FAILS TO MEET	1	2
	34	34

REQUIREMENT FECKER SYSTEMS FAILS TO MEET -
WEIGHT "1" - CONSIDERED INSIGNIFICANT -

    2.1.5   ANGULAR READOUT RECORDING
             DEVICE - ACCURATE TO $.5° \pm .1°$

REQUIREMENTS CARCO FAILS TO MEET - BOTH
WEIGHT "5" - CONSIDERED CRITICAL

    2.1.9   GUIDANCE UNIT COOLING - CRYOGENIC -
             ROTATING JOINT

    2.4.2.6 BANDWIDTH: YAW   25 HZ
                       PITCH 25 HZ
                       ROLL 25 HZ

3   5/11/71
                            RBH

OTHER FACTORS

CARCO ELECTRONICS   -   SMALL BUSINESS
                              MENLO PARK, CALIF.

FECKER SYSTEMS DIV.   -   LARGE BUSINESS
                              PITTSBURGH, PA.

PERCENT OF WORK THAT WOULD BE SUBCONTRACTED:

        BY CARCO ELECTRONICS   30%
        BY FECKER SYSTEMS DIV.   14%

BOTH COMPANIES ARE EXPERIENCED IN THE PRODUCTION OF FLIGHT
MOTION SIMULATORS. DUE TO OUR EXPERIENCE WITH BOTH COMPANIES,
WE HAVE GREATER CONFIDENCE IN FECKER SYSTEMS DIVISION.

CONCLUSIONS

SYSTEM PROPOSED BY CARCO ELECTRONICS DOES NOT MEET TECHNICAL
REQUIREMENTS. THIS OUTWEIGHS COST DIFFERENTIALS.

AWARD RECOMMENDED TO FECKER SYSTEMS DIVISION OF OWENS-ILLINOIS.

4   5/11/71
                                         RBH

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3. Expansion of the 680 capability by acquisition of additional multiplier and resolver trays plus necessary power supplies. This approach will probably be the most convenient and cost effective way to achieve the desired stand-alone capability.

4. In spite of possible procurement problems, trading-up from a 680 to a 7800 should not be overlooked.

Because of its critical function in the system, it is considered very desirable that the EAI 680 computer be made available to GE during the Philadelphia assembly, integration, and test phases.

5.5.7 ELECTROMAGNETIC COMPATIBILITY

Good EMI design practices will be followed throughout the design of the control console and related equipments. These practices will insure that the IRSS will not be susceptible to interference generated by nearby electrical/electronic equipment, and will, also, not be a source of interference to other sensitive equipment within the ACDF facility.

Particular attention will be paid to grounding, shielding, and interconnection techniques in order to minimize noise and offset errors introduced through common mode and pickup coupling. Adequate bypassing and the use of suitably low circuit impedances will be followed as a general design philosophy. Where necessary, physical isolation and separation will be maintained between high noise level harness lines and sensitive signal lines to supplement normal cable shielding. Interfacing of the IRSS to the MICOM hybrid computers and other signal sources will employ differential analog and digital receivers to insure rejection of common mode and induced error and noise sources.

As a final precaution, the design will be reviewed at progressive stages by GE-RESD EMC consultants to insure satisfactory performance of the completed design with respect to existing electromagnetic interference standards.

5.5.8 MAINTAINABILITY

Maintainability of the IRSS electronic equipment has been considered as one of the fundamental design considerations during the Phase I effort and will continue to be emphasized during the remaining design activity. Although high quality commercial grade components, adequately derated, are being specified throughout, random part failures are to be expected during the service life of the IRSS. To enable location and repair of these failed parts in a reasonably expedient and painless manner, the following philosophies are being followed:

1. Plug-in card construction will be employed.

2. Test points will be provided at key points and card extenders will be supplied for troubleshooting purposes.

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3. Consistent with meeting performance requirements, selection of active and passive components will be restricted to a controlled list of parts having an established history of performance and a high potential of long term availability on the replacement market.

4. A high degree of commonality among the various sub-assemblies will be maintained in order to obtain maximum usefulness from any spare parts stocking.

5. Documentation to be supplied will be sufficiently detailed to permit straight-forward logical troubleshooting.

6. The diagnostic self-checks planned as a software package will allow defective areas to be isolated quickly.

6.0 GROWTH POTENTIAL

It is a matter of major concern that the Infrared Simulation System not only be adequate to meet recognizable immediate needs, but have sufficient flexibility to assure its usefulness in the future in as yet undefined applications. Consequently, room for growth and modification must be built into the system from the beginning. There are four logical directions for such future growth to take: extension of optical capabilities, extension of dynamic capabilities, expansion of the command and data management system for open loop testing, and new applications.

6.1 EXTENSION OF OPTICAL CAPABILITIES

The optical capabilities of the Infrared Simulation System are defined in terms of the spatial complexity possible in the generated scene, the spectral range and complexity possible, the radiant power available, the optical resolution, and the field of view. In our design approach, all these features are capable of extension without major redesign, with the largest potential existing in the areas of image complexity (signatures as well as scenes).

The principle of compound projection is not limited to the single-stage compounding built into the present design. Each projector in the array can be made to project a target subassembly which itself is the product of compounding. The principle is illustrated in Figure 6-1. Extremely complex scenes can be synthesized in this way. The reserve of radiance available in the presently specified sources is adequate to allow two-stage compounding at least through the 0.3-to 3-micron region.

The source in each projector can also be made compound, thereby allowing the practical synthesis of complex spectra. Examples include the addition of line radiation to an otherwise continuous plume, or the synthesis of a two-component infrared terrain background.

In Table 5-10, it was shown that the radiance available with presently specified sources is adequate to exceed all specified requirements by varying degrees, except for flares in the 3-to-5-micron region, which just meet the requirements. By projection of multiple, superposed images, however, superradiant flares up to 600 percent higher than specified can be generated.

The optical resolution of the system was computed to be .7 mrad. This might be increased slightly by using a better projection lens but is primarily limited by the display subsystem performance.

The present display window subtends 7 degrees, adequate to ensure filling a 6-degree sensor field at all times. Although the display is not inherently limited to 7 degrees, the mechanical design limits expansion to 8 or 9 degrees without major redesign of the display arm.
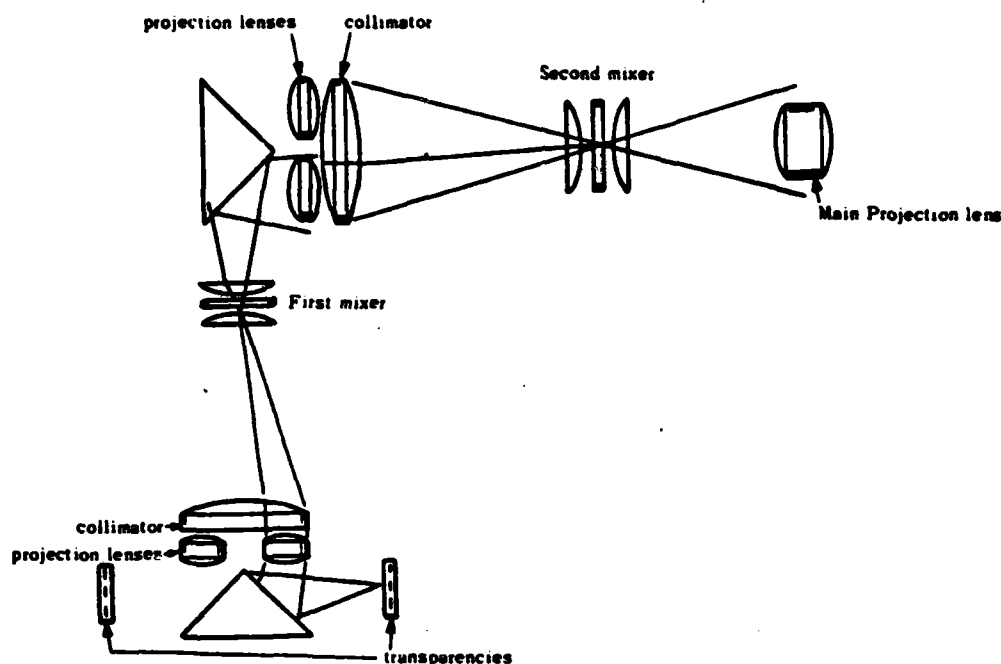
Figure 6-1. Extension to 2-State Compound Projection

6.2 EXTENSION OF DYNAMIC CAPABILITIES

Dynamic requirements affect the Guidance Unit Mount, the target positioning apparatus, and the target range control mechanisms.

The principal point to be noted here is that to a large extent this extension of dynamic capabilities has already been achieved in the IRSS design because the Supplemental Specification guidelines provided to GE-RESD by MICOM on 2 February 1971 have been incorporated to the fullest extent possible in the dynamic design requirements of the various subsystems, and particularly of the Guidance Unit Mount.

Target rates could be increased further, possibly with some sacrifice of accuracy, but other major changes probably would involve significant redesign effort.

6.3 EXPANSION OF THE COMMAND AND DATA MANAGEMENT SYSTEM CAPABILITY FOR OPEN-LOOP TESTING

In its present configuration, the command and data management system does not have the capacity to provide arbitrary complex function generation for all of the servo loops in the system for the nominal 10 second engagement. However, by trading off program complexity, program length, and number of targets, the IRSS will be more than adequate for present open loop testing needs. If in the future these needs increase, however, a drum storage unit may be added to the present system which will increase system capacity tremendously.

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Another growth item, providing increased system capability, is a graphic display unit. This would greatly simplify off-line program generation while adding the capability for real time visual monitoring of the engagement.

6.4 FUTURE ALTERNATIVE USES

The immediate application of the Infrared Simulation System will be to Army ground-to-air missiles employing passive infrared and electro-optical homing sensors. Other, future applications might include Army ground-to-ground and air-to-ground missiles employing laser semi-active or command-to-line-of-sight guidance. The IRSS design concept is easily adapted to tests of either of these forms of guidance.

To test missiles employing laser semi-active guidance (target designator systems), it is only necessary to substitute the laser for the presently specified Varian collimated arc source (possibly with a beam expander), employ a flare transparency, and with neutral density filters and the dynamic iris control the apparent radiance of the spot at the target. Jitter is readily introduced at the projector controls. If sensors fixed to the missile are involved, the display window will, of course, be slaved to the guidance unit mount.

Command-to-line-of-sight guidance usually involved two electro-optical systems, both of which can be tested in this apparatus. In a typical system of this type, the command unit held by the gunner observes the target and the receding missile and, based on a comparison of missile position and line of sight, transmits an up, down, left, or right command to the missile via modulation of the command beam. The missile, on the other hand, observes a receding source whose position in the field varies (if an imaging sensor) and whose signal is changing. Both ends of the command link can be tested in this simulator. The missile can be mounted tail first and presented with an image of a receding source whose modulation changes as its computer-directed relative position changes. Such a test can evaluate the optical capabilities of the sensor when working against realistic backgrounds, and the dynamic response of the missile. Next, the command unit can be mounted in the Guidance Unit Mount and presented with an image of the receding missile to test its ability to track and generate the proper commands. The command modulation can be picked up at the projector assembly by a missile receiver (it travels backward through the simulator) and used to control apparent missile position, employing the dynamic characteristics derived in the first part of the test.

APPENDIX·B

4 June 1971   <u>MINUTES OF MEETING</u>

To: R. Hollman, Subcontract Specialist
        Rm. 2534 Chestnut St.

Subject: <u>Management Review Board Meeting for the IRSS Subcontractors</u>

Date of Meeting: May 25, 1971

Attendees: G. Hammett, Chairman Management Review Board
             R. F. Hall, Manager, Development S/C Bus. Mgmt.
             R. Baessler, Project Engineer
             T. Pauley, Technical Staff
             R. Hollman, Subcontract Specialist
             J. Donato, Finance

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Chairman

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2. Team Presentation Charts

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2.1.2 Orthogonality ± 0.1 mrad	.15	.1	Carco will attempt .1 as design goal.	1	3	3	5	5
2.1.3 Axes Intersection .005"	.010"	.005" .010" when fully loaded	Carco will attempt .005 but guarantees .010".	1	3	3	5	5
2.1.4 Mechanical Displacement Yaw ± 90° Pitch ± 30° Roll - continuous	± 120° ± 80° continuous	±90° ±80° continuous	Pecker could also produce ± 120 in yaw if asked so this should not be considered a plus for Carco.	5	5	25	5	25
2.1.5 Angular Readout Mechanical Device accurate to .5°	± .1°		Insignificant	1	5	5	1	1
2.1.7 Test Item Mount Universal Mount	Flat Plate	Cylinder	Carco's would require different hold down brackets for each test item - minor inconvenience.	3	5	15	5	15

Weights of Importance   Rating:
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5 - High   5 - Meets

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2.1.9 Guidance Unit Cooling Cryogenic	Bottle	Rotating Joint Controlled Leakage	Carco not interested in rotating joint. Pecker has built joints	5	1	5	5	25
High Pressure	Bottle	Rotating Joint Positive Seal						
2.1.10 Leveling Screws 10 arc seconds	10	10		1	5	5	5	5
2.2.1 Electrical Connection to Payload 86 wires	86	88		1	5	5	5	5
2.2.2 Limit Switches	Will Provide	Will Provide		1	5	5	5	5
2.2.3 Fail Safe Provisions	Yes	Yes		3	5	15	5	15
2.2.5 EMI	Will Comply	Will Design But Not Test For Conform-		3	5	15	3	9

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2.3.1.2 Velocity Yaw - 100°/sec Pitch - 100 " Roll - 1800 "	150°/sec 150 " 1800 "		100°/sec 100 " 7200 "			5	5	25	5	25
2.3.1.3 Position Range Yaw 0- ±90° Pitch 0- ±80° Roll 0- ±360°	Yes Yes Require Digital		Yes Yes Require Digital			5	5	25	5	25
2.3.1.4 Position Accuracy Yaw ± .25 mrad Pitch ±.20 " Roll ±.25	Analog 1mrad 1mrad 1mrad but only to ±350°	Digital .5 .5 1mrad	Analog .5 .5 1mrad	Digital .25 .20 .25	**Digital** Fecker 15 bit Encoder (.2mrad) Carco - 720 pole inductosyn (.02mrad) **Analog** Fecker .5 mrad (implies geared .01% linearity pot but they do not mention gearing).	3	5	15	5	15

Requirement	Carco	Fecker	Comments	Weight	Carco		Fecker	
					Rating	Weighted Rating	Rating	Weighted Rating
2.1.1.3 Position Repeatability								
Yaw ± .1 mrad	.1 ⎫ with	.1 ⎫ with		3	5	15	5	15
Pitch ± .1 mrad	.1 ⎬ Pot	.1 ⎬ Pot						
Roll ± .1 mrad	.1 ⎭	.1 ⎭						
2.1.1.2 Rate Mode (Roll)								
Acceleration 7200°/sec.	7200	7200		5	5	25	5	25
Range 0 - ±7200	7200	7200		5	5	25	5	25
2.3.3.1 Position Readout	Analog	Analog	Both require digital system to meet requirements.	3	5	15	5	15
Yaw ± .25 mr	± 1	± .5						
Pitch ± .2 %	± 1	± .5						
Roll ± .25 %	± 1	± 1						
2.3.3.2 Rate Readout 1% Linearity	1%	1%	Fecker - Tach Ripple <2% on Roll <1% on Pitch & Yaw Carco - Tach Ripple <4% Roll <3% Pitch & Yaw	3	5	15	5	15

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III. PERFORMANCE GOALS

Requirement	Carco	Pecker	Comments	Weight	Carco Rating	Carco Weighted Rating	Pecker Rating	Pecker Weighted Rating
2.6.1.1 Acceleration Consistent with Bandwidth Roll 12,337 deg/sec^2 Pitch 7,896 " Yaw 4,441 "	7200 °/sec^2 6000 " 4000 "	12,300 °/sec^2 7,830 " 4,420 "		5	3	15	5	25
2.6.1.2 Velocity	Same as 2.3.1.2			5	5	25	5	25
2.6.1.3 Position Range	Same as 2.3.3			5	5	25	5	25
2.6.1.4 Position Accuracy	Same as 2.3.1.4			3	5	15	5	15
2.6.1.5 Position Repeatability	Same as 2.3.1.5			3	5	15	5	15
2.6.1.6 Min. Smooth Velocity Yaw .0002°/sec. Pitch .0002°/sec. Roll .0003°/sec	.0004 .0004 .04		Pecker specifies as a .2° roll, .01° pitch, and .005° yaw position error.	3	3	9	3	9
2.6.1.7 Bandwidth Roll 25 Hz Pitch 20Hz Yaw 15Hz	15Hz 9Hz 6Hz	25Hz 20Hz 15Hz	Carco limited by Actuator Frequency Response.	5	3	15	5	25

III. PERFORMANCE GOALS (Continued)

Requirement	Carco	Pecker	Comments	Weighting	Carco Rating	Carco Weighted Rating	Pecker Rating	Pecker Weighted Rating
2.6.2.1 Acceleration Yaw 1,560°/sec² Pitch 1,560°/sec² Roll 3,940°/sec	4,000°/sec² 6,000 " 7,200 "	4,420°/sec² 7,830 " 12,300 "		5	5	25	5	25
2.6.2.2 Rate Range Yaw ± 100°/sec Pitch ± 100°/se: Roll ± 7200°/sec	150°/sec 150 " 7,200 "	100°/sec 100 " 7,200 "		5	5	25	5	25
2.6.2.3 Rate Accuracy Yaw 5% Pitch 5% Roll 5%	5% 5% 5%	5% 5% 5%		3	5	15	5	15
2.6.2.4 Rate Ripple Yaw 2% Pitch 2% Roll 2%.	2% 2% 2%	1% 1% 2%		3	5	15	5	15
2.6.2.5 Minimum Smooth Velocity Yaw .01°/sec. Pitch .01°/sec. Roll .72°/sec.	.02 .02 .72	.01 .01 .72		3	3	9	5	15
2.6.2.6 Bandwidth Yaw 25Hz Pitch 25Hz Roll 25Hz	9 12 21	15 20 25		5	1	5	3.	15

IV. PRELIMINARY EVALUATION SUMMARY

	CARCO	FECKER
MECHANICAL & ELECTRICAL REQUIREMENTS	110	130
PERFORMANCE REQUIREMENTS	185	185
NOMINAL SYSTEM	295	315
MECHANICAL & ELECTRICAL REQUIREMENTS	110	130
PERFORMANCE GOALS	213	249
HIGH PERFORMANCE SYSTEM	323	379

PROGRAM: INFRARED SIMULATION SYSTEM

CUSTOMER: U.S. ARMY MISSILE COMMAND
                REDSTONE ARSENAL, ALABAMA

PRIME CONTRACT: DAAH01-71-C-0571

REQUEST FOR PROPOSAL: RE-A 4110

ITEM TO BE PURCHASED:

    3 AXIS GIMBAL TYPE GUIDANCE UNIT MOUNT
    FOR FLIGHT MOTION SIMULATOR

COMPANIES SOLICITED:

    AEROFLEX LABORATORIES
    CARCO ELECTRONICS
    GOERZ OPTICAL COMPANY
    FECKER SYSTEMS DIV. OF OWENS-ILLINOIS

5/11/71
RBH

1

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COST PROPOSALS RECEIVED:

NOMINAL SPECIFICATIONS:

FECKER SYSTEMS DIV. $ 221,132 FFP
CARCO ELECTRONICS $ 238,004 FFP
CARCO (ALTERNATE) $ 180,090 FFP

HIGH PERFORMANCE SPECIFICATIONS:

FECKER SYSTEMS DIV. $ 257,419 FFP
CARCO ELECTRONICS $ 238,516 FFP
CARCO (ALTERNATE) $ 180,602 FFP

PRICES INCLUDE DIGITAL/ANALOG
CONVERTER-ENCODER

NOMINAL SPECIFICATIONS MEET OUR CUSTOMER'S
REQUIREMENTS

COMPANIES FACT FOUND:

FECKER SYSTEMS DIV. OF OWENS-ILLINOIS

2

5/11/71
RBH

ENGINEERING EVALUATION:

RATED ON 34 TECHNICAL REQUIREMENTS

RATING	FECKER SYS	CARCO
5 MEETS SPECS.	30	25
3 NEARLY MEETS	3	7
1 FAILS TO MEET	1	2
	34	34

REQUIREMENT FECKER SYSTEMS FAILS TO MEET -
WEIGHT "1" - CONSIDERED INSIGNIFICANT -

  2.1.5   ANGULAR READOUT RECORDING
           DEVICE - ACCURATE TO $.5^{o} \pm .1^{o}$

REQUIREMENTS CARCO FAILS TO MEET - BOTH
WEIGHT "5" - CONSIDERED CRITICAL

  2.1.9   GUIDANCE UNIT COOLING - CRYOGENIC -
           ROTATING JOINT

  2.4.2.6 BANDWIDTH: YAW   25 HZ
                       PITCH 25 HZ
                       ROLL 25 HZ

3   5/11/71
                                RBH

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OTHER FACTORS

CARCO ELECTRONICS   -   SMALL BUSINESS
                            MENLO PARK, CALIF.

FECKER SYSTEMS DIV.   -   LARGE BUSINESS
                            PITTSBURGH, PA.

PERCENT OF WORK THAT WOULD BE SUBCONTRACTED:

        BY CARCO ELECTRONICS   30%
        BY FECKER SYSTEMS DIV.   14%

BOTH COMPANIES ARE EXPERIENCED IN THE PRODUCTION OF FLIGHT
MOTION SIMULATORS. DUE TO OUR EXPERIENCE WITH BOTH COMPANIES,
WE HAVE GREATER CONFIDENCE IN FECKER SYSTEMS DIVISION.

CONCLUSIONS

SYSTEM PROPOSED BY CARCO ELECTRONICS DOES NOT MEET TECHNICAL
REQUIREMENTS. THIS OUTWEIGHS COST DIFFERENTIALS.

AWARD RECOMMENDED TO FECKER SYSTEMS DIVISION OF OWENS-ILLINOIS.

4   5/11/71
                                          RBH

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APPENDIX C

DRAWINGS

SK56205-537
47D178914
47D178910
47D178912
47D178946
47D178947
47D178918
47D178948
47R196990
SK56205-538
SK56205-534
47R196992
SK56205-914
47R196993
47E193825
47R196994
SK56205-903

SIDE ELEVATION
(ROTATED 90° CCW)

SECTION THRU PLANES A & B

NOTES:
1 MATERIAL: PYREX GLASS

2 SURFACE QUALITY: 80/50

3 THICKNESS: TO BE SPECIFIED BY VENDOR

4 WEIGHT: 3 LBS MAXIMUM LIGHTWEIGHT CONSTRUCTION

5 COATINGS: NONE

6 FLATNESS:

ORIENTATION #1

POWER 1.0 λ (λ = 0.5 μ)

ORIENTATION #2

POWER 1.5 λ
ADDITIONAL SLOPE ERROR DUE TO IRREGULARITY NOT TO EXCEED 0.1 λ/INCH

7 TESTING: TESTING IS TO BE DONE IN THE ORIENTATIONS SHOWN ABOVE WITH MIRROR SUPPORTED AT ITS' THREE MOUNTING POINTS. TEST METHOD EMPLOYED MUST PROVIDE CONTOUR OF ENTIRE SURFACE.

8 QUANTITY: 1

9 INTERPRETATION OF DIMENSIONS AND TOLERANCES PER S34060

10 MARK PART "GE 47D178914 P1" PER 118A1526, CLASS 17.

MAJOR DIA

45°

D 47D178914

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON:					
2-PLACE DECIMALS ±.01 ALL					
3-PLACE DECIMALS ±.005 SURF.					
ANGLES ±1°					
FRACTIONS ±					
MATERIAL-					

GENERAL ELECTRIC
R E S DIV   LOC PHILA PA/C1

MIRROR #1
ELIPTICAL

FOR U.S. ARMY MISSLE COMMAND
CONTRACT NO DAAH01-71-C-0571

SIZE	CODE IDENT NO.	
D	18876	47D178914

SCALE 1/2   SHEET 1 OF 1
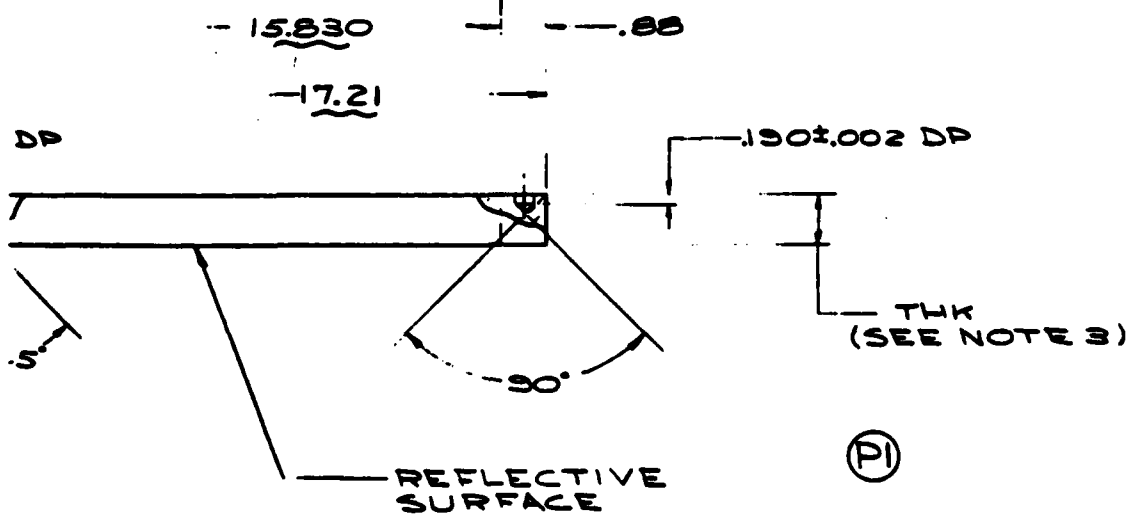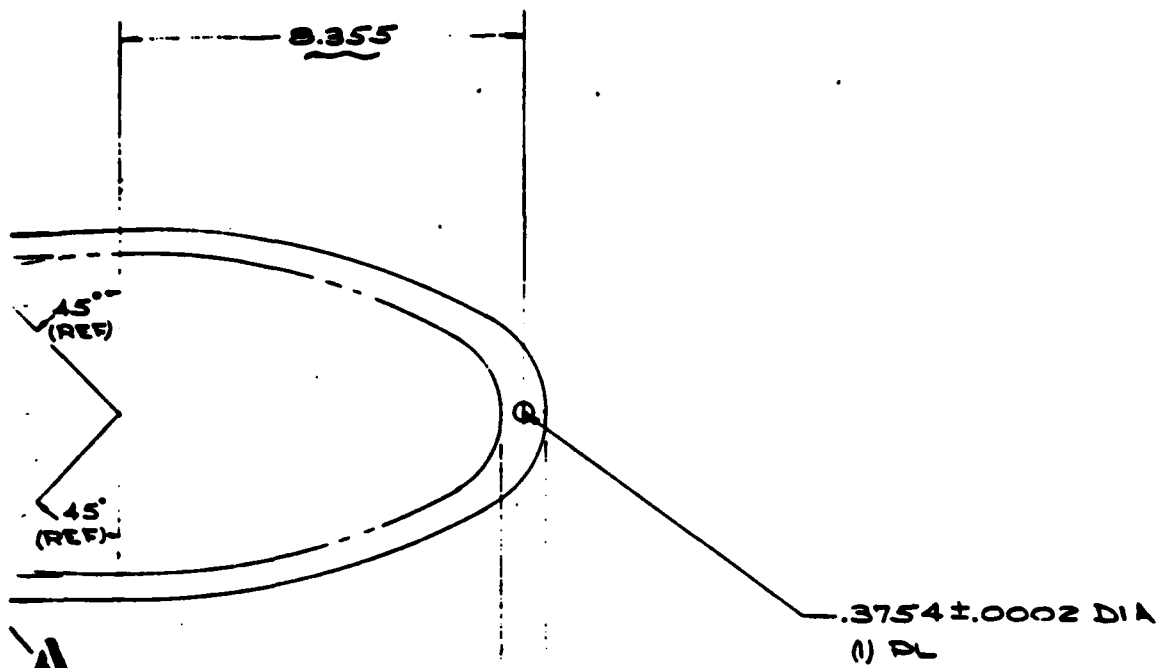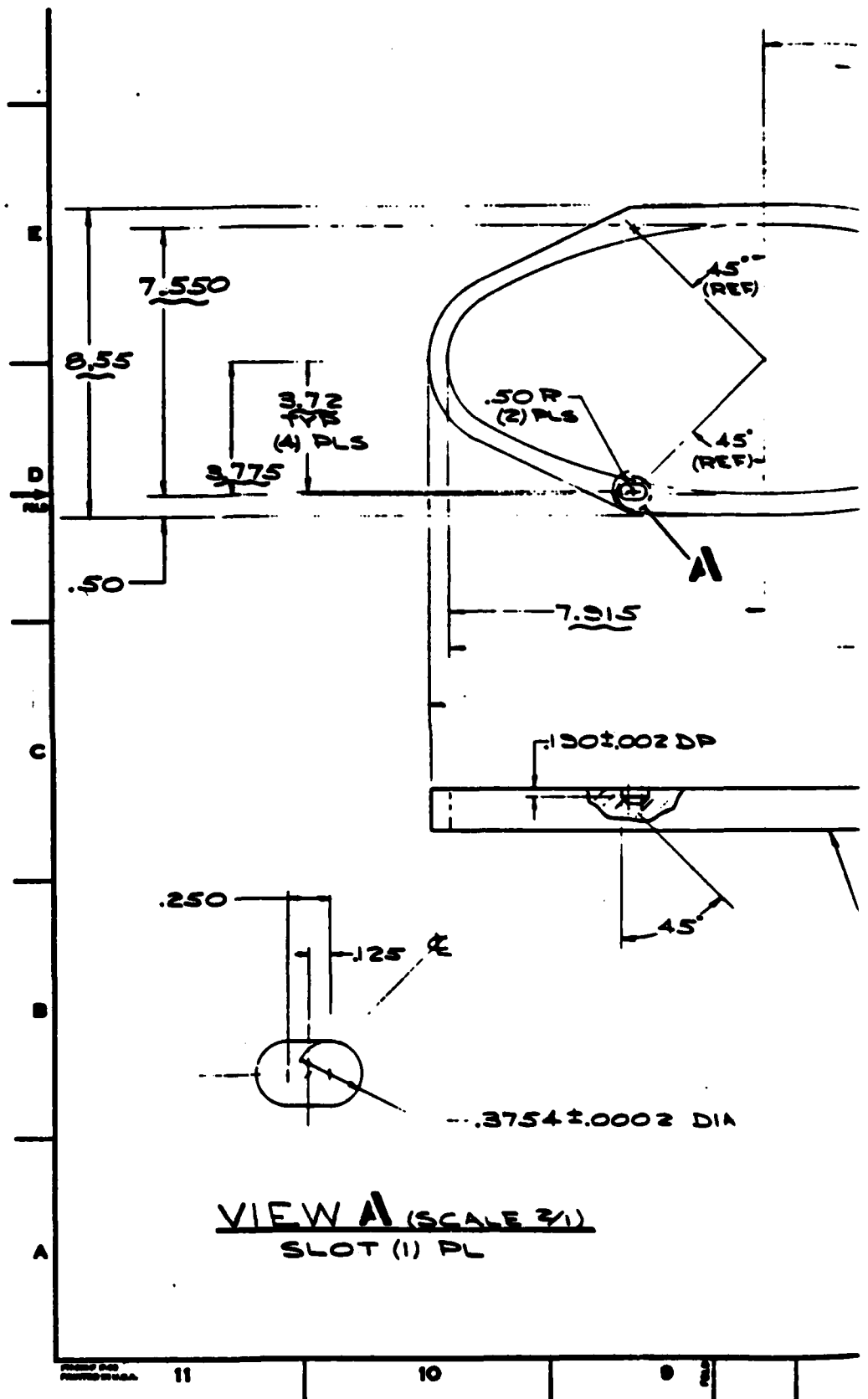
34 C1

217

8.355

45°
(REF)

45°
(REF)

A

.3754±.0002 DIA
(1) PL

15.830 .88

17.21

DP

.190±.002 DP

THK
(SEE NOTE 3)

5

90°

Ⓟ1

REFLECTIVE
SURFACE

DIA

7.550

8.55

3.72
TYP
(4) PLS

3.775

.50

45°
(REF)

.50 R
(2) PLS

45°
(REF)

A

7.915

.130±.002 DP

45°

.250

.125

⊄

.3754±.0002 DIA

VIEW A (SCALE 2/1)
SLOT (1) PL

11   10   9

NOTES:
1. MATERIAL: PYREX GLASS

2. SURFACE QUALITY: 80/50

3. THICKNESS: TO BE SPECIFIED BY VENDOR

4. WEIGHT: 20 LBS MAXIMUM LIGHTWEIGHT CONSTRUCTION

5. COATINGS: NONE

6. FLATNESS:

    ORIENTATION #1

    POWER 1.0 λ (λ = 0.5 μ)
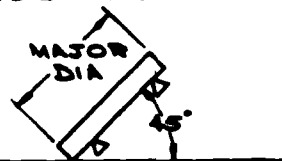
    ORIENTATION #2

    POWER 1.5 λ
    ADDITIONAL SLOPE ERROR DUE TO
    IRREGULARITY NOT TO
    EXCEED 0.1 λ/INCH.

7. TESTING: TESTING IS TO BE DONE IN THE ORIENTATIONS SHOWN ABOVE WITH MIRROR SUPPORTED AT ITS'

8. QUANTITY: 1

9. INTERPRETATION OF DIMENSIONS AND TOLERANCES PER S34060.

10. MARK PART "GE 47D178910 D1" PER 11BA1526, CLASS 17.

MAJOR DIA

45°

.0002 DIA

FLECTIVE
FACE

SD

TE 3)

SIGNATURES

GENERAL ELECTRIC
RES DIV   PHILA PA /C1

MIRROR #2
ELIPTICAL
FOR U.S. ARMY MISSLE COMMAND
CONTRACT NO DAAH01-71-C-0571

SIZE | CODE IDENT NO.
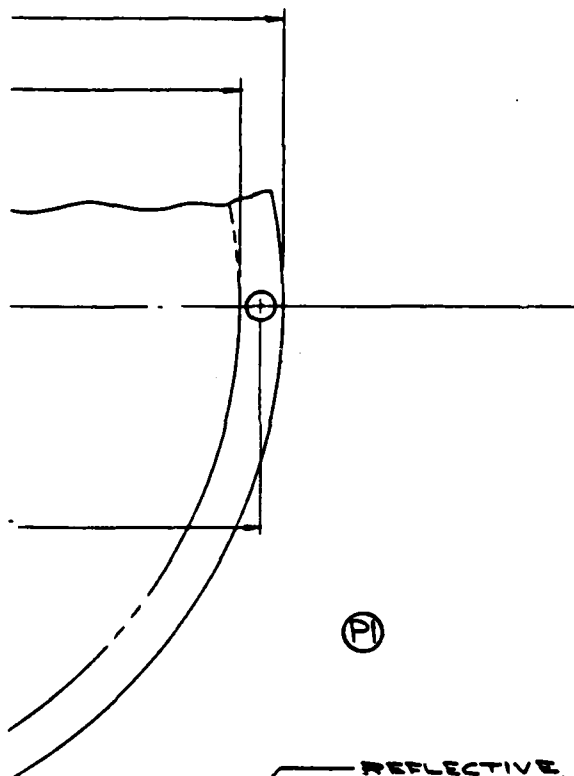D | 18876 | 47D178910

SCALE 1/2   SHEET 1 OF 1
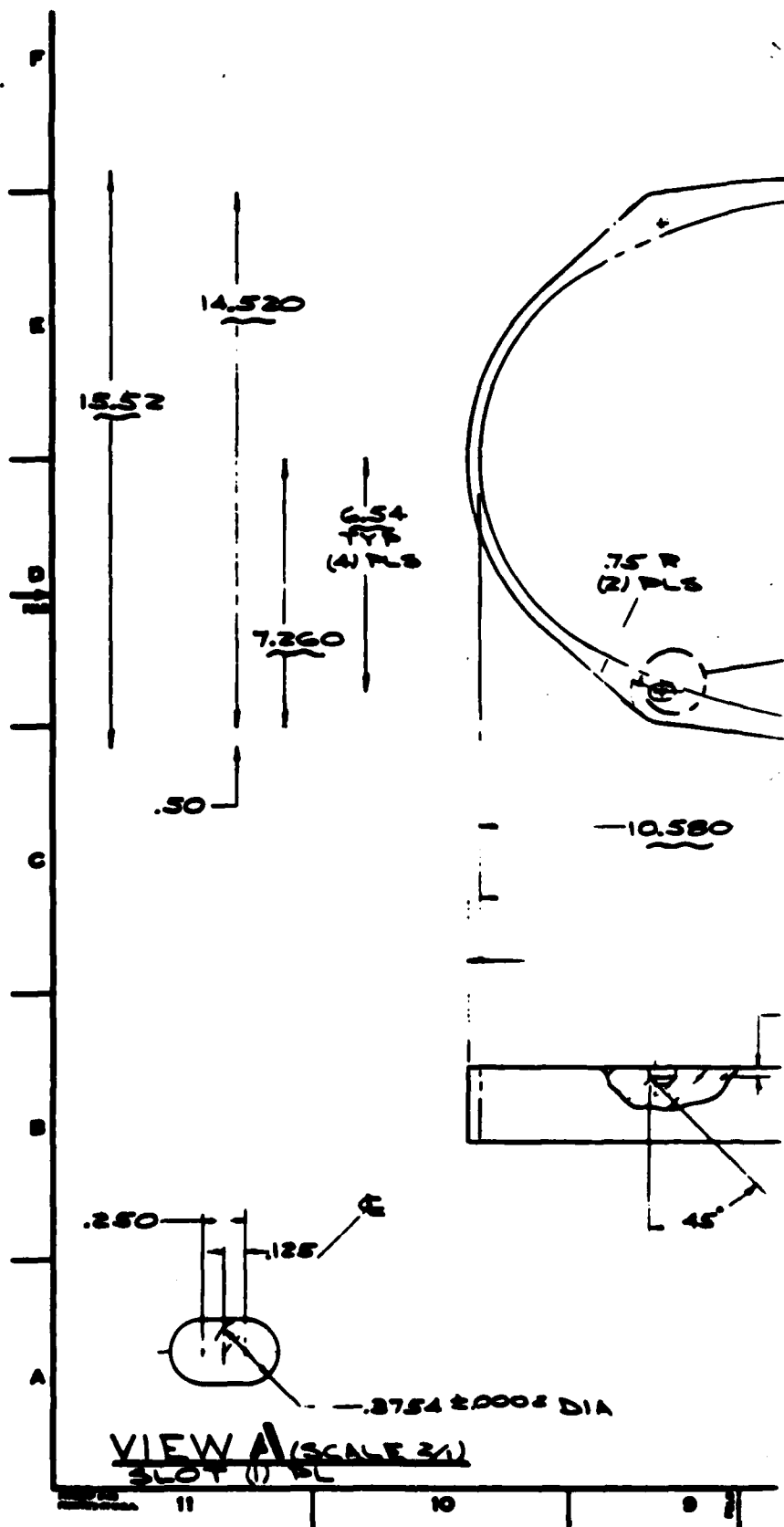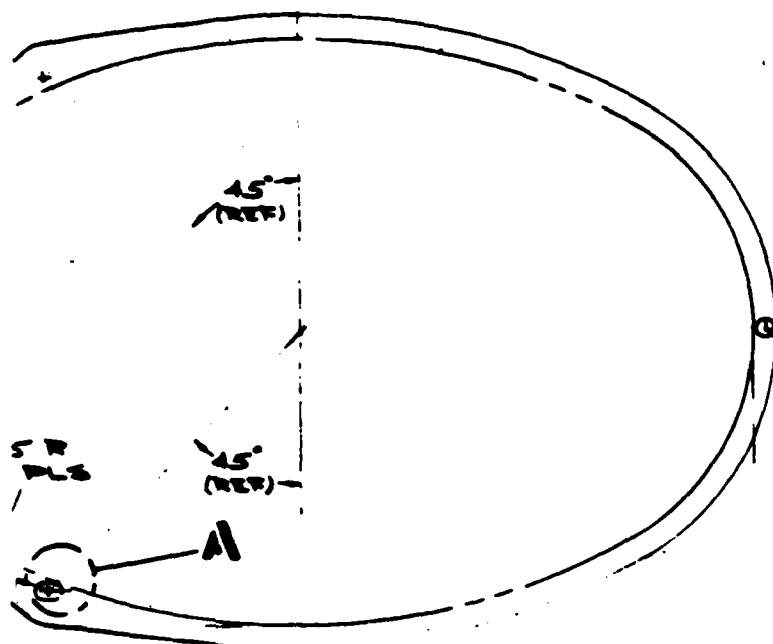
34 C1

14.520

15.52

6.54
TYP
(4) PLS

7.260

.50

.75 R
(2) PLS

—10.580

.250

125

45°

—.875 ±.0005 DIA

VIEW A (SCALE 3/1)
SLOT (1) PL

-10.830

45°
(REF)

5 R
PLS

45°
(REF)

A

.3754 ±.0002 DIA
(1) PL

REFLECTIVE
SURFACE

10.580

-21.160

-.50

-21.95

.130 ±.002 DP

.130 ±.002 DP

THK
(SEE NOTE 2)

45°

30°

P1

2.5
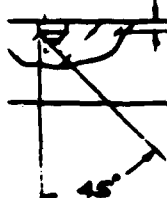
.3754±.0002 DIA
(1) PL

NOTES:
1. MATERIAL: PYREX GLASS

2. SURFACE QUALITY: 80/50

3. THICKNESS: TO BE SPECIFIED BY VENDOR.

4. WEIGHT: 35 LBS MAXIMUM LIGHTWEIGHT CONSTRUCTION.

5. COATINGS: NONE

6. FLATNESS:
    ORIENTATION #1

    POWER 1.0λ(λ=0.5μ)

    ADDITIONAL SLOPE ERROR DUE TO IRREGULARITY NOT TO EXCEED 0.1λ/INCH.

7. TESTING: TESTING IS TO BE DONE IN THE ORIENTATIONS SHOWN ABOVE WITH MIRROR SUPPORTED AT ITS' THREE MOUNTING POINTS. TEST METHOD EMPLOYED MUST PROVIDE CONTOUR OF ENTIRE SURFACE.

8. QUANTITY: 1

9. INTERPRETATION OF DIMENSIONS AND TOLERANCES PER S34060.

10. MARK PART "GE 47D178912 P1" PER 11BA152G, CLASS 17.

P1

-.190±.002 DD

THK
(SEE NOTE 3)

MAJOR DIA
45°

47D178912

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON:	SIGNATURES			
2-PLACE DECIMALS ±.01 ALL		0.5	2	71
3-PLACE DECIMALS ±.005 SURF.				
ANGLES ±1°				
FRACTIONS ± ✓				
MATERIAL-				

GENERAL ⊕ ELECTRIC
RES DIV   PHILA PA/C1

MIRROR #3
ELIPTICAL
FOR U.S. ARMY MISSLE COMMAND
CONTRACT NO DAAH01-71-C-0571

SIZE	CODE IDENT NO.	
D	88876	47D178912
SCALE 1/2		SHEET 1 OF 1

34 C1

12⎯.⎯5

.3754 ±.0002 DIA
(1) PL

45°
(REF)

45°
(REF)

R
PLS

A

P1

.075

4.150

.62

25.39

.190 ±.002 DP

.190 ±.002 DP

THK
(SEE NOTE 3)

90°

45°

REFLECTIVE
SURFACE

UNLESS OTHERWISE SPEC
DIMENSIONS ARE IN INCH
TOLERANCES ON:
2-PLACE DECIMALS ±.01
3-PLACE DECIMALS ±.OC
ANGLES ± 1°
FRACTIONS ± ⅛
MATERIAL—

16.650

17.72

7.45
TYP
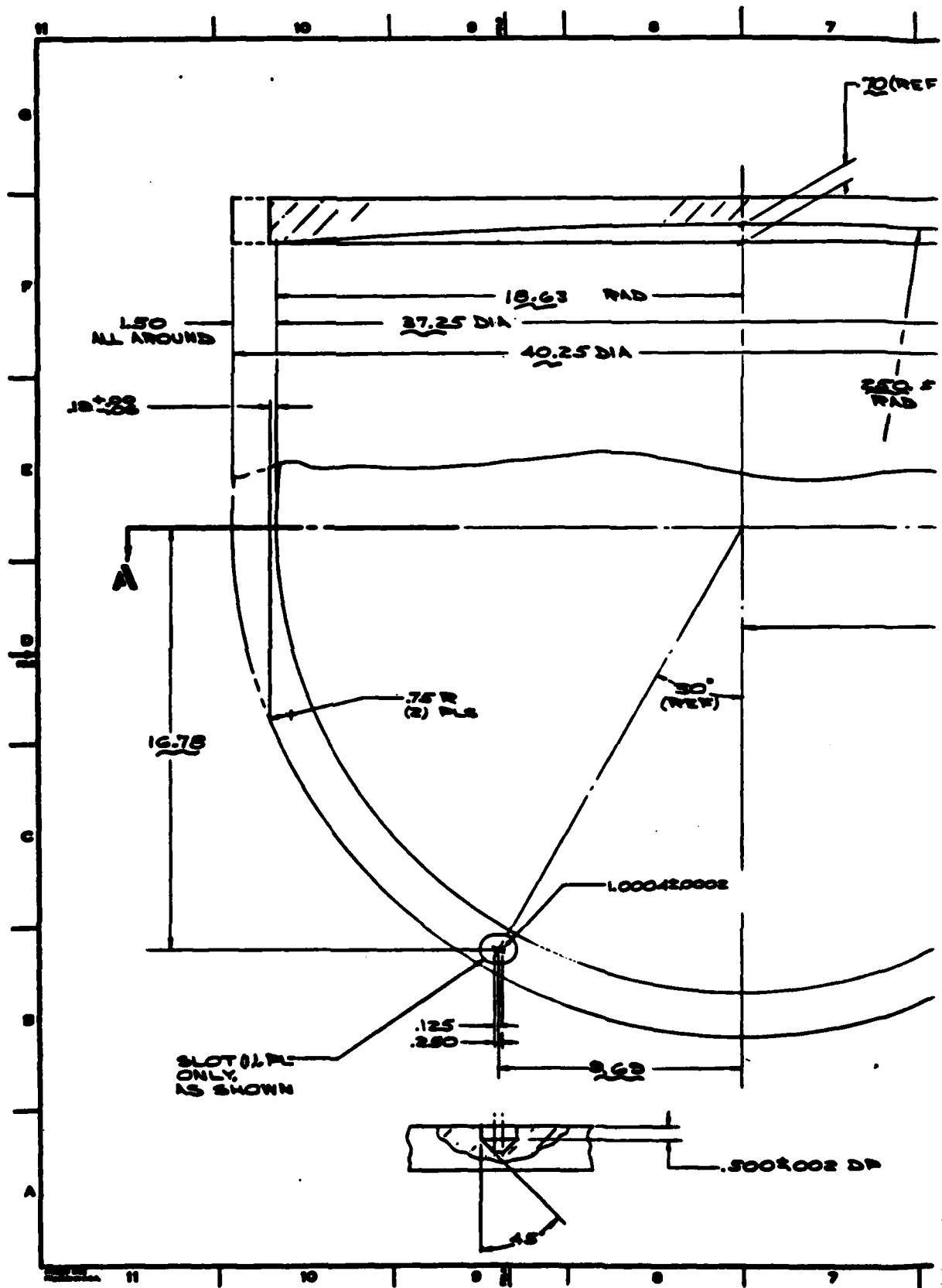(4) PLS

8.325

.75 R
(2) PLS

45°
(REF)

45°
(REF)

A

.62

12.075

24.150

25.3

.190±.002 DP

45°

.250

.125

.375±.0002 DIA

VIEW **A** (SCALE 3/1)
SLOT (1) PL

11   10   9   8

NOTES:

1. MATERIAL: PYREX GLASS

2. SURFACE QUALITY: 80/50

3. THICKNESS: TO BE SPECIFIED BY VENDOR

4. WEIGHT: TO BE SPECIFIED BY VENDOR.

5. COATINGS: NONE

6. FLATNESS:

   ORIENTATION

   POWER 0.5λ (λ=0.5μ)
   ADDITIONAL SLOPE ERROR DUE TO
   IRREGULARITY NOT TO
   EXCEED 0.1λ/INCH.

7. TESTING: TESTING IS TO BE DONE
   IN THE ORIENTATION SHOWN ABOVE
   WITH MIRROR SUPPORTED AT ITS
   THREE MOUNTING POINTS. TEST
   METHOD EMPLOYED MUST PROVIDE
   CONTOUR OF ENTIRE SURFACE.

8. QUANTITY: 1

9. INTERPRETATION OF DIMENSIONS
   AND TOLERANCES PER S34060.

10. MARK PART "GE 47D178946 P1"
    PER 118A1526, CLASS 17.

REFLECTIVE
SURFACE

P1

.7504 ±.0002 DIA,
.375 ±.002 DP

THK
(SEE NOTE 3)

90°

.250

.125

¢

.7504 ±.0002 DIA

VIEW A (SCALE 3/1)
SLOT (1) PL

29.00 DIA

1.10
ALL AROUND

26.80 DIA

13.40 RAD

30°
(REF)

13.25

12.08

A

6.98

.375 ±.002 DIA

45°

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED

DIA

16.55

REFLECTIVE
SURFACE

(M)

NOTES:
1 MATERIAL: PYREX GLASS

2 SURFACE QUALITY: 80/50

3 THICKNESS: TO BE SPECIFIED BY
  VENDOR

4 WEIGHT: TO BE SPECIFIED BY
  VENDOR.

5 COATINGS: NONE

6 FLATNESS:

   ORIENTATION

   POWER 0.5λ(λ=0.5μ)
   ADDITIONAL SLOPE ERROR DUE TO
   IRREGULARITY NOT TO
   EXCEED 0.1λ/INCH.

7 TESTING: TESTING IS TO BE DONE
  IN THE ORIENTATION SHOWN ABOVE
  WITH MIRROR SUPPORTED AT ITS
  THREE MOUNTING POINTS. TEST
  METHOD EMPLOYED MUST PROVIDE
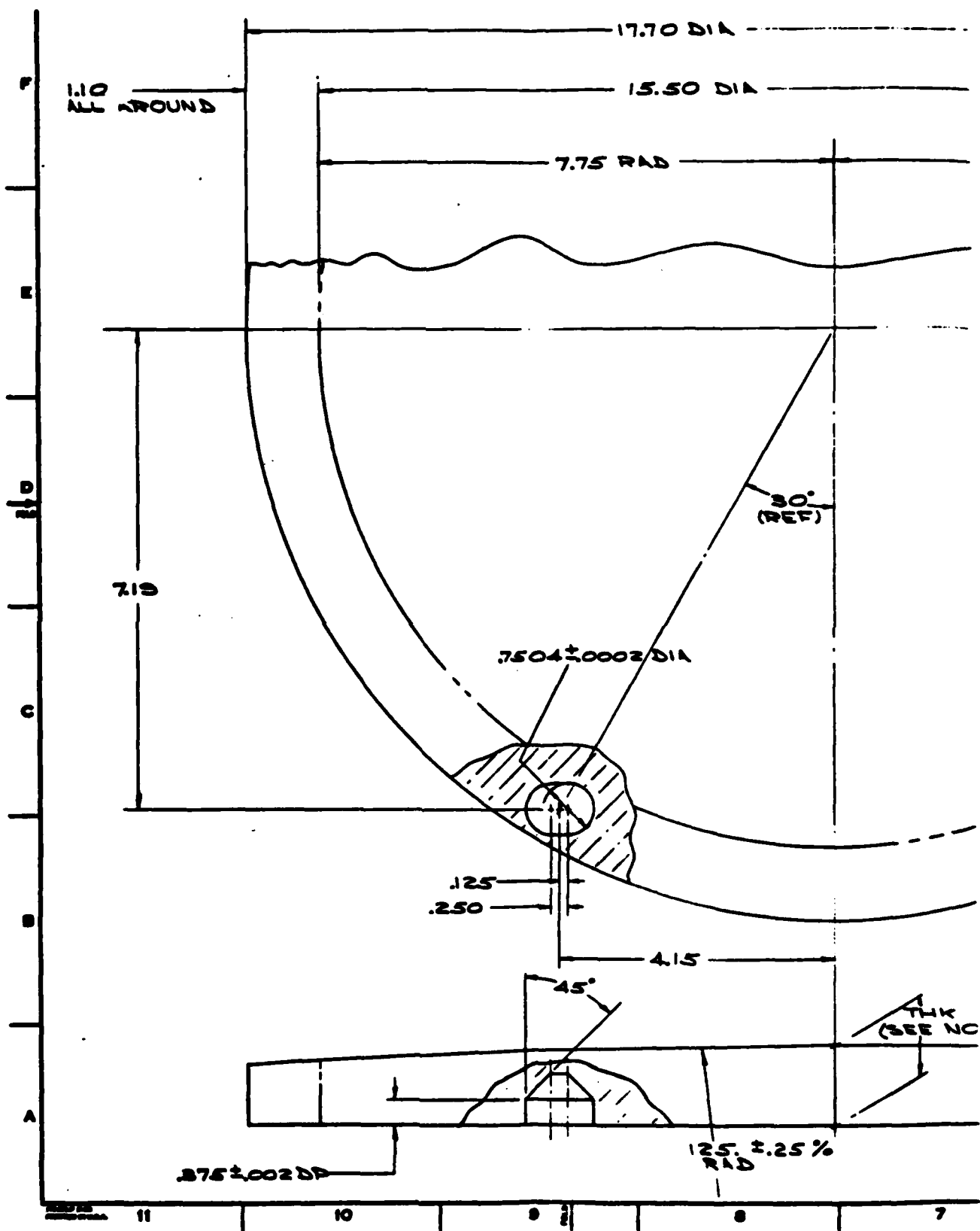 CONTOUR OF ENTIRE SURFACE.

8 QUANTITY: 1

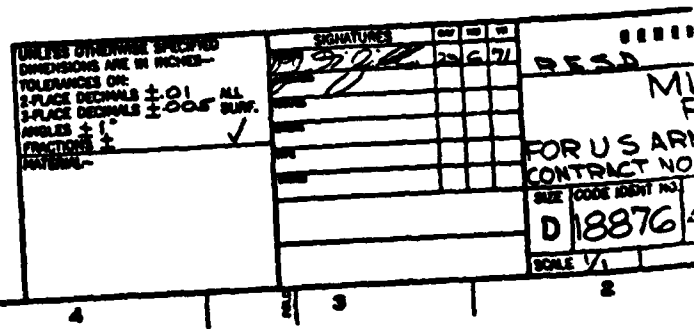9 INTERPRETATION OF DIMENSIONS
  AND TOLERANCES PER S34060.

10 MARK PART "GE 47D178947 P1"
   PER 116A1526, CLASS 17.

.7504±.0002 DIA.
.375±.002 DP

90°

THK
(SEE
NOTE 3)

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES—
TOLERANCES ON:
2 PLACE DECIMALS ±.01   ALL
3 PLACE DECIMALS ±.005 SURF.
ANGLES ± 1°
FRACTIONS ± 1/
MATERIAL—

GENERAL ELECTRIC
RES D   PHILA PA/C1

MIRROR #5
ROUND

FOR US ARMY MISSLE COMMAND
CONTRACT NO DAAH01-71-C-0571

SIZE	CODE IDENT NO.		
D	18876	47D178947	

SCALE 1/2   34 C1   SHEET 1 OF 1

VIEW A (SCALE 2/1)
SLOT ∪∩ ₵L

.250
.125
₵
.7504±.0002 DIA

34.20 DI
1.10
ALL AROUND
32.00 DIA
16.00 RAD
30°
(REF)
14.33
A
8.25
.375±.002 DP
45°

SECT A-A

90°

THK
(SEE NOTE 3)

1.000±.002 DIA.
.500±.002 DP.

±2%

CONCAVE
REFLECTIVE
SURFACE

A

NOTES:
1. MATERIAL: PYREX GLASS
2. SURFACE QUALITY: 80/50
3. THICKNESS: TO BE SPECIFIED BY VENDOR.
4. WEIGHT: TO BE SPECIFIED BY VENDOR
5. COATINGS: NONE
6. PERFORMANCE: MAXIMUM SLOPE ERROR FROM BEST FIT SPHERE DUE TO IRREGULARITY TO BE 0.1λ/INCH (λ=0.5μ)

ORIENTATION

7. TESTING: TESTING IS TO BE DONE IN THE ORIENTATION SHOWN ABOVE WITH MIRROR SUPPORTED AT ITS' THREE MOUNTING POINTS. TEST METHOD EMPLOYED MUST PROVIDE CONTOUR OF ENTIRE SURFACE.
8. QUANTITY: 2
9. RADII OF 2 MIRRORS TO BE MATCHED WITHIN 0.5 INCHES.
10. INTERPRETATION OF DIMENSIONS AND TOLERANCES PER S34060.
11. MARK PART "GE 47D178918 PER 116A1526, CLASS 17.

R & D DIV PHILA PA/C1

MIRROR #6
ROUND
FOR U.S. ARMY MISSLE COMMAND
CONTRACT NO DAAH01-71-C-0571

D | 18876 | 47D178918

227

20 (REF

19.63 RAD

37.25 DIA

40.25 DIA

1.50
ALL AROUND

250.5
RAD

$12^{+.22}_{-.00}$

A

.75 R
(2) PLS

30°
(REF)

16.78

1.000±.0002

.125
.250

SLOT .125
ONLY.
AS SHOWN

3.63

.500±.002 DP

15°

227

NOTES:

1. **MATERIAL:** PYREX GLASS

2. **SURFACE QUALITY:** 80/50

3. **THICKNESS:** TO BE SPECIFIED BY VENDOR.

4. **WEIGHT:** TO BE SPECIFIED BY VENDOR.

5. **COATINGS:** NONE

6. **PERFORMANCE:** MAXIMUM SLOPE ERROR FROM BEST FIT SPHERE DUE TO IRREGULARITY TO BE $0.1\lambda/$INCH $(\lambda=0.5\mu)$

   ORIENTATION

7. **TESTING:** TESTING IS TO BE DONE IN THE ORIENTATION SHOWN ABOVE WITH MIRROR SUPPORTED AT ITS' THREE MOUNTING POINTS. TEST METHOD EMPLOYED MUST PROVIDE CONTOUR OF ENTIRE SURFACE.

8. **QUANTITY:** —1

9. INTERPRETATION OF DIMENSIONS AND TOLERANCES PER 334060.

10. MARK PART "GE 47D178948 P1" PER J18A1526, CLASS 17.

CONVEX REFLECTIVE SURFACE

(P1)

90°

.048 .0002 DIA, .25 DP

— 8.30 —

Ⓟ

CONVEX
REFLECTIVE
SURFACE

30°

(NOTE 3)

.7504±.0002 DIA.
.375±.002 DD

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES—
TOLERANCES ON:
2-PLACE DECIMALS ±.01 ALL
3-PLACE DECIMALS ±.005 SURF.
ANGLES ± ½°
FRACTIONS ± ½
MATERIAL—

SIGNATURES

DESD

M

FOR US ARM
CONTRACT NO

SIZE	CODE IDENT NO	
D	18876	

SCALE ½/1

7   6   5   4   3   2

SOC HD CAP SCR
°10-24 NC 1.50 LG
(2) PLS

WASHER SPLIT
°10 (2) PLS

NC
THRU
CUT HL.

.50
.750
.40
-.062
(2)PLS

°10-32 NC
THRU HL
(2) PLS

.50
STK

.15

32°

CHAM .06 x 45° 22'
(2) PLS

LUM ALLOY
061-T6
70-A-200/06

231

This is an engineering drawing with multiple views and part callouts. Visible labels include:

EXT SPRING
SET SCR, HD HAB
SHOULDER SCR
ASSY

PAD
MAT'L: NYLON, FM101, WHITE
MIL-R-17091B, TYPE I
(SCALE 4/1)

TOOLING BALL (MODIF)
AMERICAN DRILL
BUSHING CO

PLATE
MAT'L: ALUM ALLOY

MTG SURFACE

FINE ADJUSTMENT

EXT SD'
LEE BE
CAT NO
(2) PLS

SHOULDER SCR (5)
10-32NC (3"-.1600)
DG CAT° 4327 (PG 20)
(2) PLS

.250±.0000 DIA
REAMED THRU
TA FLANGE
(S) 240 SH

10-32 NC
THRU HL
(S) 240 SH

BRACKET
MATL ALUM ALLOY
6061-T6
QQ-A-200/61
ALL RADII : .06
ALL CHAM : .06 x 45° 22'

233

VERTICAL DRIVE
TORQUE MOTOR

SUPPORT STRUCTURE

FIXED HUB

ROTATING HUB

SUPPORT STRUCTURE

VERTICAL
DRIVE PULLEY

TOP PLATE

AZIMUTH
DRIVE BANDS

SIDE WEB

BACK PLATE

STIFFENER
(TYP 6 PLACES
EACH SIDE)

VERTICAL DRIVE COUNTERWEIGHT

VERTICAL DRIVE BAND

IDLER PULLEY

DISPLAY ASM - 1255

FOR U.S. ARMY MISSILE COMMAND

R 18876 SK56205-538

SIDE VIEW
(AZIMUTH DRIVE MOTOR &
TILT MOTORS NOT SHOWN)

SECTION B-B.

SECTION A-A
(TILT MIRROR SHOWN
TILTED 60° FROM VERTICAL)

SECTION C-C

TYPE T-2955
TORQUE MOTOR
(KOLLMORGEN)
MAGNET
ROTOR

TYPE TG-2158
TACHOMETER GENERATOR
(KOLLMORGEN)
MAGNET
ROTOR

A

A

MIRROR

SHAFT

1.62

MIRROR #1
47D178914P1

CRADLE

REVISION A

SURFACE OF
TRAVERSE
CARRIAGE

SEAT

CS:14 SETSCREW
(PIC)(2 PL)

1/4-28 UNF
CAP SCREW
(8 PLACES)

4 1/2 UNEF THREAD

BEARING HOUSING

SHAFT

COLLAR

6.25

.150

3.50

.180

MIRROR

.125

CRADLE

1.50

1.90

60°

30°
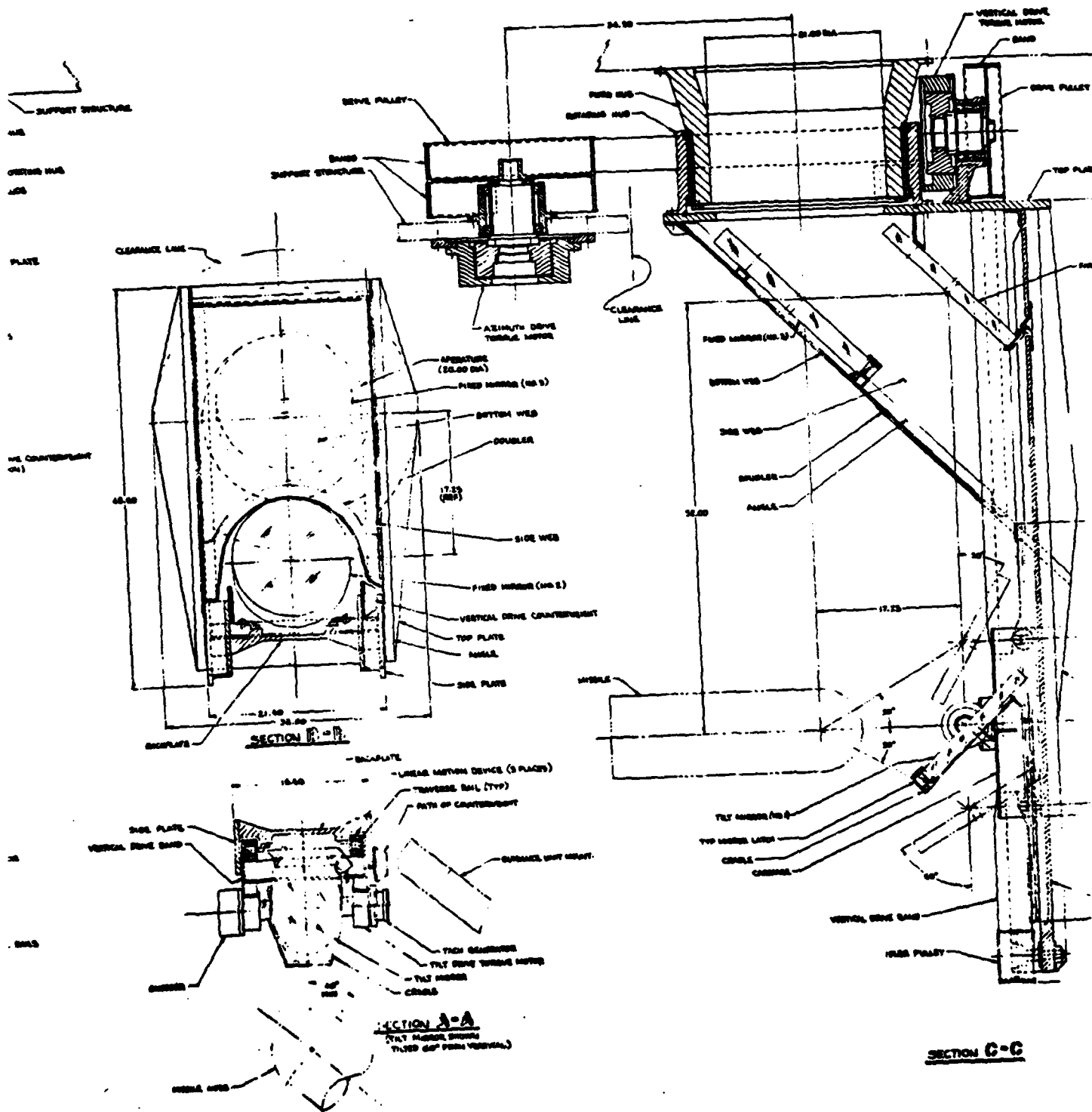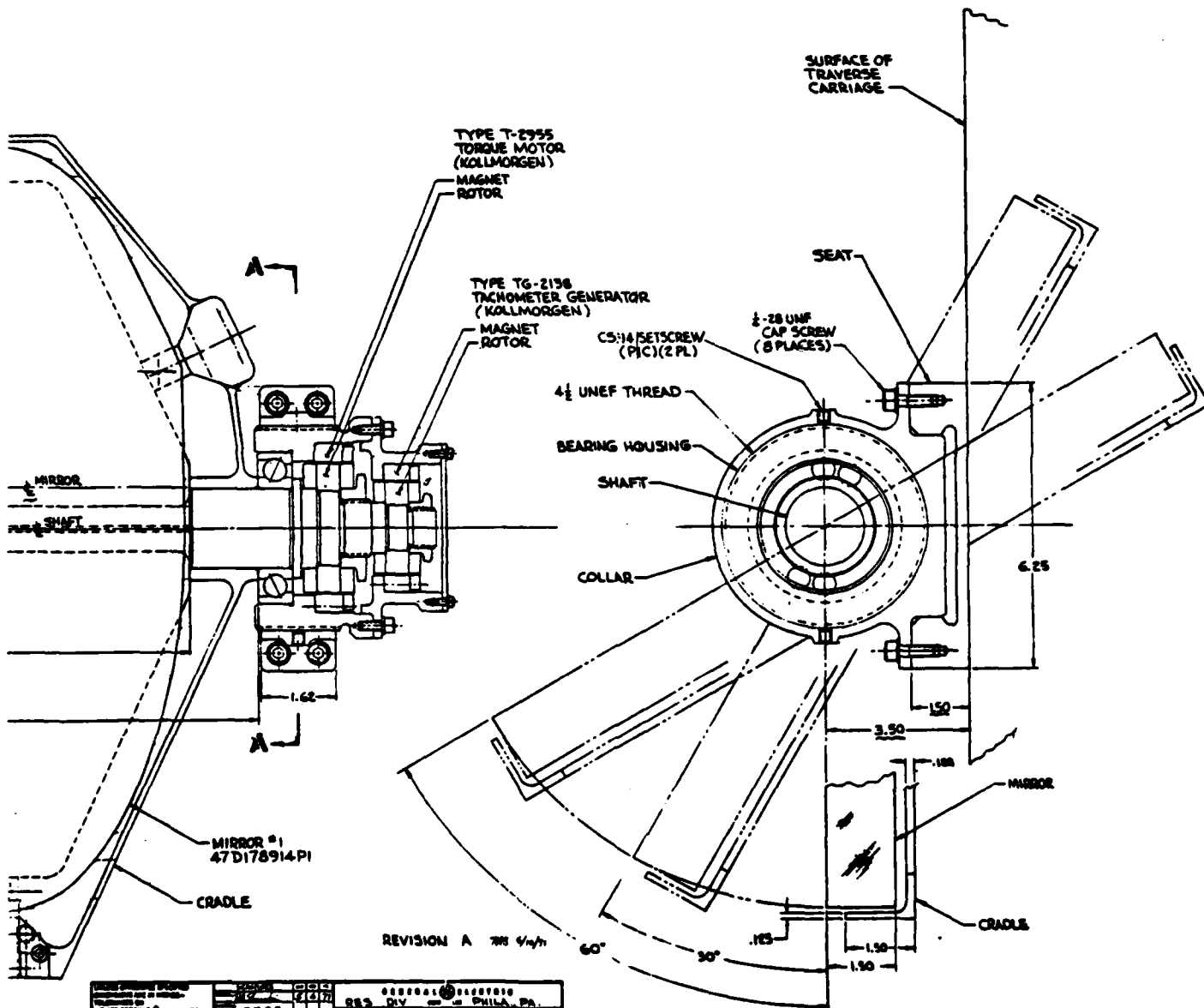
SECTION A-A
SCALE: 1/2

LONG
X1/2
1/1

R83 DIV   PHILA, PA.
MOVABLE MIRROR MOUNT
FOR U.S. ARMY MISSILE COMMAND
DAAH01-71-C-0571
R 18876   SK 56205 - 534

235

H20209 1 BEARING
(NEW DEPARTURE)
TYP BOTH SIDES

DIGISEC RA_/55(S)
ENCODER (ITEK)

8.00

.91 MIRROR

SHAFT

8.60

11.60 1.62

8.27

ADJ & OVERRIDE ALLOWANCE (TYP BOTH ENDS)

DISPLAY ARM STRUCTURE

MIRROR #1
47 D178914 P1

CRADLE

REVISIO

000 DIA FULLY SUPPORTED SHAFT (2 PL)

ERTICAL DRIVE BAND

SECTION ALONG
SHAFT AXIS
SCALE: 1/1

MOVABLE MIR

R 18876

235

VERTICAL DRIVE BAND

TO DRIVE PULLEY

SKF LINEAR MOTION ASSY (3 PL)

TRAVERSE CARRIAGE

SEAT (2 PL) (SEE SECT A-A)

MIRROR

20.00

10.00

5.12

4.00

VIEW LOOKING INBD
(DISPLAY ARM STRUCTURE REMOVED FOR CLARITY)

20.00 STROKE

14.97

48.00

25.00

2.50 ADJ & OVERIDE A

1.000 DIA PULLY S

VERTICAL D.

LINEAR MOTION TRAVERSE SYSTEM
SCALE: 1/2
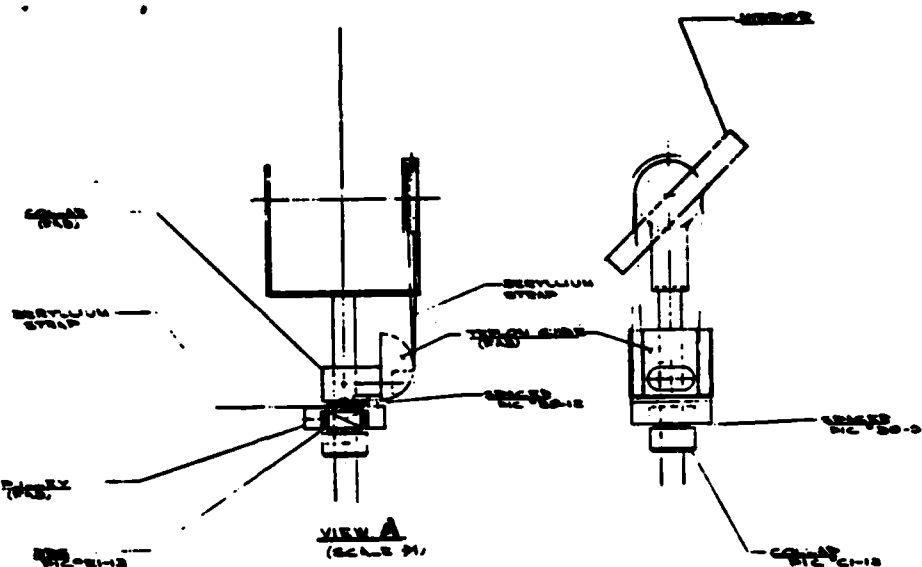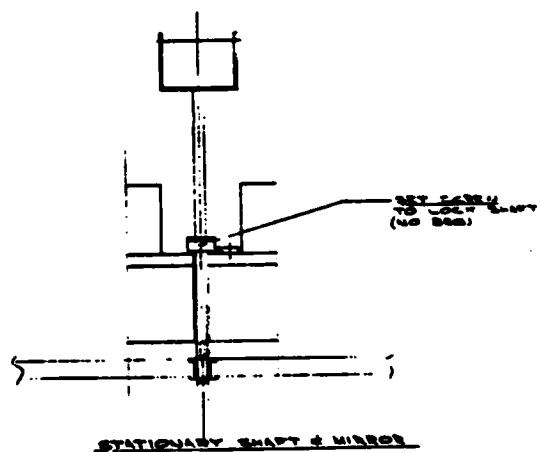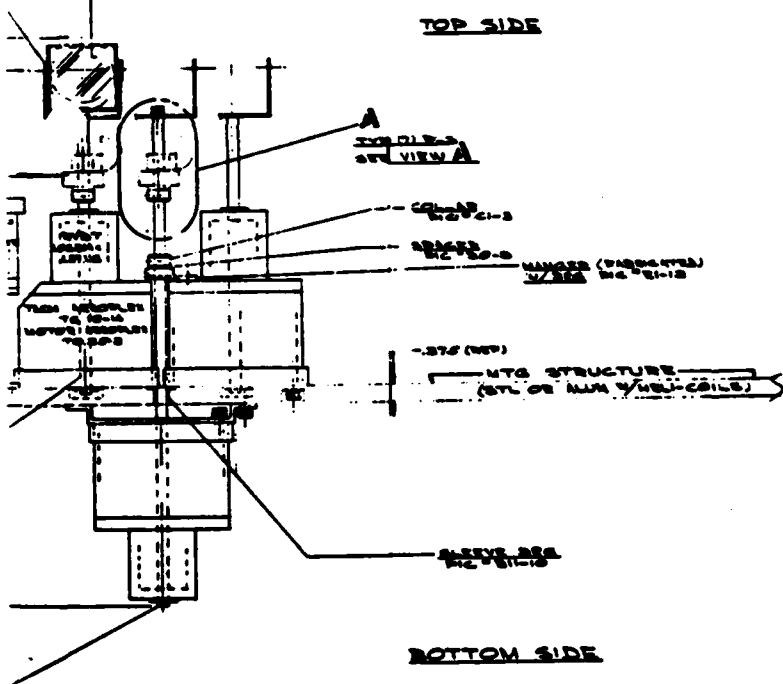
DIRECTIONAL MIRROR CORE ASSEMBLY

STATIONARY SHAFT
& MIRROR

MIRROR BRACKET
(MASONITE)

MIRROR

SHAFT

A

SHAFT

SHAFT

SHAFT

VIEW FROM
TOP SIDE

SECTION C-C
SCALE: 1/1

VIEW LOOKING DOWN
SCALE: 1/2

239

SECTION A-A
SECTION B-B

SECTION D-D

SECTION C-C

SECTION F-F
SCALE: ½

SECTION E-E
SCALE: ½

SECTION D-D
SCALE: ½

BUSHING

DIA ST. STL
STATIONARY SHAFT

SAGINAW
BALL NUT BCD-.1875
BALL SCR LEAD-.0625
ROOT DIA - .132

.16

1.50

1.00

TRANSPARENCIES

SLEEVE COUPLING
(NON-FLEX)
PIC °DI-10
($ TO $ SHAFTS)

BOURNS
POTENTIOMETER
° 2504
SERVO MOUNT

1.88

2.10

2.50

ASSY SAME AS TRANSPARENCY
MECHANISM 47B10C033 EXCEPT
FOR MINOR MODIFICATION
TO CARRIAGE.

TRANSPARENCIES

SAGINAW
BALL NUT B.C.D. - 375

SLEEVE CPLG
(NON-FLEX)
B.C. DI-10
(¼ TO ¼ SHAFTS)

TORQUE MOTOR
(COMPANY - - NONE - -
#U12N4

SAGINAW
B.C.D.
LEAD - .333
ROOT DIA - .628

BOURNS
POTENTIOMETER
#3500
SERVO MOUNT

TECH
MOTOR
MAGNETIC
TECH
#B375-068

FLEX CPLG
LO-TORSY CPLT TC-L-P54
#802 40 PA-068

1.00

2.52

SHAFT ADAPTER
(½ TO ¼)
FABRICATE - 11

THOMSON BALL BUSHING
#IUST-258-35

DIA ST STL
STATIONARY SHAFT

.75

L50

L00

.50 MAX (SQUARE)
GROOVING

RT HAND THD
.16
LEFT HAND THD

FUSELAGE
TRANSPARENCY
MECHANISM
(ONE CHANNEL)
DAAH01-76-C-0841

R18876 47R196294

34 C1

THOMS
IUST-

TRANSPARENCIES

15.24

SAGINAW
BALL NUT B.C.D .375

6.70

EVE CPLG
(FLEX)
*DI-10
+ SHAFTS)

SAGINAW
BALL SCR
LEAD .2223
ROOT DIA .238

TORQUE MOTOR
(COMPANY - BY ROCKWELL)
*U12M4

FLEX CPLG
LOVEJOY CAT JC-G3 PG3
SIZE NO PA-033

TACH
IMOTOR
MAGNETIC
TECH
*7275-063

1.00

2.22

6.16

AD'
2
WEIGHT-M

SLEEVE CPLG
(NON-FLEX)
PIC #D1-10
(½ TO ¼ SHAFTS)

BOURNS
POTENTIOMETER
#3684
SERVO MOUNT

TACH
MOTOR
MAGNETIC
TECH
#2375-06

2.22

SHAFT ADAPTER
(¼ TO ⅛)
FABRICATE.?

TORQUE MOTOR
INLAND MOTOR CORP
TYPE NO. T-1342
40 OZ-IN.

IRIS DIAPHRAGM
OPERATING LEVER

PIN-TYPE GEAR
STERLING INSTRUMENT
CAT.# A15-80 P3

HUBLESS GEAR
STERLING INSTRUMENT
CAT.# S24-280 P3

2.25

SINGLE ROW
RADIAL BEARING
NEW DEPARTURE
CAT.# 3L10

1.65

6.12

4.09 DIA

A - A

SIGNATURES				GENERAL ⊛ ELECTRIC RES DIV PHILA., PA.
7M Shanaha	8	6	71	IRIS ASSEMBLY — IRSS
				FOR U.S. ARMY MISSILE COMMAND
	8	6	71	DAA H01-71-C-0571
				SIZE D CODE IDENT NO. 18876 SK 56205-903
				SCALE 1/1 SHEET 1 OF 1

247

TACHOMETER
MAGNETIC TECHNOLOGY
MODEL 2375-063
45 OZ-IN.

SINGLE ROW
RADIAL BEARING
NEW DEPARTURE
CAT.# 3LO1
(TYP 2 PLACES)

4.88

3.12

3.56
DIA
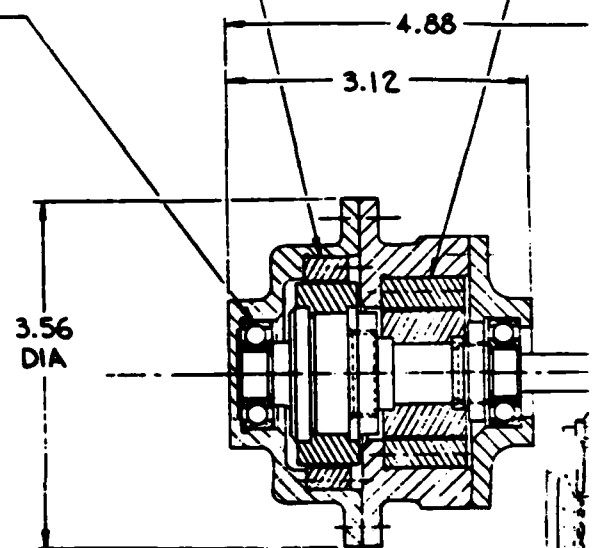
IRIS DIAPHRAGM
THE EALING CORP
CAT. # 22-3339
MAX OPENING: 55 mm
MIN OPENING: 2.5 mm
O.D: 75.5 mm
LEVER OPERATING

SECTION A

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
General Electric Company Re-entry and Environmental Systems Division Philadelphia, Pa. 19101	Unclassified
	2b. GROUP —

3. REPORT TITLE

Infrared Simulation System (IRSS)

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report - Phase I

5. AUTHOR(S) *(Last name, first name, initial)*

R.J. Baessler
H. Popper

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1971	258	—
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b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* 71SD484
d.	

10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	US Army Missile Command Redstone Arsenal, Alabama 35809

13. ABSTRACT

This report documents the analytical and design efforts performed by the General Electric Company in synthesizing an Infrared Simulation System (IRSS). This design meets or exceeds the requirements of MICOM Technical Requirement No. 1276, can be implemented in a reasonable interval, and will operate reliably, safely and with minimum alignments thereafter.

The Infrared Simulation System will be used for the development and evaluation of advanced infrared missile guidance components, subsystems and systems as a part of MICOM's Advanced Concepts Development Facility (ACDF) now under construction.

This report covers, in addition to the detailed description of the design approach, selected rationales leading to important choices, results of analyses and trade-offs made, a consideration of interfaces among key subsystems and with the Hybrid Computation Laboratory, and planned potential for future growth in both capability and application.

DD FORM 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Infrared Simulation						
Target Display						
Collimating Optics						
Infrared Projection						
Computer Control						

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