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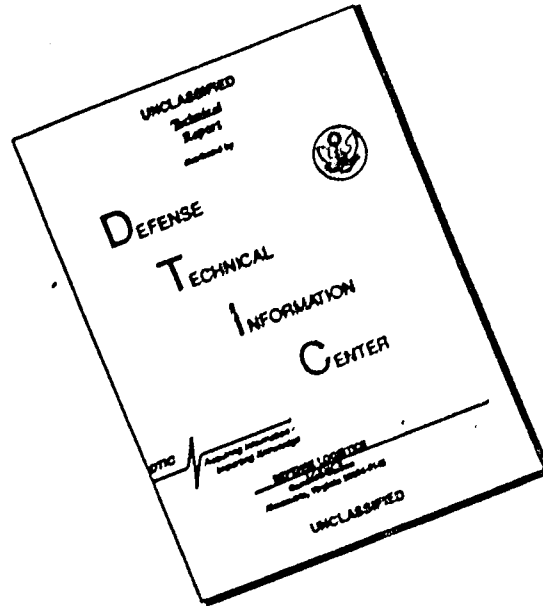
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ASD-TDR-63-586

DESIGN, FABRICATION, AND TEST OF A FEASIBILITY-MODEL  
RELATIVE STAR-ANGLE COMPARATOR

Technical Documentary Report No. ASD-TDR-63-586

May 1963

Navigation and Guidance Division  
AF Avionics Laboratory  
Aeronautical Systems Division  
Air Force Systems Command  
Wright-Patterson Air Force Base, Ohio

Project No. 4200, Task No. 420005

Project Scientist: S. Young

(Prepared under Contract No. AF33(657)-7997 by Kearfott

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FOREWORD

This final Technical Documentary Report was prepared by the Kearfott Division, General Precision Aerospace, Little Falls, New Jersey. It was done as part of our performance under Contract AF33(657)7997, for the Navigation and Guidance Laboratory (ASRNG)\*, Aeronautical Systems Division. The project and task numbers are 4200 and 420005 respectively, and have to do with producing a feasibility model Star-Angle Comparator. The project scientist at ASD was Mr. Seth Young.

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Monthly contract status reports were submitted during the twelve-month period of contract performance. This report is the culmination of the entire work effort.

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\* Now designated Navigation and Guidance Division, Air Force Avionics Laboratory.

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ABSTRACT

A new and unique aerospace vehicle attitude system, designed around the Star-pair Angle Comparator, is described. The system basically measures the direction to any three of the fifty (50) brightest stars, computes the angles between them and processes the information to provide a two-star identification and a highly accurate spatial attitude determination.

System operation and performance are discussed along with a detail description of the feasibility model subsystems and their components. It is shown that the optical-electrical subsystems provide an equivalent star tracker accuracy within ten arc seconds. The overall system accuracy, including scanner, gimbaling and electronics, exceeds contractual requirements by a factor of two and is 20 arc seconds, demonstrated over-all system error excluding computation error.

TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
1.1 Purpose	1
1.2 History	1
2. SOME GENERAL CONSIDERATIONS	4
2.1 Theory of Comparator Techniques	4
2.2 Some Design Considerations	4
3. SUMMARY OF RESULTS	6
3.1 Contractual requirements	6
3.1.1 Statement of Work	6
3.2 Additional Suggested Requirements	7
3.3 Achievements	7
4. CONCLUSIONS AND RECOMMENDATIONS	9
4.1 General	9
4.2 Results	9
4.3 Recommendations	10
4.3.1 Future Application	10
4.3.2 A Specialized Application	11
4.3.3 Future Instrumentation	12
5. OPTICAL SYSTEM ENGINEERING AND TEST	16
5.1 System Components	16
5.1.1 Objective System	16
5.1.2 Reticle System	17
5.1.3 Energy Transfer System	17
5.1.4 Folding Mirror	19
5.2 Optical System Performance Tests and Measurements	19
5.2.1 Objective System	19
5.2.2 Reticle Measurements	20
5.2.3 Energy Transfer System	21
5.2.4 Back-up Optical System	22
5.3 Alignment Techniques	22
5.3.1 General	22

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TABLE OF CONTENTS (cont'd)

	<u>Page</u>
6. DETECTOR SYSTEM DESIGN AND DEVELOPMENT	24
6.1 Photomultiplier	24
6.1.1 General	24
6.1.2 Subsystem Test	24
6.2 Photomultiplier Electronics	25
6.2.1 General	25
6.2.2 Preamplifier	25
6.3 Filter and First Postamplifier	30
6.4 Discriminator	30
6.5 Differentiator	30
6.6 Second Postamplifier	31
6.7 Output circuitry	31
7. STAR COUNTER	33
7.1 General Description	33
8. MECHANICAL DESIGN	34
8.1 General	34
8.2 Orthogonality	34
8.3 Axis Rigidity	34
8.4 Optical Axis Alignment	35
8.5 Encoder Coupling	36
8.6 Drive System	36
8.7 Material Selection	37
9. SYSTEM TEST	38
9.1 General	38
9.2 Field Testing	39
APPENDIX A THEORY OF ALIGNMENT	41
APPENDIX B SLEW AXIS SERVO DESIGN COMPUTATIONS	47
APPENDIX C INDEXING AXIS SERVO COMPUTATION	59
APPENDIX D OPTICAL TILT TABLE DATA	72
APPENDIX E STAR COUNTER	75
APPENDIX F SYSTEM TEST PROCEDURE	85
APPENDIX G SCHEMATICS	90

TABLE OF ILLUSTRATIONS

<u>Table</u>	<u>Title</u>	<u>Page</u>
6-1	Comparison of Photomultiplier Characteristics	27
6-2	ASCOP Photomultiplier	28
6-3	Preamplifier Model 203	29
6-4	First Preamplifier	32
<u>Figure</u>	<u>Title</u>	
1-1	The Relative Star-Angle Comparator	2
4-1	Possible Accuracy Improvement	13
5-1	Reticle Design	18
6-1	Signal Processing Electronics	26
A-1	Mirror-Shaft Alignment	43
A-2	Shaft Orthogonality	43
A-3	Autocollimator Alignment	44
A-4	Mirror Alignment	44
B-1	Slew Axis Servo CX	48
B-2	Model 597-3 Power AMP Characteristics	50
B-3	Scan Tachometer Loop	51
B-4	Azimuth Tachloop Slew Axis	52
B-5	Azimuth Position Loop Slew Axis	53
B-6	Slew-Axis Position Loop	55
B-7	Saturating Conditions of Position & Slew Loops	57
B-8	Finalized Slew Axis Position and Velocity Loops	58
C-1	Control Transformer	60
C-2	Index Tachometer Loop	62
C-3	Elevation (Index) Loop	64
C-4	Elevation (Index) Loop (50DB TACH F.B.)	65

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TABLE OF ILLUSTRATIONS (cont'd)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
C-5	Elevation (Index) Loop (40DB TACH F.B.)	67
C-6	Saturating Condition For The Indexing Axis Servo Loop	70
C-7	Finalized Position and Velocity Loops of The Index Axis	71
D-1	Optical Rotary Tilt Table Data	74
E-1	Star Counter Block Diagram	77
E-2	Star Counter	83
G-1	Photomultiplier Preamplifier	91
G-2	First Post Amplifier	92
G-3	Second Post Amplifier	93
G-4	Star Counter Schematic (3 pages)	94
G-5	Chassis Layout Diagram	97
G-6	Block Diagram, Synchro Standard, Pulse Operated	98

## 1. INTRODUCTION

### 1.1 PURPOSE

The Relative Star-Angle comparator is a new, unique, self-contained system designed for application in either manned or unmanned Aerospace Vehicles. See Figure 1-1. Its purpose is to provide fundamental attitude or orientation information, without which navigation and guidance is not possible.

The Comparator performs basically the same function that a map-matcher is intended to perform, except that the comparator works without any assumption of attitude information and, therefore, has the unique capability of performing under the most general conditions. In contrast with special-case devices which work with star fields, the Relative Star-Angle Comparator determines attitude by identifying stars on the basis of the angular separations between the brightest stars. The system detects and locates bright stars by systematically scanning a portion of the celestial sphere, and then compares the angular separations between these stars with star-angle separation data stored in a computer.

In general, if any three of the fifty (50) brightest stars (second order of magnitude or better) are observed, it is possible to identify at least two of them. (Identification is always possible if additional stars are observed, though these are rarely needed). Analysis shows that ambiguity concerning star identity is rare. A conservative estimate based on these studies indicates that in ninety-eight percent (98%) of the possible star combinations only three stars will be required for a unique solution. In only two percent (2%) of the cases will ambiguity necessitate the acquisition of a fourth star.

### 1.2 HISTORY

Kearfott Division, General Precision, Inc., conceived the Star-Angle Comparator and proposed it to ASD, USAF in 1958. A contract was then awarded to Kearfott to study the system with regard to theoretical considerations. During this study program the

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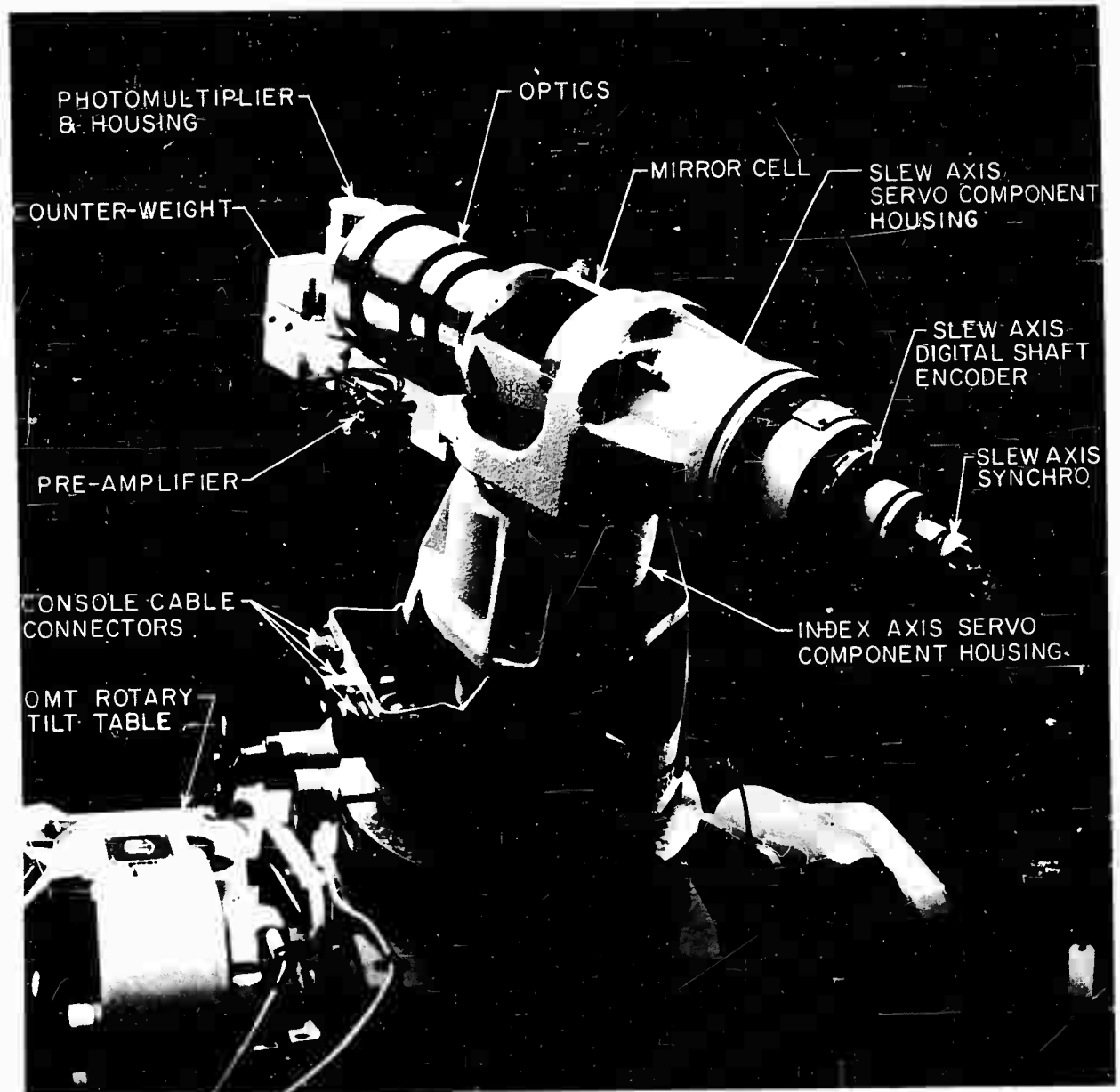


FIG 1-1 THE RELATIVE STAR-ANGLE COMPARATOR

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system was shown to be theoretically feasible and the system parameters were determined. The basic star population, conditions for definite identification (e.g., system accuracy required), and identification logic were also determined.

A second (subject) contract was then awarded to build a breadboard model of the Comparator to demonstrate hardware feasibility. Very exacting requirements were imposed by the Air Force, among which were: (1) a maximum of 60 seconds to scan a hemisphere for the bright stars, (2) to determine vehicle or platform attitude to an over-all accuracy of 60 arc seconds (equivalent star tracker line of sight accuracy of approximately 10 arc seconds), (3) a high signal-to-noise ratio for reliable detection.

For the purposes of the subject contract, it was not necessary to show that identification can be made for all possible triples which might be encountered amongst the bright stars. This is so because it was shown during the aforementioned study program that all such triples can easily be identified if the system accuracy is considerably worse than 60 arc seconds (present specification). Therefore, it was to be demonstrated that the required field-of-view could be covered in the specified time (60 seconds) with high reliability, to an overall system accuracy of 60 arc seconds.

The following will show that the resulting Star-Angle Comparator exceeded these stringent specifications considerably.

## 2. SOME GENERAL CONSIDERATIONS

### 2.1 THEORY OF COMPARATOR TECHNIQUE

Assume that a portion of the celestial sphere is systemically scanned and that the sensing equipment is properly biased so as to detect only the  $n$  brightest stars. Assume, for simplicity, that all of the star pair separation angles that can be formed from a group of  $n$  stars are unique. Assume further that these separations are available in the vehicle as stored information.

Any one of these stored angular separations will then correspond to (identify) a star pair  $S_i S_j$  (i.e., a pair of observed stars, say  $S_1, S_2$ ). To identify each individual star of the pair, additional information is required. This information need simply consist of a second angular separation measurement using a third observed star, which measurement will identify individually stars  $S_1$  and  $S_2$ . In so doing, the third star  $S_3$  will also be identified, though identifying any two stars will suffice to establish a right-handed inertial reference frame.

(In practice, the critical assumption of uniqueness of separation angles is not realized due to system errors. However, the few cases where ambiguities result are dealt with by making an additional observation).

### 2.2 SOME DESIGN CONSIDERATIONS

The Comparator's radically different search field requirement, the critical discrimination requirement, and the requirement to maintain a high signal-to-noise ratio while scanning at an extremely high rate, preclude the use of conventional star trackers or scanners, or modified trackers with dual modes. (Conversely, however, the Comparator can perform as a tracker with high accuracy, hence it is not "extra equipment" functionally).

Since variable focal length optics yield extremely poor resolution (either on or off axis), and large fields of view similarly result in poor resolution (and often low off-axis sensitivity), it follows that the optics field of view cannot be large.

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However, the number of fields of view to be searched is then extremely large. If the searching is accomplished in discrete steps (e.g., vidicon, image disector, solid state, semiconductor), then either a prohibitive length of time (or number of telescopes), in conjunction with a large number of undesirable stepping motions necessarily follows. This implies a large number of accelerations and decelerations, all of which must be accomplished with high accuracy and extremely short settling times.

These considerations led to the photomultiplier constant-speed scanning system. Here, the number of indexing motions required is at least an order of magnitude less than alternate approaches. Moreover, the indexing accuracy requirement (position) is at least an order of magnitude less than that required for discrete step-scanning. The indexing time allowable is then easily realized, as are the acceleration levels and accuracy requirements. The system has the added advantage that the photomultiplier detector was successfully employed in the Explorer-series satellites.

### 3. SUMMARY OF RESULTS

#### 3.1 CONTRACTUAL REQUIREMENTS

##### 3.1.1 STATEMENT OF WORK

###### 3.1.1.1 Objectives:

The objective of this program is to verify the feasibility of establishing an inertial coordinate reference frame at any time from within an aerospace vehicle (without continuous operation of equipment) by detecting, locating, and measuring selected star-pair angular separation. This instrument is intended to be operated only upon demand, as required to determine the vehicle's attitude without use of stored or otherwise acquired knowledge regarding present position, velocity, or vehicle orientation.

###### 3.1.1.2 Approach:

The approach is to design and fabricate a device capable of detecting, locating and measuring the star angular separations; so that in conjunction with a proper computer, attitude can be determined, within an accuracy of one(1) arc minute.

###### 3.1.1.3 Problems to be considered:

In the following areas, worst case conditions will be assumed wherever applicable to assure that the objective may be realized.

3.1.1.3.1 It may be assumed that the instrument can be inertially stabilized by use of a platform for a period of one minute. This determines the scanning time.

3.1.1.3.2 The sensing equipment must be capable of detecting at least the brightest  $n$  visual magnitude stars and rejecting all other stars while maintaining a signal to noise ratio  $N_s$ , the magnitude of which must be such that there will not be one false signal over the entire effective field of view. The sensor must be capable of detecting the first  $n$  stars and rejecting all other stars in the presence of all possible backgrounds varying from bright sections of the Milky Way to areas of the Celestial sphere where there is comparatively little background.

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3.1.1.3.3 The variables',  $n$  stars, maximum effective field of view ( $\emptyset$ ) and signal to noise ratio (N) will be optimized for the proposed technique in accordance with the given scanning time (one minute maximum).

3.2 ADDITIONAL SUGGESTED REQUIREMENTS

The above statement of work was modified by verbal agreement. It was agreed that all possible backgrounds for detecting did exclude the possibility of trying to detect a star against the sun as background. Furthermore, the one minute scanning time was for scanning only and did exclude computation time. In agreeing to these interpretations, the ASD Project Scientist requested that all possible effort be given to making a "dual purpose" design. That is, a design which would permit operation as a star tracker as well as the star angle comparator.

3.3 ACHIEVEMENTS

3.3.1 DETECTOR

A detection scheme, based on a photomultiplier was designed. In order to avoid any possibility of a false decision, a group of stars (K) containing the group of  $n$  brightest stars was selected. The photomultiplier was then biased so that the  $n$  brightest stars would be detected ( $n=20$ ). Due to uncertainty in bias level adjustment, viewing conditions, and the electronics, the computer was programmed for the complete group of stars (K=50). In this way, most of the time the stars K- $n$  would be rejected but if detected would be usable.

3.3.2 SIGNAL TO NOISE

An extremely high signal to noise ratio was obtained by using a high gain photomultiplier and a special reticle mask and small field of view optics. The reticle and optical systems are discussed in Section 5.

3.3.3 SYSTEM OPERATIONS

The system rotates about the elevation axis at 36rpm, with the optics continuously scanning a five (5) degree field of view through 180 degrees in less than one (1) second.

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It indexes in 5 degree increments in azimuth thus scanning the entire celestial hemisphere in less than one (1) minute.

**3.3.4 MEASURED ANGULAR ACCURACY**

**3.3.4.1 Scan Axis**

	Arc
	Seconds
Rotational Axis-to-Axis Orthogonality (max)	3
Optical Distortion (max)	5
Uncertainty of Slit Orientation (1 $\sigma$ )	2
Mirror (Optical Axis) Alignment (max)	5
Detector PPM Noise (1 $\sigma$ )	6
Digital Readout (15 bit)	
(1) Quantum Error = 11.6 (1 $\sigma$ )	
(2) Instrument Error = 5.9 (1 $\sigma$ )	
(3) Electronics Error = 3.0 (1 $\sigma$ )	
	13.4
$\Delta \phi$ (RSS) =	16.8

**3.3.4.2 Index Axis**

Sensitivity Ratio Accuracy (1.59 $\Delta \phi$ )	26.7
Digital Readout	
	13.4
	$\Delta \lambda$ (RSS) = 30.0

**3.3.4.3 Total RSS Error of Star Position  $\epsilon$  becomes**

$$\epsilon = \sqrt{\Delta \phi^2 + \Delta \lambda^2} = 34.4 \text{ arc seconds.}$$

3.3.4.4 The above analysis is based on theoretical interpretation of actually measured tolerances on the mechanical and optical designs. Laboratory testing of systems accuracy using simulated stars clearly demonstrated a 20-arc-second overall total system error excluding computation errors.

#### 4. CONCLUSIONS AND RECOMMENDATIONS

##### 4.1 GENERAL

The following general conclusions are made from the results of this contract:

- a) The basic instrumentation required to demonstrate the feasibility of the Star-Angle Comparator technique has been both synthesized and optimized.
- b) Existing Air Force specifications relating to system operation and performance characteristics have been met and in some cases exceeded. A wide range of stringent performance specifications can be satisfied.
- c) The high-performance scanning subsystem is applicable to stellar inertial systems generally.

##### 4.2 RESULTS

A three-inch aperture optical system coupled with an EMI-541B photomultiplier was found to be the best optical-detector combination. Programming the optical system to slew and then to index at fixed angular increments was found to be the most desirable celestial scanning technique. Digital readouts coupled with appropriate electronics and a printer yielded the optimum means of recording angular data for test and evaluation.

The opto-mechanical system is capable of scanning the complete hemisphere in less than one minute of time (60 secs were specified) with a total system angular accuracy significantly better than sixty seconds of arc (60 arc seconds were specified)- the equivalent star tracker accuracy is better than 10 arc seconds. The Detection-Electronics subsystem yields a high signal-to-noise ratio resulting in very reliable detection.

Performance tests of the instrument developed under contract were witnessed by Air Force Personnel representing ASD. The test results showed instrument performance exceeding contractual requirements.

#### 4.3 RECOMMENDATIONS

##### 4.3.1 FUTURE APPLICATIONS

The successful performance of the Star-Angle Comparator demonstrated not only the feasibility of the approach, but also the wide range of system parameters allowable (e.g., scanning time, field-of-view coverage, system and subsystem accuracy, and number of bright stars considered). The accuracy of attitude information is independent of the Comparator technique or concept, and dependent solely on the component hardware accuracy.

Thus, although a particular (but stringent) set of parameters was contractually specified, the Star-Angle Comparator's operating parameters are extremely flexible; the Comparator can in fact be designed to perform for large classes of space vehicles and for many different missions, both manned and unmanned, civilian and military.

In particular, the Comparator, which was conceived to provide all-mission capability, is ideally suited for a space guidance system that would be applicable to all (or most all) missions, in either near-earth, earth-moon, or interplanetary environments. Moreover, such a utilization of the Comparator would provide the space guidance system with true self-contained all-mission capability, independent of attitude, availability of the sun, or position (orbit) initial conditions.

A possible major by-product of the capability of the Comparator to operate after being completely turned off, is that it can pass through radiation zones (e.g. Van Allen) with all power off, thereby minimizing component radiation damage. Power could then be turned on in safe zones, whenever navigation information is required.

The Comparator inherently has capabilities in addition to star identification. That is, with additional programming instructions it can perform the usual star tracker (scanner) functions. Moreover, it inherently has the possibility of near body (e.g., planet, moon) detection and tracking.

Finally, but perhaps also of major significance, the basic idea developed to distinguish planets from stars may be modified to locate planets. This would remove a major storage and computational requirement from the on-board navigation computer.

#### 4.3.2 A SPECIALIZED APPLICATION

The power and uniqueness of the Comparator concept, in large measure, is the technique of identifying stars under the most general conditions. A separate consideration, which the subject contract is addressed to, is the design of the Comparator when independent system specifications are imposed on the instrumentation.

By careful consideration and a certain degree of insight, a basically simple scanning system was developed which nonetheless satisfies all of the stringent system specifications imposed contractually on the Comparator.

Because of its basic simplicity, this high-performance scanning system lends itself (with minor modifications) to important applications which are not necessarily concerned with identifying stars.

Foremost among these applications is that of stellar corrections for ballistic missiles.

Typically, a stellar inertial system involves pointing a telescope to a fixed direction in space and searching for a star in a field centered on this direction. This is accomplished by scanning within the focal plane, either electrically (deflection coils and readout circuitry) or mechanically (drive mechanism and readout/encoder circuitry).

However, this drive and readout instrumentation about the line-of-sight (within the focal plane) is actually redundant. Further, it produces an additional source of error. That is, drive and readout instrumentation is already available from the telescope gimbals which normally point the telescope to the fixed direction in space.

Utilizing the scanner of the Comparator, the gimbals need merely be indexed and held fixed in azimuth and then rotated at constant speed in elevation through the small search field. The reticle configuration provides both azimuth and elevation information by two sequential readings from the gimbal elevation axis encoder.

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The basic feasibility of this approach was experimentally verified with the Comparator system. Moreover, high accuracy can be obtained consistent with the most stringent specifications of daylight background, field-of-view and search time. It should also be noted that the detector can be either a photomultiplier or a semiconductor. In the latter case, because of semiconductor miniaturization, higher signal-to-noise ratios can be obtained with very little increase in volume.

### 4.3.3 FUTURE INSTRUMENTATION

The next generation of Comparator instrumentation should eliminate servo component redundancy through the use of a digital servomechanism whose input both in angle and in rate is the digital readout and whose output is but a single torquer. This technique could be used on both the slew and indexing axes.

If a longer scanning time were permitted for a particular application, the size of the optical system could be reduced in proportion to the square root of this time increase. For example, if the overall scanning time were increased from one minute to ten minutes, the diameter of the optics could be reduced from three inches to approximately one inch ( $3/10 = 1/2$ ) and still maintain the same signal-to-noise ratio. The overall volume would then be considerably reduced inasmuch as the optical system is the greatest inertial load of the servo drive.

As was shown in sections 3.3.4.2 through 3.3.4.4, the two largest sources of error are the digital readout and the optical system. A 15-bit encoder was used for the feasibility model. Considerable improvement can be obtained if a 20-bit encoder is employed. Similarly, if the sensitivity ratio is improved (by optical design) then further accuracy improvement can be obtained. A graph of system accuracy plotted against encoder accuracy for two values of sensitivity ratio is given in Figure 4-1.

To carry the analysis started in the above-referenced sections further, a calculation of the maximum tolerable readout error and the inherent accuracy of the system without readout error both with present and improved optics follows.

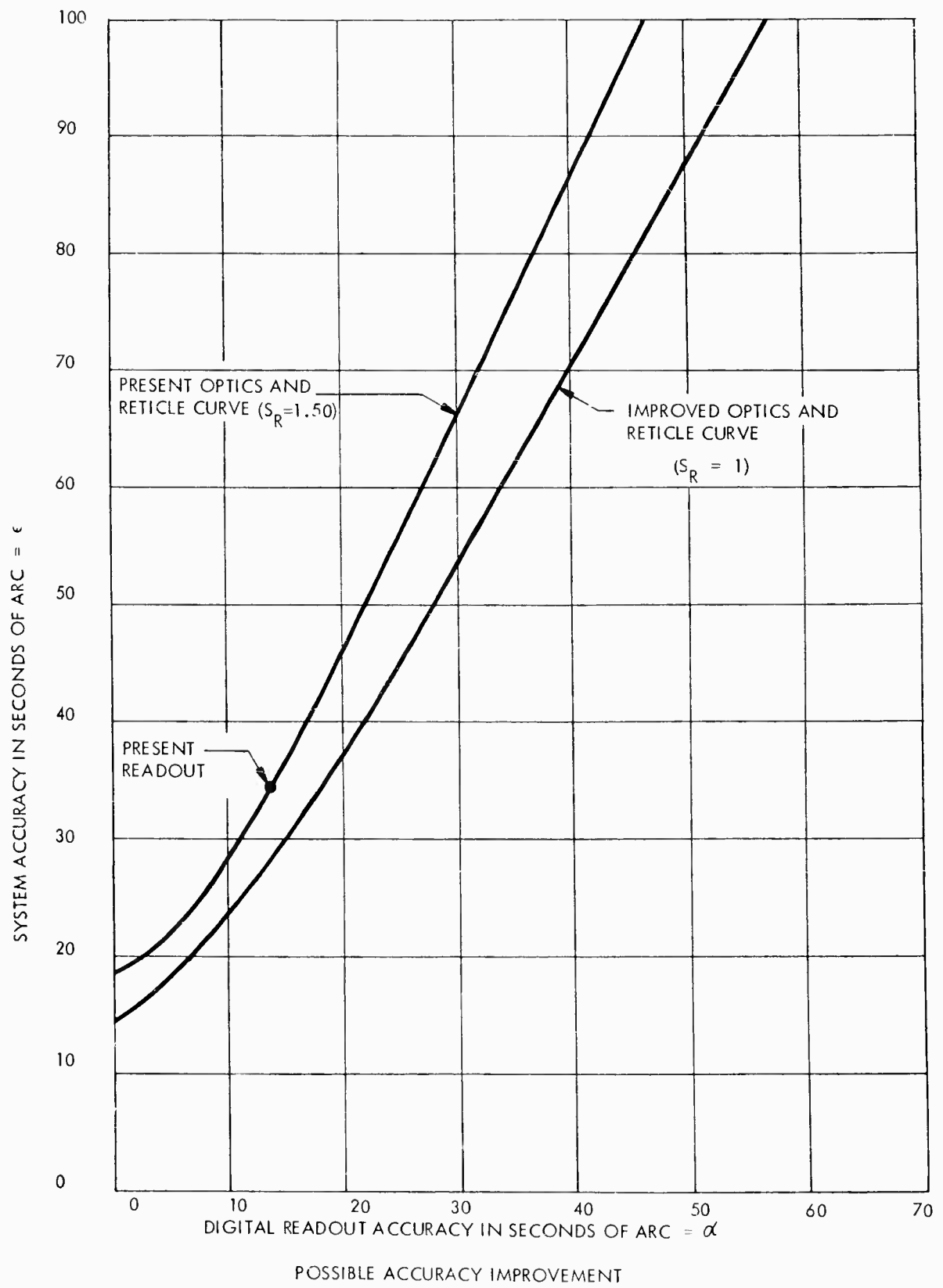
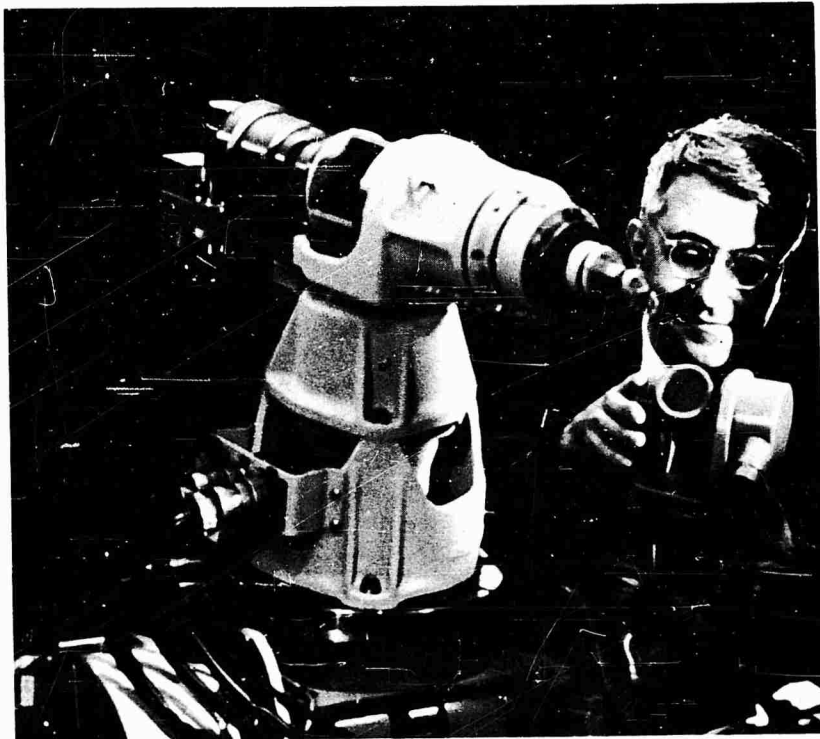


FIGURE 4-1



**COMPARISON OF FEASIBILITY MODEL AND WOODEN MOCKUP,  
ILLUSTRATING POSSIBLE SIZE REDUCTION**

4.3.3.1 Maximum Tolerable Readout Error =

$\Delta \phi$  = RSS Scan Axis error

$\Delta \lambda$  = RSS Index Axis error

Sr = Sensitivity Ratio = 1.59

$\theta$  = RSS Scan Axis error without readout

$\epsilon$  = Total RSS Error of Stor Position

$$\epsilon = \sqrt{\Delta \phi^2 + \Delta \lambda^2}$$

$$\Delta \lambda^2 = \alpha^2 + Sr^2 \Delta \phi^2$$

$$\Delta \phi^2 = \alpha^2 + \Sigma \theta^2$$

$$\epsilon = \sqrt{(\alpha^2 + \Sigma \theta^2) + (\alpha^2 + Sr^2 (\alpha^2 + \Sigma \theta^2))}$$

$$= \sqrt{\alpha^2 (2 + Sr^2) + \Sigma \theta^2 (1 + Sr^2)}$$

$$= \sqrt{4.52 \alpha^2 + 3.52 \Sigma \theta^2}$$

$$\epsilon = 2.12 \sqrt{\alpha^2 + 0.78 \Sigma \theta^2}$$

$$\text{or } \alpha^2 = \frac{1}{4.52} [\epsilon^2 - 3.52 \Sigma \theta^2]$$

$$\alpha = 0.472 \sqrt{\epsilon^2 - 3.52 \Sigma \theta^2}$$

Since  $\epsilon = 60$  arc sec

and  $\Sigma \theta^2 = 99$

$$\alpha = 0.472 \sqrt{3600 - 349}$$

$\alpha = 27$  arc sec

4.3.3.2 Inherent Accuracy of System Without Readout Error

$$\epsilon = \sqrt{4.52 \alpha^2 + 3.52 \Sigma \theta^2}$$

$$= \sqrt{3.52 \Sigma \theta^2}$$

Since  $\alpha = 0$  w/o readout

$$\epsilon = 1.88 \Sigma \theta$$

Since  $\Sigma \theta = \sqrt{99} = 10$

$$\epsilon = 18.8 \text{ arc seconds}$$

4.3.3.3 Inherent Accuracy of System With Better Optics ( $S_R = 1$ ) without Readout Error

$$\epsilon = \sqrt{\alpha^2 (2 + S_r^2) + \Sigma \theta^2 (1 + S_r^2)}$$

If  $S_r = 1$   $\epsilon = \sqrt{3 \alpha^2 + 2 \Sigma \theta^2}$

If  $\alpha = 0$   $\epsilon = \sqrt{2 \Sigma \theta^2} = 1.414 \Sigma \theta$

$\epsilon = 14.4$  arc seconds

$\alpha$	$\epsilon$
0	14.4
10	23.6
20	27.5
30	54
40	70.7
50	88.9
60	

NOTE: Recall that the equivalent star tracker accuracies are significantly greater than these system accuracies.

5. OPTICAL SYSTEM ENGINEERING AND TEST

5.1 SYSTEM COMPONENTS

The following paragraphs describe the components of the optical system along with the inherent characteristics and properties which make the system unique to the Comparator's operation.

The optical system consists of four major components: Objective System, Reticle System, Energy Transfer System, and Folding Mirror.

5.1.1 OBJECTIVE SYSTEM

The objective system collects energy from stars and focuses this energy on the reticle surface. The objective design is essentially a monocentric catadioptric system consisting of one zero-power doublet, a spherical primary mirror, and a combined corrector-shell and secondary mirror. It was designed and built by Perkin-Elmer Corporation in accordance with the Star-Angle Comparator specifications of Kearfott Division.

Its essential characteristics are:

- |                            |  |
|----------------------------|--|
| a) Effective Focal Length: | Six inches   |
| b) Relative Aperture:      | f/2.4  |
| c) Field of View:          | eight degrees, circular  |
| d) Spectral Region:        | visible  |
| e) Circle of Confusion:    | two arc seconds  |
| f) Transmission:           | sixty per cent   |
| g) Distortion:             | 0.035 per cent   |
| h) Field Surface:          | spherical, concentric with mirror, approximately six-inch radius of curvature    |
| i) Central Obstruction:    | not larger than 55 per cent of clear aperture area                               |
| j) Vignetting:             | the objective system is designed to avoid vignetting of oblique pencils of light |

### 5.1.2 RETICLE SYSTEM

The reticle was designed with straight lines on a plane. However, the reticle had to be projected onto the 6-inch radius of curvature field surface. Essentially, the straight lines in the plane had to map onto the spherical surface as great circles.

Because of this projection problem, which is state-of-the-art, two companies were contracted to perform the job. One company generated the pattern mechanically on a precision machine, while the other company used a glue-silver process which leaves the entire background black with clear transparent lines.

The reticle system consists of two parallel-lined slits which form a 'V' configuration. In the center of the 'V' is a cross. See Figure 5-1. The 'V' slits are transparent and have a 45-micron thickness in the Y-direction. The crossed slits are transparent and have a 45-micron thickness also.

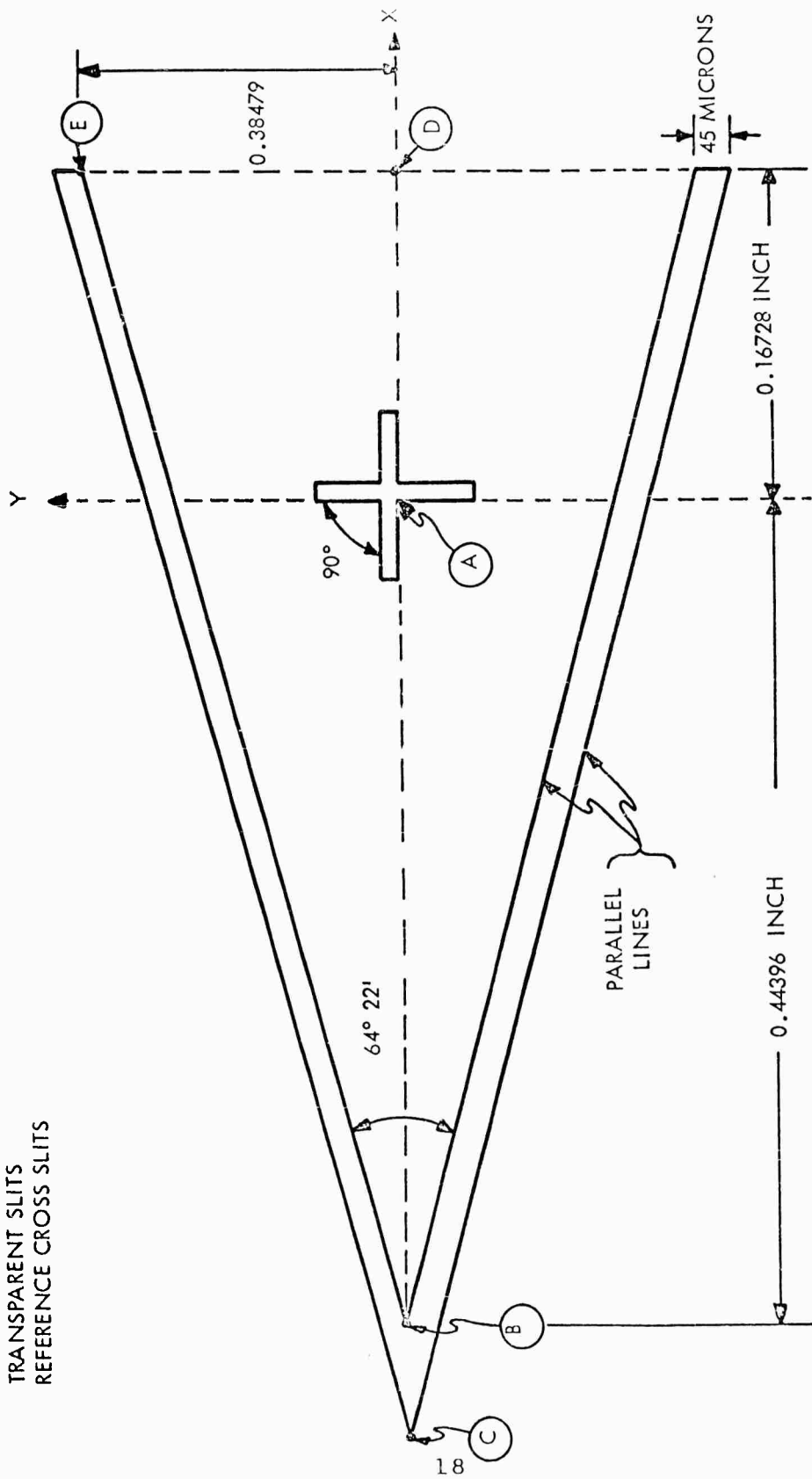
The cross forms a reference for all measurement and optical alignments and is blocked out with a small piece of black tape when the Star-Angle Comparator is in operation. The length of the cross arms is 0.1 inch. The cross is so constructed that the lower edge of the horizontal arm is the X-axis of the system and the edge of the vertical arm facing the direction of the closed 'V' is the Y-axis of the system. The intersection point (A in Figure 5-1) of the cross defines the intersection point of the X and Y axes and is the origin of the coordinate system for all measurement procedures. The 'V' arms intersect the X-axis and are symmetrical about it.

The linear and angular dimensions of the specified reticle are as shown in Figure 5-1.

### 5.1.3 ENERGY TRANSFER SYSTEM

The energy transfer system is a conventional lens system, designed to image the aperture of the objective system on a 10-millimeter area. The system is free from vignetting and aberrations for the best uniformity of transmission over the field of view.

OPAQUE BACKGROUND  
TRANSPARENT SLITS  
REFERENCE CROSS SLITS



RETICLE DESIGN  
Figure 5-1

#### 5.1.4 FOLDING MIRROR

The folding mirror is flat to within one-fourth of a wavelength. It is on elongated octagon about four inches long, 2.75 inches wide, and 0.4 inches thick.

#### 5.2 OPTICAL SYSTEM PERFORMANCE TESTS AND MEASUREMENTS

The performance tests and measurements designed to substantiate these properties and characteristics will now be described.

##### 5.2.1 OBJECTIVE SYSTEM

The objective was placed in front of a collimator which was suitably fitted with an artificial star. At a given angle of view, a pinhole 0.001 inch in diameter was placed on the focal surface where the image of the artificial star is formed. The amount of light accepted by the pinhole was measured with a type 6199 photomultiplier fitted with a filter to restrict its spectral response to visible radiation. This procedure was repeated with a 0.125-inch diameter pinhole substituted for the 0.001-inch pinhole. This test was performed at nine positions in the field, on the optical axis and at one-degree intervals on each side of the optical axis, until the entire field was covered.

Specifications were met when the ratio of the readings were 0.80 or more between the different pinholes. With the use of the Comparator's unique reticle in place of the 0.001 diameter pinhole, the ratio obtained was between 0.92 and 0.96. This substantially increased the energy content hoped for and substantially improved the optical performance from a system's point of view.

The readout of the photomultiplier was visually observed on an oscilloscope. It is from these observed readings that ratios were determined. The data recorded are as follows:

O. A. = optical axis  
cm = centimeter readings of peak voltage appearing on oscilloscope  
pinhole = 0.125 inch  
cm = 4.5  
pinhole = 0.001 inch

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Field	-4°	-3°	-2°	-1°	O.A.	+1°	+2°	+3°	+4°
CM	3.5+	3.6	3.6	3.6	3.6	3.5+	3.5+	3.6	3.6

Focal length was next determined by placing the objective on a rotary table. A hole of 0.875 inch diameter was placed in the focal plane. A simulated star was focused on the optical axis point and the table was rotated so that the image point of light moved to the edge of the hole. The total movement of the image point was simply the radius of the hole. The angle through which the rotary table moved was noted. Knowing this angle and the radius of the hole in the focal plane, the focal length of the system was computed. With many readings the focal length varied between 5.95 and 6.08 inches. Distortion was measured after the entire optical system was assembled. The test procedure and measurement results will be discussed later in the report.

#### 5.2.2 RETICLE MEASUREMENTS

When the reticles were received at Kearfott two critical measurements were performed to determine the best reticle suitable for inclusion into the optical system. Use was made of a measuring device located in Kearfott's Metrology Laboratory. This instrument, known industrially as "SIP" is a standard measuring machine, type number 214MU, and has an accuracy of 20 microinches.

After repeated measurements on all reticles, it was found that the reticle constructed by mechanical process was most suitable for use in the Comparator's optical system. The major reasons for accepting this reticle are as follows:

- a) It was mentioned earlier in the description of the reticle system that the slits had to be projected onto the 6-inch radius of curvature focal surface as great circles. This reticle came closest to realizing this requirement. Errors involved were of a magnitude of 1-arc second to 3-arc seconds, a highly acceptable figure.

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- b) It was found that the slit edges of the mechanically constructed reticle were extremely linear and parallel, while the other reticle had jagged and non-linear slits.

(With respect to the reticle dimensions, it was found that both reticles were able to meet the requirements).

5.2.3 ENERGY TRANSFER SYSTEM

To test the transfer lens assembly, the transfer system was mounted with the objective system. There were neither reticles nor pinholes in the focal plane. The objective was then placed in front of a collimator fitted with a small bright source at its focal plane. A circular window, 0.4 inch in diameter, was placed where the detector would normally be positioned. A photomultiplier was then placed behind the window and the relative amount of light arriving at the photomultiplier was measured at various positions throughout the field. It was found that no variation in intensity of the light hitting the photomultiplier could be detected, i.e., no hot spots.

The window was then visually inspected for hot spots, but none were observed.

Distortion measurements were made after the inclusion of the selected reticle into the optical system. This testing procedure called for placement of the objective reticle system onto a rotary table. A source of light illuminated the reticle in such a manner that an image of the 'V' reticle was projected back through the optical system. The 'V' reticle was rotated in its optical cell until one line of the 'V' was made horizontal. A microscope was used to observe the image of the reticle. The horizontal cross-hair of the microscope was placed coincident with the now horizontal slit of the reticle. Upon rotation of the rotary table, the image of the reticle could be seen to move across the field of view of the microscope. Any displacement occurring between the horizontal slit of the reticle and the horizontal cross-hair of the microscope would be due to distortion inherent in the optical system and the displacement of the slit lines from the great circles.

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Measured values of this combined error were found to be less than five arc-seconds.

5.2.4 BACKUP OPTICAL SYSTEM

To facilitate testing of the other subsystems of the Comparator while awaiting the delivery of the Perkin-Elmer optical system, a backup optical system was developed. The Wollensak Division of Revere Camera Company was contracted for an objective and transfer system. The objective system has a six-inch  $f/2.7$  Raptor Telephoto Pro-35 lens assembly. The characteristics of the system made the assembly a suitable substitute.

A reticle was constructed by Keorfott utilizing a photographic emulsion technique. Testing of other subsystems was undertaken after assembly of the complete backup system and optical alignment techniques and procedures were worked out.

5.3 ALIGNMENT TECHNIQUES

A summary of the optical alignment techniques and procedures originated for purposes of ensuring successful system integration follows. (Refer to Appendix A for detailed Alignment Technique).

5.3.1 GENERAL

The optical system had to be critically aligned in order to ensure the accuracy of the Comparator System. If imperfections existed after alignment, the errors would have to be measured in order that their magnitude could be incorporated into the final system calculations. Otherwise correct interpretation of generated information could not be made.

For a perfectly controlled and predictable system, the following alignments are necessary:

- a) Orthogonality must be maintained between the elevation and azimuth rotational axes.
- b) The folding mirror must be properly aligned with respect to the optical cell. This enables one to define the optical axis.
- c) Since the Star-Angle Comparator is set and clamped to an Optical Rotary Table, the azimuth axis of the Comparator must be parallel to the vertical axis of the table.

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- d) The reticle must have the proper orientation in the optical cell.

In order to perform the critical alignments called for, it was necessary to work in a controlled environment with highly accurate optical instruments. The Kearfott Division Metrology Laboratory was used because its environment is completely controllable and predictable. It is a type-3 clean room having an ambient temperature of  $68 \pm 1$  degree. All measurements and alignments were performed on a Granit Surface Plate, KDS61130, having an over-all flatness within 0.0002 inches. Use was made of two Hilger-Watts Electronic Automatic autocollimators, type TA-3, KDS61150. These instruments have an accuracy of 0.5 arc seconds. In conjunction with the autocollimators, use was made of the KDS61112 Penta Prism which gives 90-degree beam deflections to 1/4-arc second accuracy. It should be stated at this point that all standards referred to above are traceable to the National Bureau of Standards where test reports are on file.

6. DETECTOR SYSTEM DESIGN AND DEVELOPMENT

6.1 PHOTOMULTIPLIER

6.1.1 GENERAL

A detailed study and survey was made of high-performance photomultipliers presently available. The Ascop tube was selected for use in the Star-Angle Comparator partly because its noise and sensitivity characteristics were better than the tubes of the other manufacturers. Furthermore, its environmental performance, although not required for this model of the comparator, also was better than that of competitive photomultipliers.

6.1.2 SUBSYSTEM TEST

Early in October, photomultiplier testing was initiated. Verification of tube parameters and optimization of signal-to-noise ratio were the initial considerations.

Based on the data received with the Ascop photomultiplier tube, light flux from stars of known magnitude (previously calibrated with the laboratory photometer) was impinged on the photomultiplier cathode through an optical system which simulated the final comparator optical system. Results using the Ascop unit compared favorably with the original data submitted by the manufacturer. The subsystem test setup included a chopper wheel with synchronous drive motor to modulate the simulated star flux. This setup was used for all signal-to-noise measurements made during the time the electronics were being optimized.

The chopper wheel was designed to have the convenient feature of an adjustable width slit. The chopper drive motor speed was frequency controlled from an audio oscillator. This combination provided a range of observation times about a nominal value based on the comparator slow axis speed of 36 rpm.

Signal information rate was correlated with the chopping rate through the use of a magnetic pickoff mounted so that a soft iron slug near the periphery of the rotating wheel actuated

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the pickoff, creating one pulse for each revolution of the wheel. This facilitated observation of the signal on a dual-channel scope, with the pickoff output being used for synchronization.

6.2 PHOTOMULTIPLIER ELECTRONICS

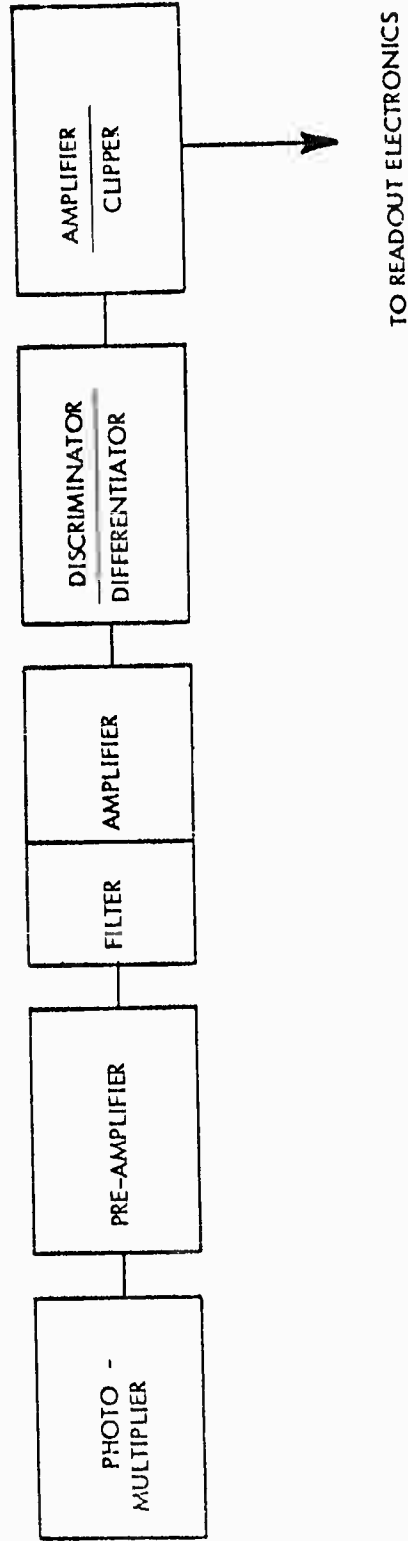
6.2.1 GENERAL

A block diagram of the signal-processing electronics is shown in Figure 6-1. Each block is described separately and in the case of commercial equipment, the specifications are given.

6.2.2 PREAMPLIFIER

The preamplifier used in the final circuitry is a commercial type, manufactured by Quantech Laboratories of Boontown, New Jersey. It is an extremely compact, low-noise, high-gain unit, providing a fixed gain of 100 over a frequency range from 30 cps to 500 kc. An obvious advantage with regard to hum pickup and power supply ripple is the internal mercury-battery supply.

Specifications for the preamplifier are listed in Table 6-3 and a schematic is shown in Figure G-1, Appendix G.



SIGNAL PROCESSING ELECTRONICS  
Figure 6-1

TABLE 6-1  
COMPARISON OF PHOTOMULTIPLIER  
CHARACTERISTICS

	CATHODE											ENVIRONMENTAL								
	CON- FIGURATION	DIMENSION INCHES	PROJECTED CATHODE DIA. (IN.)	PHOTO CATHODE	SPECTRAL RESPONSE	NUM. OF STAGES	CATHODE LUMINOUS SENSITIVITY (A.A.L.)	CATHODE RADIANT SENSITIVITY (A/W)	QUANTUM EFFICIENCY (%)	OVERALL GAIN ( $\rho 10^5$ )	ANODE SENSITIVITY (A.A.)	NOMINAL REQUIRED VOLTAGE (V)	TOTAL DARK CURRENT @ 20°C (A)	EQUIV. DARK CURRENT INPUT (LUMENS @ 20°K)	MAX. RATED GAIN	MAX. RATED OVERALL VOLTAGE (V)	MAX. STABLE D.C. CURRENT (M.A.)	* EQUIV. NOISE INPUT (LUMENS)	SHOCK	VIBRATION
ASCOP 541B	SIDE VIEW	1-1/4 x 4-5/8	0.48 D	5b-C1	5-17	18	120 (AVG)	0.100 @ 4200 Å	18 (MIN) 37 (AVG) @ 4500 Å	1	120 (A.A.)	1800	2x10 <sup>-19</sup> @ G=10 <sup>6</sup> (AVG)	1.0 x 10 <sup>-11</sup>	10 <sup>8</sup>	3000	0.1	.8 x 10 <sup>-13</sup> (AVG)	100G <sup>1/2</sup> for 1.5 SEC 10 8% 60 CPS	30-50 SINE WAVE UP TO 3000 CPS MFG TEST 1 1/2 HOUR
Back-up A	SIDE VIEW	1-1/2 x 3-3/4	0.65 W x 0.50 H	5b-C1	5-17	10	105 (MIN) 125 (MEDIAN)	0.085 @ 4900 Å	22 @ 4900 Å 27 (MAX)	0.22	10 (MIN) 40 (MED) 300 (MAX)	1000	4x10 <sup>-9</sup> @ G=10 <sup>6</sup> (MIN)	4.0 x 10 <sup>-10</sup> (MED)	10 <sup>7</sup>	1250	0.12	1.1 x 10 <sup>-11</sup> (MED)	NONE	NONE
Back-up B	HEAD ON	2.28 x 7.5	1.68 D	5b-C1	5-20	14	105 (MIN) 15% (MEDIAN)	0.064 @ 4200 Å	19 @ 4200 Å	9.35	165 (MIN) 1400 (MED) 6000 (MAX)	2400	5x10 <sup>-9</sup> @ (MIN) G = 10 <sup>6</sup>	2 x 10 <sup>-10</sup> (MED) 6 x 10 <sup>-10</sup> (MAX)	10 <sup>7</sup>	3000	1.0	7.5 x 10 <sup>-13</sup> (MED)	NONE	NONE
Back-up C	SIDE VIEW	1-3/16 x 3-11/16	5/16 W x 15/16 H	5b-C1	5-4	9	20 (MIN) 40 (MEDIAN)	0.04 @ 4000 Å	NOT GIVEN	1	40 (MIN) 20 (MED) 300 (MAX)	1000	NOT GIVEN	5 x 10 <sup>-10</sup> (MAX)	4 x 10 <sup>7</sup>	1250	0.1	5 x 10 <sup>-13</sup> (MED)	NONE	NONE

\* 5.2070<sup>6</sup> x 10<sup>13</sup> CPS BW

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TABLE 6-2

ASCOP PHOTOMULTIPLIER  
Model 541 B-03-18-01000  
Serial #127

Characteristics:

Cathode Radiant Sensitivity @ 4100A	$59.5 \times 10^{-3} \text{ A/W}$
Cathode Quantum Efficiency @ 4100A	18 per cent
Average Luminous Sensitivity	$65 \mu \text{ A/Lumen}$

Current Amplification:

@  $10^6$  Amplification      1560 volts, Dark Current  $2.6 \times 10^{-9} \text{ A}$

Max Ratings, Absolute Values:

Max D. C. Anode - Supply voltage	3000 volts @ 25°C
Max Ambient Temperature	75°C

N.E.P. =  $4.0 \times 10^{-16}$  Watts @ 20°C @ 4100A

TABLE 6-3

PREAMPLIFIER MODEL 203  
Specifications

Voltage Gain:	100:1 $\pm 0.5$ db
Frequency Response:	Flat within $\pm 0.5$ db 30 cps to 100 kc -3db @ 500 kc
Input Impedance:	Approximately 80,000 ohms shunted by 100 $\mu$ $\mu$ f
Output Impedance:	Less than 100 ohms
Output Voltage:	1 volt peak to peak, maximum
Noise:	Equivalent broad band input noise (10 cps to 500 kc) less than 5 rms $\mu$ V input shorted.  Typical narrow band input noise voltage $5 \times 10^{-9}$ rms volts, noise current: $3 \times 10^{-12}$ rms amps per root cycle above 1 kc.
Distortion:	Less than 0.5% at rated output
Battery Life:	Approximately 500 hr with 3 type ZM 9 mercury batteries
Dimensions:	1-5/8 x 2 x 4-1/4 in. overall
Weight:	8 oz

### 6.3 FILTER AND FIRST POSTAMPLIFIER

Filtering is accomplished at the input to the first amplifier. The filter network was placed at the amplifier input in order that the physical size of the components located on the comparator would be minimized. Overall noise reduction was also considered in the location of this filter.

The first amplifier is a low-noise commercially available type, manufactured by H. H. Scott Company. It is a tube-type modular unit, having a fixed gain of 40 db. Typical specifications are listed in Table 6-4 and a circuit diagram is shown in Figure G-2, Appendix G.

### 6.4 DISCRIMINATOR

Discrimination is accomplished by diode-controlled biasing circuitry at the output of the first postamplifier where the biasing voltage is adjustable.

The final biasing level was checked statistically using a Berkeley counter-timer to record the star signal output over a known time interval. A chopper disc was used to generate star pulses at a rate of 15 pulses per second. The star pulse rate was checked first by monitoring the magnetic pickoff (see Section 6.1.2) output on the counter-timer. The count from the magnetic pickoff is then indicative of wheel revolutions per second of time. If a star pulse occurred per each wheel revolution, the star count registered on the counter would equal the number of wheel revolutions per second.

### 6.5 DIFFERENTIATOR

Differentiation was used in this system in order to detect the position of the star pulse relative to the V-slit reticle.

The circuit held the rms zero crossing of the differentiated wave to within six arc seconds of the actual star input pulse position.

#### 6.6 SECOND POSTAMPLIFIER

The second modular amplifier in the detector electronics provides high gain in order to boost the attenuated differentiated signal output. The unit is manufactured by H. H. Scott Company and is similar to the first amplifier used in the detector system circuitry (Section 6.3) except for gain. This second amplifier has an additional 10 db of gain, making an overall gain figure of 50 db. See Figure G-3, Appendix G for the schematic.

Specifications are similar to those given in Table 6-4 except for gain.

#### 6.7 OUTPUT CIRCUITRY

From the output of the second amplifier the star signal was directed to a transistorized squaring amplifier. Since the output from the second amplifier was essentially a square wave having a peak-to-peak amplitude of approximately 80 volts, the signal was attenuated with a resistor divider network in combination with a blocking diode which eliminated the positive portion of the wave. This provided a negative going pulse in which information was obtained, from the leading edge at a level of minus two volts.

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TABLE 6-4

FIRST PREAMPLIFIER  
Type 1440

Specifications

Rise Time:	1.0 sec
Gain:	40 db or x 100
Frequency Response:	10 cps - 300 kc ( $\pm 0.2$ db) 2 cps - 1.1 mc (-3db)
Equiv. Input Noise:	$< 7 \mu V$ broadband $< 1 \mu v/10$ kc bandwidth
Input Impedance:	10 megohms + 25 mmf
Output Impedance:	30 ohms + 200 mmf
Power Requirements:	+ 180v dc @5 ma; + 6v dc @1 amp well filtered

## 7. STAR COUNTER

### 7.1 GENERAL DESCRIPTION

(Refer to Block Diagram, Figure E-1, Appendix E)

The star counter is used to record azimuth and elevation data corresponding to a star's position. Two forward-reverse decade counters, one for azimuth and one for elevation data, store a count proportional to the amount of azimuth and elevation of the measuring equipment. This count is in the form of a five-digit BCD number. When a star pulse is received, the numbers in the azimuth and elevation counters are clocked into one of two output registers indicating the star's position (non-destructive readout is used).

A reference and slew control circuit provides a relay contact closure and a signal to drive a remote relay.

Front panel controls and internal circuitry provide means to simulate actual operation.

## 8. MECHANICAL DESIGN

### 8.1 GENERAL

The resultant measured accuracy and mechanical precision of the Star-Angle Comparator are summarized as follows:

- |    |                            |           |
|----|----------------------------|-----------|
| a) | Axis-to-axis orthogonality | 5 seconds |
| b) | Optical axis alignment     | 5 seconds |
| c) | Axis wobble                | 2 seconds |
| d) | Encoder coupling           | 2 seconds |

### 8.2 ORTHOGONALITY

It was determined that the machining of two shaft bores to an accuracy in orthogonality of five arc seconds would be very difficult and probably not feasible. It therefore was decided to provide a design in which orthogonality adjustment could be made by optical means. The housing containing the slew axis is attached to a relatively large surface integral with the index shaft. This surface is referred to as an interface between the slew and index axes. The interface is a hand-lapped surface which provides a very stable tie of the two axes and allows a minimum of distortion when attaching one member to the other. The hand lapping is biased to one side or the other until the orthogonality is less than five seconds of arc. The hand lapping operation is checked by the optical procedure described in Appendix A.

### 8.3 AXIS RIGIDITY

The shaft axes require a high degree of rigidity to minimize deflection and wobble of the axis of rotation. Ball bearings have high load capacity were selected in order that normal loadings would cause little deflection. Normal loads are those caused by the cantilever support of the telescope and unbalanced loads that result when the mechanism is tilted. The bearings are also highly precise to minimize shaft wobble.

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The bearings selected are manufactured by Fafnir to a class ABEC7 precision. They are angular-contact type bearings which are preloaded at assembly so that a highly rigid axis of rotation is maintained under varying loads.

All important dimensions of these bearings are held to 0.0002 in. (max), while runout of the inner race is held to 0.00015 in. This means that the eccentricity is half that, or 0.000075 (in.). With a bearing span of 4.5 in. and assuming the worst condition where each bearing has the maximum runout at 180 deg out of phase, the maximum wobble error would be 3.45 arc seconds. However, the bearings have the high spots marked to permit assembly with the eccentricities in phase. If the bearings are so assembled and assuming a difference in amplitude of 1/2 the maximum, then the wobble error is reduced to 1.72 arc seconds.

In optical checkout of the entire assembly, the shaft wobble was found to be better than two arc seconds. It should be noted that translation of the shaft axis, as would occur with the eccentricities in phase, has no effect on system accuracy.

Shaft axis deflection due to normal loads is minimized by ball bearings having high enough load capacity that normal loads cause an insignificant deflection. For example, the cantilever telescope produces a load of 30 lb on a bearing which has a static load capacity of 6000 lb. At full load the bearing deflects not more than 0.002 in. Assuming a linear deflection curve, the deflection at 30 lb is only 0.00002 in. In terms of angular deflection, this is only 0.5 arc seconds with a 4.5 in. bearing span.

### 8.4 OPTICAL AXIS ALIGNMENT

The telescope is attached to a mirror cell which in turn is attached to a flanged surface integral with the slew-axis shaft. This arrangement allows optical alignment to be achieved primarily with an adjustable 45-deg mirror. The optical axis of the telescope itself is not critical with respect to the shaft axis since overall alignment is obtained with the 45-deg mirror. The mirror is adjusted so that the line of sight is orthogonal to the slew axis. This adjustment can be made to one sec of arc accuracy.

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The mirror is mounted in the mirror cell to within the accuracy of the machined parts (of the order of one minute of arc). Finer adjustment is then made with two tapered screws that permit tilting and cocking of the mirror as required.

The screws are tapered 0.004 in. per in. Machining tolerances on the base which supports the mirror are held to one minute of accuracy. The screws can move longitudinally  $\pm 1/2$  in. to provide an angular adjustment of  $\pm$  two minutes of arc.

#### 8.5 ENCODER COUPLING

A high-precision coupling was supplied by Metal Bellows Corp. in accordance with the following requirements:

- |    |                       |                         |
|----|-----------------------|-------------------------|
| a) | Maximum axial stroke  | $\pm 0.062$ in.         |
| b) | Maximum windup        | 0.8 arc sec at 10 in-oz |
| c) | Angular misalignment  | 2 degrees               |
| d) | Parallel misalignment | 0.010 in.               |

Since the maximum torque to the encoder is only 4 oz-in, and since mechanical alignment exceeds specification requirements, the error due to coupling is far less than the 0.8 arc sec specified above.

#### 8.6 DRIVE SYSTEM

The requirements of a drive system include a dc torquer and tachometer for each axis and synchros for positional information. The torquers and tachometers are mounted between the ball bearings in order to conserve space and minimize inertia. The inner and outer sleeves that contain the units also serve as spacers for preloading the bearings. They are exactly equal in length in order to preload the bearings as recommended by the manufacturer. The index axis rotates in five-degree steps and after 180 degrees resets to zero. Because of the limited rotation, slip rings are not required.

8.7 MATERIAL SELECTION

Important considerations in the selection of materials were dimensional stability after heat treatment and uniform coefficient of expansion. The ball bearing material was SAE 52100 so the other material had to match its thermal coefficient of expansion. The materials selected are listed with their coefficients of expansion in inches per deg F times  $10^{-6}$  :

SAE52100	6.4
Meehanite cast iron	6.0
Stainless Steel 416	5.5

9. SYSTEM TEST

9.1 GENERAL

System test was performed in part with the following three simulated stars which demonstrated the system's mode of operation:

<u>Star</u>	<u>Right Ascension</u>	<u>Declination</u>	<u>Mv</u>
Agena	13H 56.8 M	-59° 53'	+0.69
$\beta$ Cru	12H 41.9 M	-59° 9'	+1.32
Capella	5H 9.3 M	+45° 54'	+0.13

The above stars were mounted, aligned, and fixed atop a concrete table which, in turn, rested on an isolated concrete pier (volume = 200 cubic feet). The angular stability of the mounting platform exceeded one second of arc.

The Star-Angle Comparator was mounted on a two-axis rotary tilt table (see Appendix D) which was placed in juxta-position on the concrete table being aligned with respect to the three simulated stars. The rotary tilt table was calibrated by the Kearfott Metrology Laboratory, and was found to have a maximum error of five arc seconds. The calibration data of the table are given in Appendix D, Fig. D-1.

Appendix F, System Test Procedure, details the switching operations and sequences required for a final system test. Data regarding cabling and continuity is given in this appendix.

System test basically involved the checking of the following two objectives:

- o) To test the system's ability to scan a continuous angle of 180 degrees in less than 60 seconds and detect the presence of at least three stars without giving a false indication or failing to detect the presence of a star.

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- b) To test the system's ability to accurately measure an incremental change in the angular location of a star and thereby establish the scanning system's angular resolution and accuracy performance characteristics.

Both of the above tests were performed at Kearfott in an "optically dark" room located in the Aerospace Research Center. The first test cited above was completed within a time interval of less than one minute. The second test was accomplished by scanning the sector of the celestial sphere which contained the critical star (angular position error less than two arc secs) and recording the star's angular position. The table on which the Comparator is mounted was then rotated through any arbitrary (but accurately known) angle and the star was again detected recording its new angular position. The difference between the old and new angular positions was then compared to the angle through which the table was rotated. This test yielded two results. First, it demonstrated the system's reliability of detection in that the star was repeatedly detected without a false indication or detection failure. Secondly, it demonstrated the system's combined azimuth and elevation angular error to be less than thirty arc seconds.

Both tests were demonstrated to USAF personnel at the culmination of the highly successful system test operations.

## 9.2 FIELD TESTING

A number of severe limitations are imposed on the feasibility testing of the Comparator under the night-sky rather than "laboratory stars". Simulated stars in the laboratory more closely represented the actual operating conditions the Comparator would experience when placed outside of the Earth's atmosphere (e.g., in a satellite or space vehicle).

Stars viewed from such a space environment would have no scintillation, no refraction, and no elongation of the star's image. These distortions all have random components and hence cannot be completely compensated for or eliminated by system biasing or computation.

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To take account of these effects, both operational restrictions and hardware modifications are necessary.

The operational restrictions for night-sky testing would include: (1) operate only under extremely favorable seeing conditions (rarely experienced), (2) limit the search cone to approximately  $30^\circ$  from the local zenith (three-star availability will then be possible only one or two winter months out of the year).

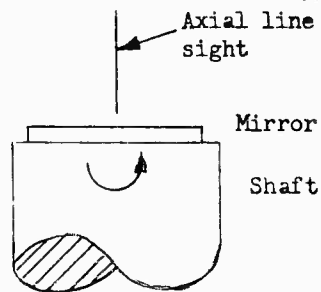
Hardware modifications would also be required because the atmosphere will reduce the signal-to-noise ratio. These include: (1) slow down the scan rate to increase the observation time, (2) modify the decision electronics. (Essentially a redesign of the discriminator and star filter).

With these restrictions and modifications, however, we would no longer be demonstrating that hardware can be built to satisfy the unique requirements and specifications of the Comparator. Rather, we would merely be demonstrating that "if" stars are detected and located within a certain angular accuracy, then the Comparator technique will identify them. But we had already demonstrated this during the Comparator study program. What remained to be shown, during this program, was that the "if" could be satisfied in conjunction with the other system requirements and specifications.

APPENDIX A  
THEORY OF ALIGNMENT

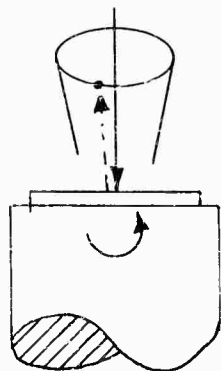
APPENDIX A  
THEORY OF ALIGNMENT

Case I - Assume mirror true to shaft, shaft true.



In this case, image of reticle will perfectly reflect back onto itself through eyepiece of auto-collimator. Image will be perfectly centered and center point of image will appear stationary as shaft is rotated (assume no wobble).

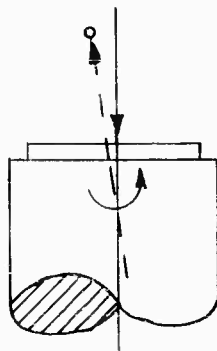
Case II - Assume shaft true, mirror angled.



In this case, image is found to be off center. As shaft is rotated, image point is seen to rotate in circular pattern about center point of eyepiece. With mirror adjustment, image point will spiral in until mirror is true to shaft. The image point will then be coincident with eyepiece center point.

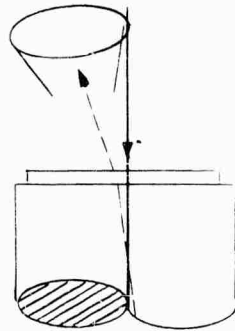


Case III - Assume mirror true to shaft, shaft angled.



In this case, image point is reflected back such that it is off center. As shaft is rotated the image point will remain stationary and keep its off-center position with respect to the center of the eyepiece (assume no wobble).

Case IV - Assume mirror angled to shaft, shaft angled.

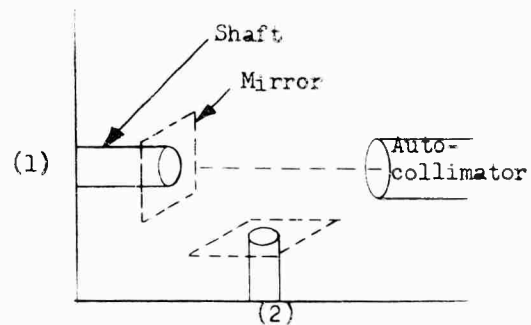


In this case, image point will be off center and a circular pattern will be traced out with shaft rotation. With mirror adjustment, the image point will spiral in to a center point. When this is attained the mirror will be true to the shaft and image point will be off center with respect to eyepiece center point (assume no wobble).

System Alignment

Shaft Orthogonality

Fig. A-1 Mirror-Shaft Alignment



Adjustable mirrors are attached to shafts (1) and (2) and an autocollimator is placed as shown in Figure A-1. The mirrors are made true to the shafts as discussed in the preceding paragraphs. If shaft (1) is not orthogonal to (2), orthogonality is established by a lapping procedure. Orthogonality is checked with a pentaprism placed as shown in Figure A-2.

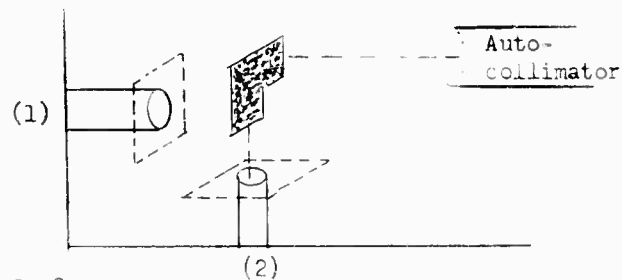


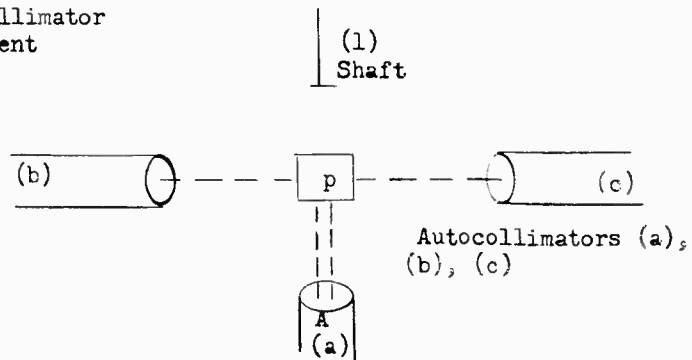
Fig. A-2 Shaft Orthogonality

When the image point from (2) is coincident with the previously determined image-point position of (1), orthogonality is achieved.

Optical System Alignment

With the attainment of shaft orthogonality, two more autocollimators are placed as shown in Figure A-3.

Fig. A-3 Autocollimator Alignment



The pentaprism is turned toward (b) without (a) being moved. When the image of (b) is seen coincident with the image of (a), orthogonality exists between (a) and (b). Coincidence will be attained with trial and error movements of (b).

The pentaprism is then turned toward (c) and the above procedure is repeated until (c) is orthogonal to (a).

When both conditions are achieved, i.e., (b) is perpendicular to (a), and (c) is perpendicular to (a), the pentaprism and (a) are removed. Autocollimators (b) and (c) should be in direct line of sight. This is checked by looking for coincidence of images. When this condition exists, the optical system is mounted onto shafts

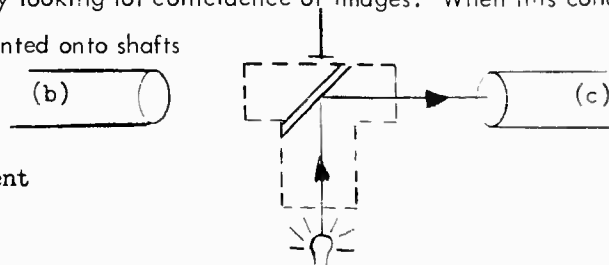


Fig. A-4 Mirror Alignment

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The reticle of the optical system is illuminated and the mirror is adjusted until the image is centered in one of the autocollimators. See Figure A-4. When the shaft is rotated, fine adjustment of the mirror should center the image in the other autocollimator. With repeated shaft rotations the image will be centered in each autocollimator eyepiece, respectively, and the optical system will be completely aligned.

### Rotary Table Alignment

After this last alignment procedure is performed, the same setup is used to obtain parallelism between the Comparator azimuth axis and the rotary table vertical axis. The comparator is locked so that it cannot rotate in elevation or azimuth. Upon centering the illuminated reticle in one of the autocollimators, the rotary table is rotated through 180 deg, and the position of the reticle in the second autocollimator, which is in the line of sight of the first autocollimator, is observed. If the reticle is centered, then parallelism between the pertinent axes exists. If the non-parallel case occurs, then a displacement of the reticle in the vertical direction will be observed. Parallelism can easily be obtained by appropriate positioning of the Comparator with respect to the rotary table.

### Reticle Alignment

The final critical alignment concerns the proper orientation of the reticle in the optical cell. The folding mirror was aligned in such a way that the line of sight is perpendicular to the axis of rotation of the optical cell. After this has been accomplished, the reticle is so aligned that a line passing through the vertex of the 'V' and the center of the reticle (when projected at infinity by the optical system) is contained in the plane defined by the line-of-sight and the mechanical axis.

The technique used to perform this alignment was as follows: An amici prism was set in such a way that half the folding mirror area was blocked by the prism. Upon illumination of the reticle, an image was projected off the folding mirror and also one was projected through the amici prism. A telescope was so set that the two identical image projections could be focused upon a screen or piece of smoked glass. Rotating the reticle in the optical cell caused the two

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images projected onto the screen to rotate in opposite directions. Coincidence of the two images denotes reticle alignment.

Summary of System Alignment Accuracies

System alignment accuracies are:

Axis Orthogonality - 3 arc seconds

Optical Distortion (max) - 5 arc-seconds

Mirror alignment (max) - 5 arc seconds

Reticle Orientation - 2 arc seconds

APPENDIX B  
SLEW AXIS SERVO DESIGN COMPUTATIONS

APPENDIX B

SLEW AXIS SERVO DESIGN COMPUTATIONS

SERVOMECHANISM ANALYSIS AND DESIGN

General

The finalized circuit diagram for the position and velocity loops of the slew axis, i.e., scan axis, is shown in Figure B-8. The detailed design analysis which led to these parameters is discussed in the body of this Appendix.

The finalized chassis layout of the electrical components is shown in Figure G-5 of Appendix G.

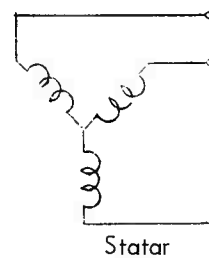
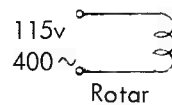
Azimuth Indexing

The azimuth indexing commands are represented functionally in Figure G-6, Appendix G. As the diagram shows, the basic five-degree commands are derived from a set of precision ratio transformers. The inherent accuracy of these transformers, although not necessary for this application, is three arc-seconds.

Slew Axis Servo Design Computations

Refer to Figure B-8 for symbols.

Transmitter  $K'_s$



$E_{\max} = 90$  volts

SLEW AXIS SERVO CX

FIGURE B-1

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$K'_s$ : R-512-2A,  $15.7 \frac{\text{volts}}{\text{degree}}$ ,  $Z_o = 2260 \text{ ohms}$   $80.5^\circ$

Fundamental Null: 35 mv

Total Null: 75 mv

A<sub>p</sub>: MOD 624 Carrier Amplifier Demodulator (Inland Motors)

Gain 2500  $\frac{\text{dc}}{\text{rms ac}}$  Reference 400  $\pm 50$  cps

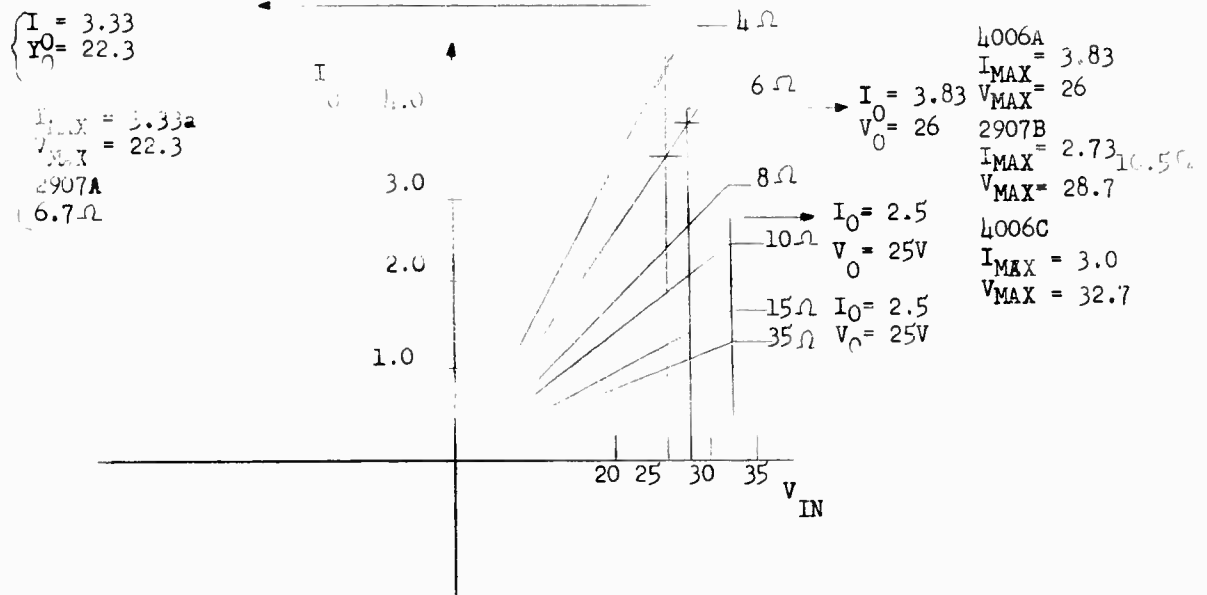
Output voltage maximum =  $\pm 35\text{v}$

Output ripple = 1% peak to peak

$Z_{in}$  = 10k minimum

Input voltage = 0-20 mv, protected to 75 volts rms

Quadrature rejection = 50:1



Used in selecting 2907A slew Servo and 4006A Indexing Servo

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$$\begin{aligned}
 2907A \quad I_{MAX} &= 3.33 \text{ amp} \\
 V_{MAX} &= 22.3 \text{ volts} & V_{IN} \text{ limit to} &= 25 \text{ volts} \\
 R &= 6.7 \Omega \\
 P_{MAX} &= 74.5 \text{ watts}
 \end{aligned}$$

$$\begin{aligned}
 4006A \quad I_{MAX} &= 3.03 \text{ amp} \\
 V_{MAX} &= 26 \text{ volts} & V_{IN} \text{ limit to} &= 27.5 \text{ volts} \\
 R &= 6.8 \Omega \\
 P_{MAX} &= 100 \text{ watts}
 \end{aligned}$$

MODEL 597-3 POWER AMP CHARACTERISTICS

FIGURE B-2

$A_z$  MOD 597-3,  $Z_{in} = 10,000$  ohms, Gain 0.75 v/v

$K_T$ : 2907A

$$\begin{aligned}
 T_{max} &= 0.85 \text{ ft-lbs} = 0.85 \times 1.35 \times 10^7 \\
 &= 1.15 \times 10^7 \text{ dyne-cm}
 \end{aligned}$$

$$V_{max} = 22.3 \text{ volts}$$

$$D = 0.014 \frac{\text{ft-lb}}{\text{rad/sec}} = 1.89 \times 10^5 \frac{\text{dyne-cm}}{\text{rad/sec}}$$

$$I_{max} = 3.33 \text{ amperes}$$

$$T_f = 0.013 \text{ ft-lb}$$

$$R_{dc} = 6.7 \text{ ohms}$$

$$L = 0.010 \text{ henry}$$

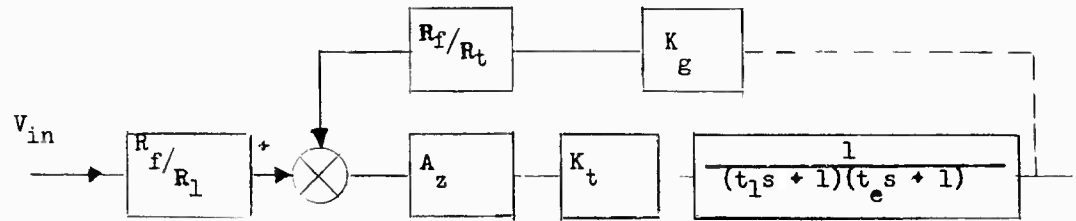
$$V_{in} = 25 \text{ volts} \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \text{ from Figure B-2}$$

$$I_o = 3.33 \text{ amperes} \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \text{ therefore, limit } V_{in} = 25 \text{ volts}$$

$$K_t = \frac{0.85 \text{ ft-lb}}{22.3 \text{ volts}} \times 1.35 \times 10^7 \frac{\text{dc}}{\text{ft-lb}} = 5.15 \times 10^5 \frac{\text{dyne-cm}}{\text{volt}}$$

$$V_{start} = 0.013/0.85/22.3 = 0.33 \text{ volts}$$

Scan (Slew) Tachometer Loop



SCAN TACHOMETER LOOP

FIGURE B-3

$$J_1 = 2.5 \times 10^{-5} \text{ gm-cm}^2 \text{ (or dyne-cm sec}^2 \text{)}$$

$$K_g = 5\text{v/rad/sec into a minimum } 40\text{k}$$

$$W_1 = \frac{1}{I_1} = \frac{D}{J_1} = \frac{1.89 \times 10^5}{2.5 \times 10^5} = 0.76 \text{ rad/sec}$$

$$W_e = \frac{R}{L} = \frac{6.7}{0.01} = 670 \text{ rad/sec} = 107 \text{ cps}$$

$$T = \text{Return Ratio} = \frac{A_2 K_t K_g}{D(t_1 s + 1)(t_e s + 1)} \cdot \frac{R_f}{R_t}$$

$$F = 1 + T = \text{Return Difference}$$

See Bode plot Figure B-4

Select

$$T_{dc} = 40 \text{ db Gain Crossover } 75 \frac{\text{rad}}{\text{sec}} \approx 12 \text{ cps}$$

Therefore,

$$F_{dc} = 101$$

$$\begin{aligned} \text{Speed voltage ratio} = S_r = \frac{\theta_o}{V_{in}} &= \frac{R_f}{R_1} \times \frac{A_2 K_r}{D} \times \frac{1}{F_{dc}} \\ &= \frac{R_f}{R_1} \times \frac{A_2 K_t}{D} \times \frac{1}{1 + \frac{A_2 K_t K_g}{D} \times \frac{R_f}{R_t}} \\ &\approx \frac{R_t}{R_1} \times \frac{1}{K_g} \end{aligned}$$

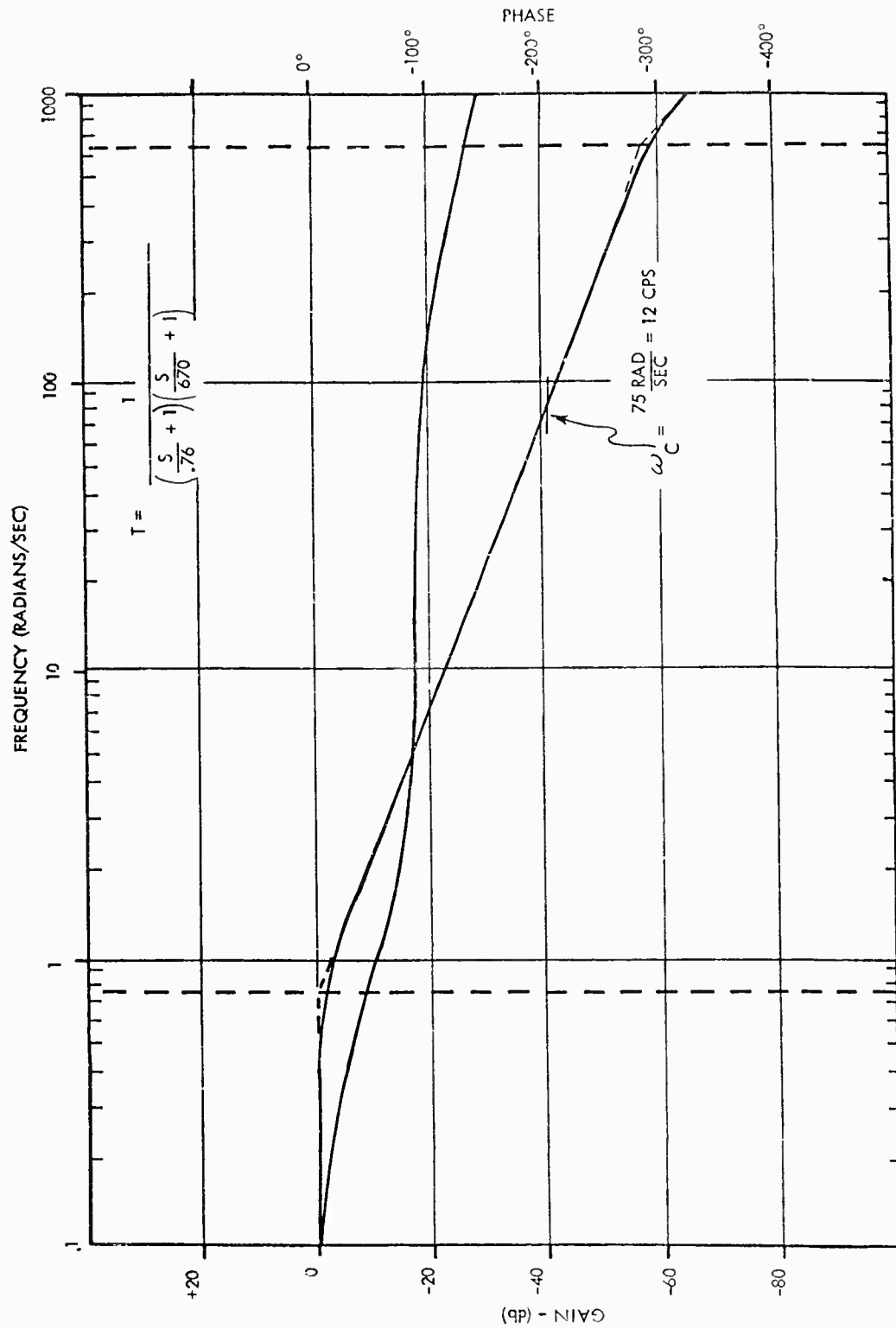


FIGURE B-4 AZIMUTH TACH LOOP SLEW AXIS

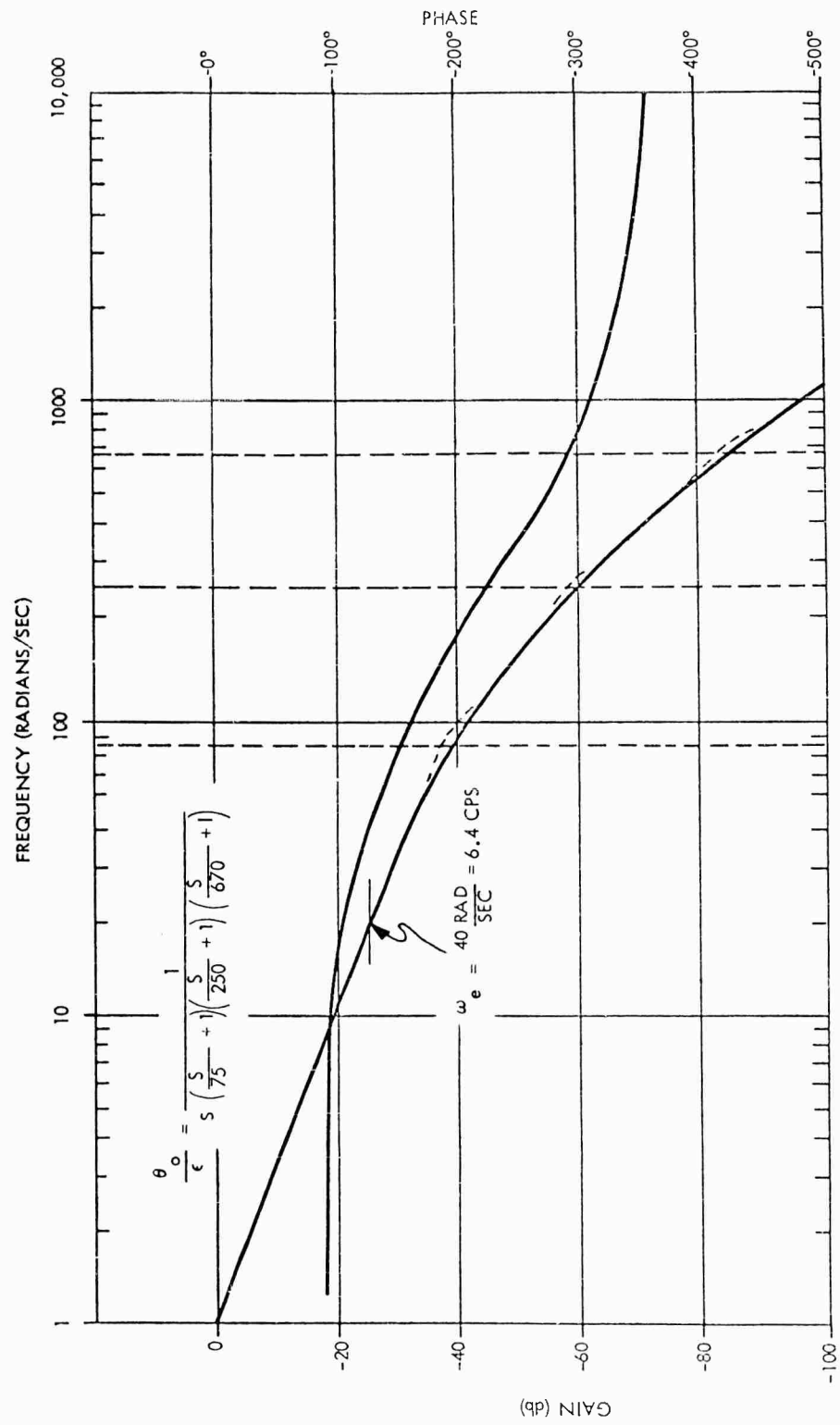


FIGURE B-5 AZIMUTH POSITION LOOP SLEW AXIS

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Required  $\dot{\theta}_o = 36 \text{ rpm} = 3.77 \text{ rad/sec}$

let  $V_{in} = 10 \text{ volts}$

$$S_r = \frac{\dot{\theta}_o}{V_{in}} = \frac{0.377 \text{ rad/sec}}{\text{volt}} = \frac{R_t}{R_1} \times \frac{1}{K_g} = \frac{3.6 \text{ rpm}}{\text{volt}}$$

Therefore,

$$\frac{R_t}{R_1} = S_r K_g = 0.377 \times 5 = 1.9$$

let  $R_t = 40k$

Therefore,

$R_1 = 21k$

} Minimum required for Tachometer loading

also  $T_{dc} = \frac{A_2}{D} K_t K_g \frac{R_f}{R_t}$

$$100 = \frac{0.75}{1.89 \times 10^5} \times 5.15 \times 10^5 \times 5 \times R_f / 40k$$

Solving for  $R_f$

$$R_f = 396k$$

Note: Tachometer Ripple =  $f_r = \text{speed (rps)} \times \text{commutator bars}$

$$= \frac{36}{60} \times 41 = 24.5 \text{ cps} = 155 \text{ rad/sec}$$

If we let  $R_2 = 21k$ , the open-loop response of the position loop (with tach loop closed) is given by:

$$\frac{\dot{\theta}_o}{\epsilon} = K_s \times \frac{A_p}{\frac{s}{\omega_n} + 1} \times \frac{\dot{\theta}_o(s)}{V_{in}(s)} \times \frac{1}{s}$$

$$S_r \text{ at } s = 0 = 0$$

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The Bode Plot is given in Figure B-5 from which we select a

$$K_v = 30\text{db} = 32$$

$$K_{s p r} A_s = 32 = K_{s p} A \frac{(0.377 \text{ rad/sec})}{\text{volt}}$$

Therefore,

$$K_{s p} A = \frac{85 \text{ volts}}{\text{radian}}$$

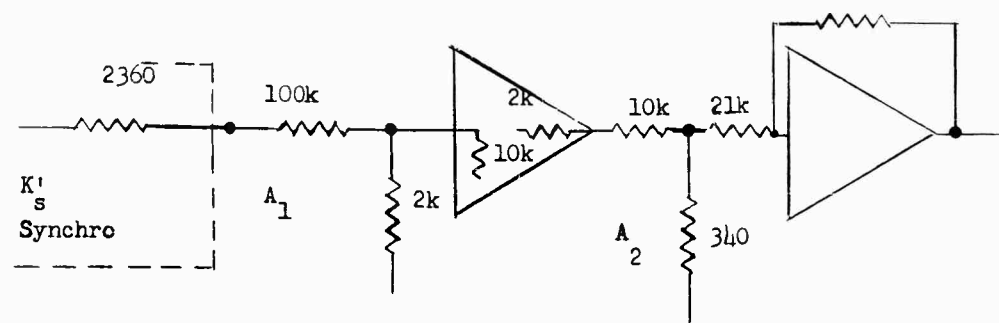
$$\text{but } K'_{s p} A' = \frac{90\text{v}}{\text{rad}} \times \frac{2500 \text{ v}}{\text{v}} = \frac{22500 \text{ v}}{\text{rad}}$$

Therefore, attenuate  $K'_{s p} A'$  by a factor  $A_t$  such that

$$A_t K'_{s p} A' = \frac{85 \text{ v}}{\text{rad}}$$

$$A_t = \frac{85}{22,500} = \frac{1}{2500}$$

Which can be realized by:



SLEW-AXIS POSITION LOOP

FIGURE B-6

$$A_t = A_1 A_2$$

$$A_1 = \frac{1.67k}{101.6k} = \frac{1}{70}$$

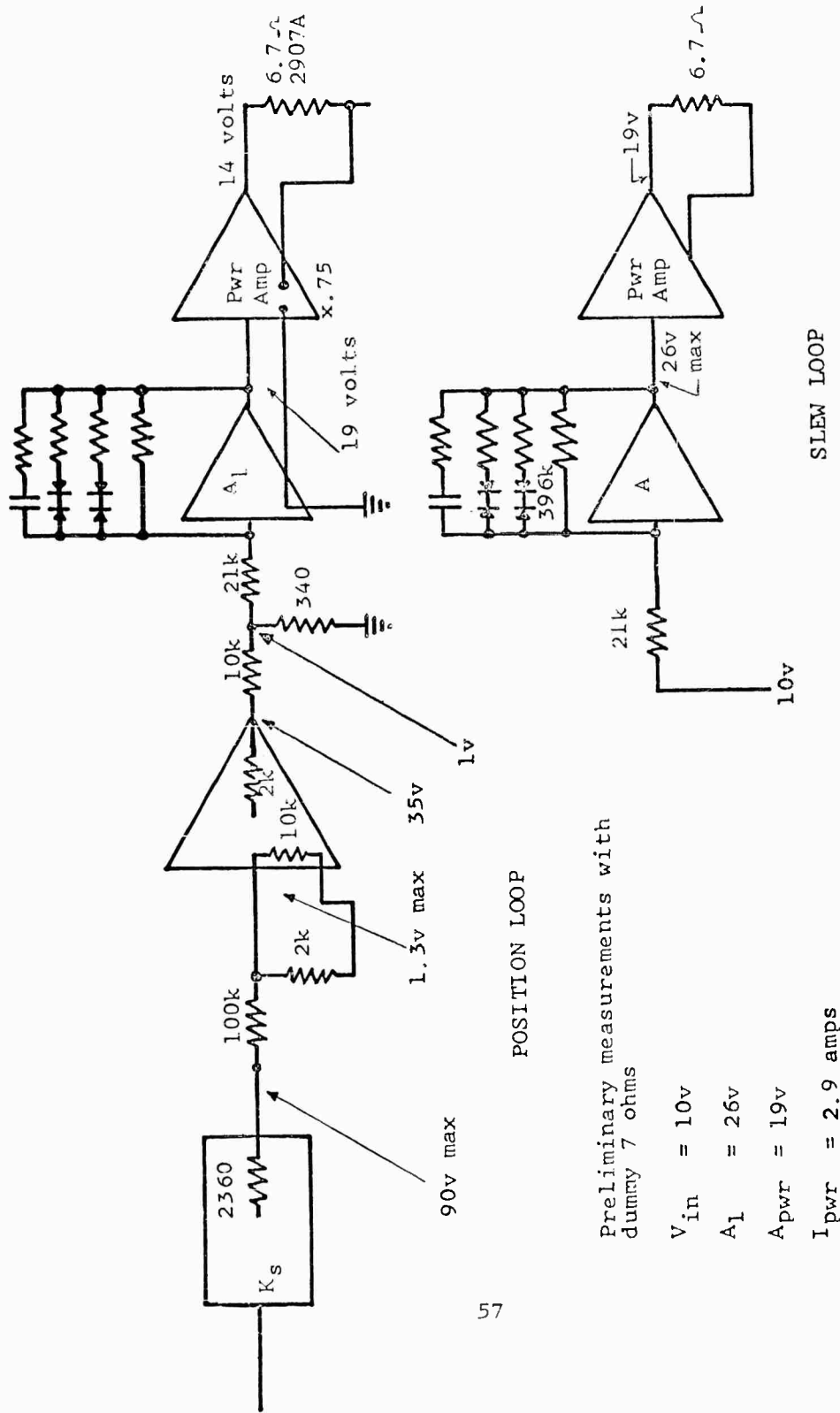
$$A_2 = \frac{340}{12000} = \frac{1}{36}$$

Therefore,

$$A_t \approx \frac{1}{2500}$$

Saturating Conditions

The saturating conditions for the position loop and slew loop are shown in Figure B-7.



Preliminary measurements with dummy 7 ohms

$$V_{in} = 10v$$

$$A_1 = 26v$$

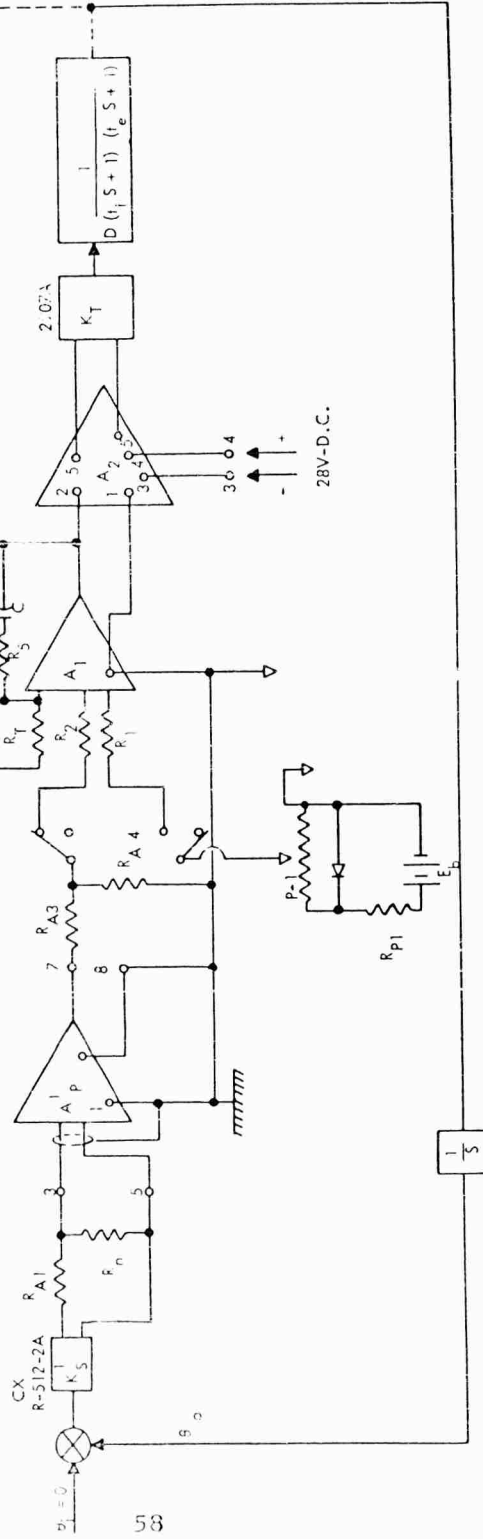
$$A_{pwr} = 19v$$

$$I_{pwr} = 2.9 \text{ amps}$$

Fig. B-7 Saturating Conditions of Position and Slew Loops

LEGEND

- $R_{A1} = 100K$
- $R_{A2} = 2K$
- $R_{A3} = 10K$
- $R_{A4} = 340 \Omega = 100K$
- $R_2 = 18K$
- $R_1 = 18K$
- $R_T = 47K$
- $R_F = 390K$
- $C = .005 \mu\mu f$
- $R_5 = 100 \Omega$
- $R_6 = 4.3K$
- $R_{P1} = 470 \Omega$
- $R_7 = 4.7K$
- $P-1 = 20K, 10 \text{ TURN}$
- $E_b = 22.5V$
- $D-1 = 3/4 M 20Z$
- $D-2 = 3/4 M 30Z$



FINALIZED SLEW AXIS POSITION AND VELOCITY LOOPS  
Figure B-8

APPENDIX C  
INDEXING AXIS SERVO COMPUTATIONS

APPENDIX C

INDEXING AXIS SERVO COMPUTATIONS

General

The finalized circuit diagram for the position loop and velocity loop of the index axis is shown in Figure C-7. The detailed design analysis which led to these parameters is discussed in the body of this Appendix.

The finalized chassis layout of the electrical components is shown in Figure G-5, Appendix G.

Azimuth Indexing

The azimuth indexing commands are represented functionally in Figure G-6, Appendix G. As the diagram shows, the basic five-degree commands are derived from a set of precision ratio transformers. The inherent accuracy of these transformers, although not necessary for this application, is three arc-seconds.

Refer to Figure C-7 for symbols.

Control Transformer  $K'_5$

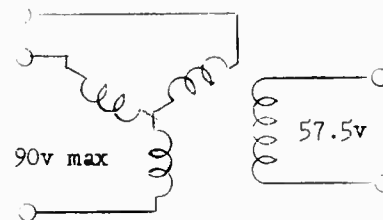


Fig. C-1 Control Transformer

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$$K'_s = CZ06200013, \frac{1.0 \text{ v}}{\text{degree}}, Z_a =$$

Fundamental Null 60 mv

Total Null 90 mv

$A'_p$  = same as Slew Servo

$A_2$  = same as Slew Servo

$$K_t = 4006A$$

$$\begin{aligned} T_{\max} &= 1.8 \text{ ft-lb} = 1.8 \times 1.35 \times 10^7 \\ &= 2.43 \times 10^7 \text{ dyne-cm} \end{aligned}$$

$$V_{\max} = 26 \text{ volts}$$

$$\begin{aligned} D &= 0.045 \frac{\text{ft-lb}}{\text{rad/sec}} \times 1.35 \times 10^7 \\ &= 6.1 \times 10^5 \frac{\text{dyne-cm}}{\text{rad/sec}} \end{aligned}$$

$$I_{\max} = 3.83 \text{ amps}$$

$$T_f = 0.035 \text{ ft-lbs}$$

$$R_{dc} = 6.8 \text{ ohms}$$

$$L = 0.013 \text{ henry}$$

$$V_{in} = 27.5 \text{ volts (See Figure B-2)}$$

$$I_o = 3.83 \text{ amps (See Figure B-2)}$$

$$K_t = \frac{1.8 \text{ ft-lb}}{26 \text{ volts}} \times 1.35 \times 10^7 = 9.4 \times 10^5 \frac{\text{dyne-cm}}{\text{volt}}$$

$$V_{\text{start}} = \frac{0.035}{1.8/26} = 0.5 \text{ volts}$$

Index Tachometer Loop

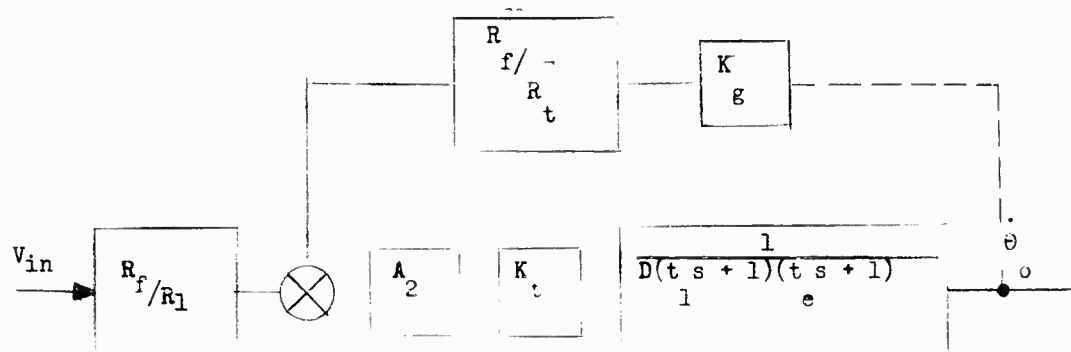


Fig. C-2 Index Tachometer Loop

$$J_1 = 6.4 \times 10^3 \text{ dyne-cm sec}^2$$

$$K_g = 5\text{v/rad/sec into a minimum 40k load}$$

$$\omega_1 = \frac{1}{T_1} = \frac{D}{J_1} = \frac{6.1 \times 10^5}{6.4 \times 10^3} = 0.095 \text{ rad/sec}$$

$$\omega_e = R/l = 6.8/0.013 = 523 \text{ rad/sec} = 83 \text{ cps}$$

Digressing for the moment to Index Position Loop:

Permissible time for servo to be indexed  $5^\circ$  depends on slew speed.

$$36 \text{ rpm} = \frac{36}{60} \text{ rps} = 0.6 \text{ rps} = 216 \text{ deg/sec}$$

$$60 \text{ rpm} = 1 \text{ rps} = 360 \text{ deg/sec}$$

Therefore, maximum time to complete index:

$$180^\circ - 8^\circ - 4^\circ \text{ max} = 168^\circ \text{ (See Appendix B)}$$

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$$T_{\max} \text{ at } 60 \text{ rpm} = \frac{168^\circ}{360^\circ/\text{sec}} = 0.47 \text{ sec}$$

(worst case)

$$T_{\max} \text{ at } 36 \text{ rpm} = \frac{168^\circ}{216^\circ/\text{sec}} = 0.78 \text{ sec}$$

The position loops BW must then be in the order of:

$$T_r = \frac{0.45}{\text{BW}} ; \text{ BW} = \frac{0.45}{T_r} = \frac{0.45}{0.47} \approx 1 \text{ cps at } 60 \text{ rpm} \approx 0.58 \text{ cps at } 36 \text{ rpm}$$

Figure C-3 is a Bode plot of tachometer loop based on values of  $\omega_1$ ,  $\omega_e$  above.

Figure C-4 is a plot of the position loop based on 50 db of tach feedback. If we make  $K_v = 20 \text{ db}$ , we see  $\text{BW} = 10/\text{rad}/\text{sec}$ , which is more than sufficient for the required  $T_r$ .

Now let us investigate the feasibility of 50 db tach feedback.

$$T_{\text{dc}} = 234 = \frac{A_2 K_t K_g}{D} \times \frac{R_f}{R_t}$$

(50 db)

$$A_2 = 0.75 \text{ v/v}$$

$$K_t = 9.4 \times 10^5 \frac{\text{dyne-cm}}{\text{volt}}$$

$$K_g = 5 \text{ v/rad}/\text{sec}$$

$$D = 6.1 \times 10^5 \frac{\text{dyne-cm}}{\text{rad}/\text{sec}}$$

$$234 = 0.75 \text{ v/v} \times 9.4 \times 10^5 \frac{\text{dc}}{\text{v}} \times \frac{5\text{v}}{\text{rad}/\text{sec}} \times \frac{1}{6.1 \times 10^5} \frac{\text{dc}}{\text{rad}/\text{sec}} \times \frac{R_f}{R_t} = 5.8 \frac{R_f}{R_t}$$

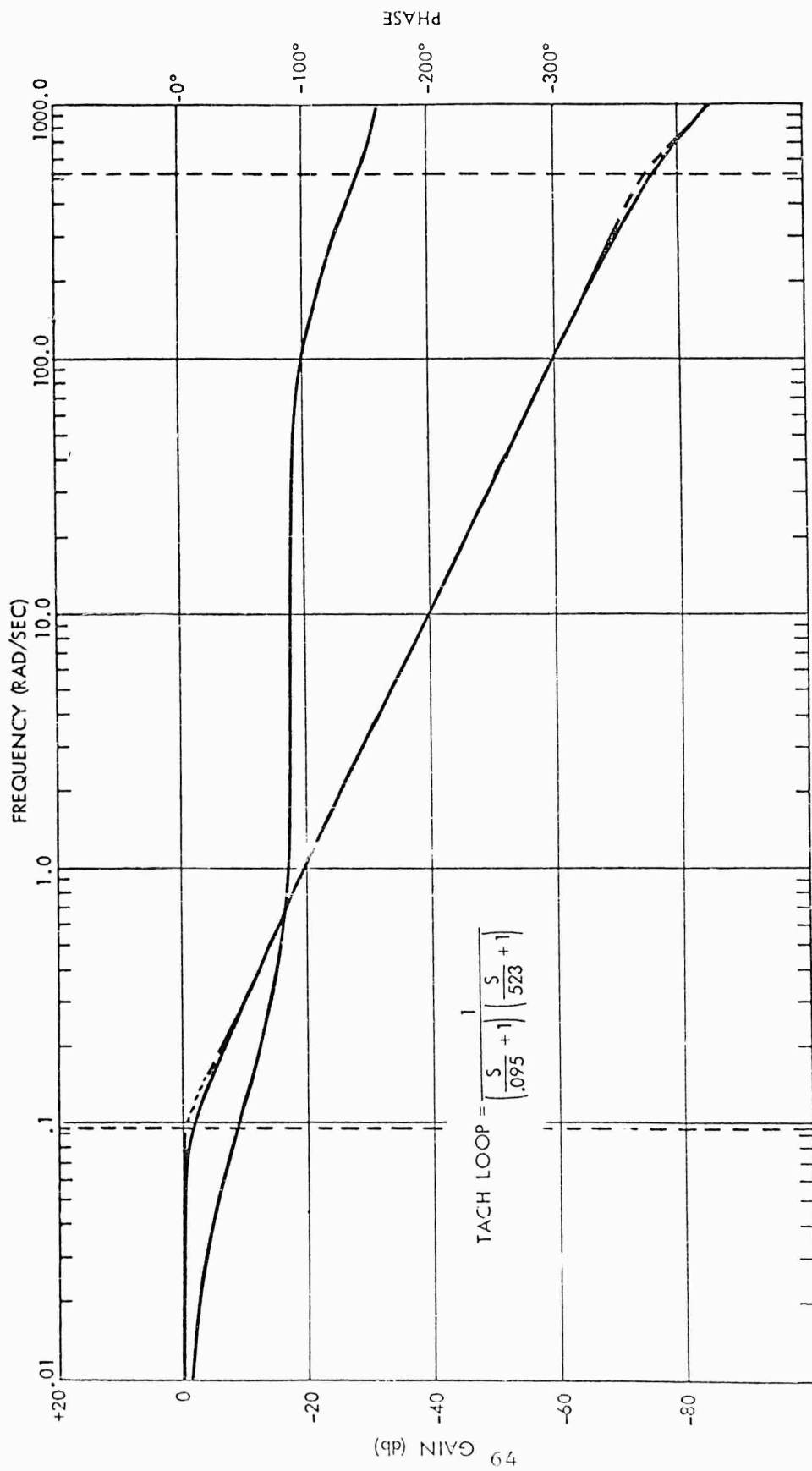


FIGURE C-3 ELEVATION (INDEX) LOOP

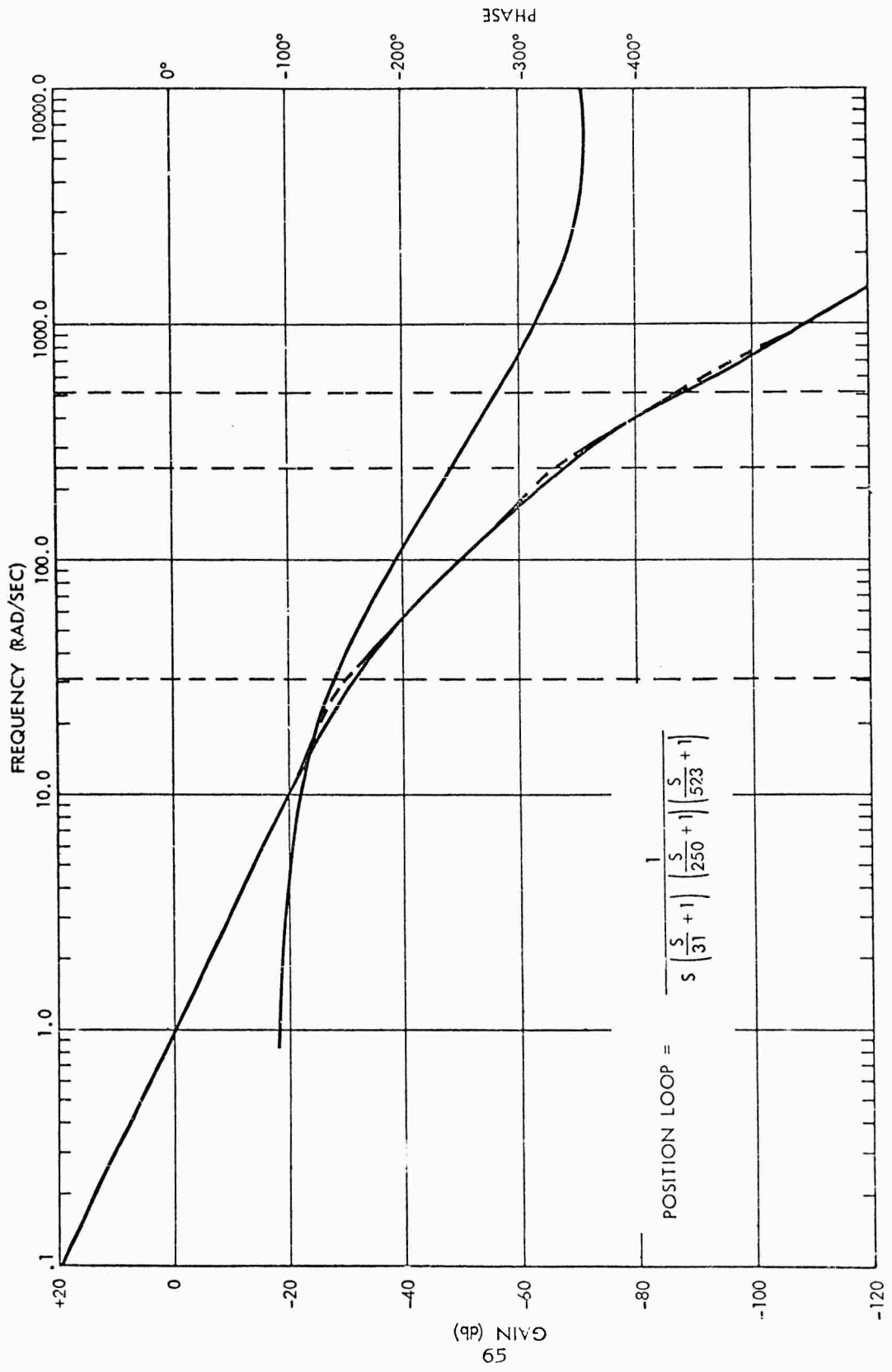


FIGURE C-4 ELEVATION (INDEX) LOOP (50DB TACH F. B.)

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Therefore,  $\frac{R_f}{R_t} = 40$

if  $R_t = 40 \text{ k}$

$R_f = 1.5 \text{ meg}$  - quite high  
(50 db)

The dc closed-loop gain of the tach loop for this condition  $\frac{\dot{\theta}}{V_{in}}$  will be:

$$S = \frac{R_t}{R_2} \times \frac{1}{K_g}$$

The  $K_g$  of the position loop will be (20 dr = 10, see Figure C-4)

$$\omega_c = 10 \text{ rad/sec}$$

Therefore,  $\frac{\theta}{\epsilon} = K_s \times A_p \times S = 10$

but  $K'_s A'_p = 57.5 \text{ v/rad} \times 2500 \text{ v/v} = 14400 \frac{\text{volts}}{\text{rad}}$

If we use the same attenuation constant of slew loop but different  $R_{o1}$ ,  $R_{a2}$ ,  $R_{a3}$ , and  $r_{a4}$  for better saturating values

$$A_t = \frac{1}{2500}$$

Therefore,  $K_s A_p = \frac{14400}{2500} = 57.5 \frac{\text{volts}}{\text{rad}}$

Therefore,  $S = \frac{10}{57.5} = \frac{R_t}{R_2} \times \frac{1}{K_g} = 0.174 \frac{\text{rad/sec}}{\text{volt}} = 1.66 \frac{\text{rev/min}}{\text{volt}}$

$$\frac{R_t}{R_2} = \frac{10}{57.5} \times 5 = \frac{50}{57.5}$$

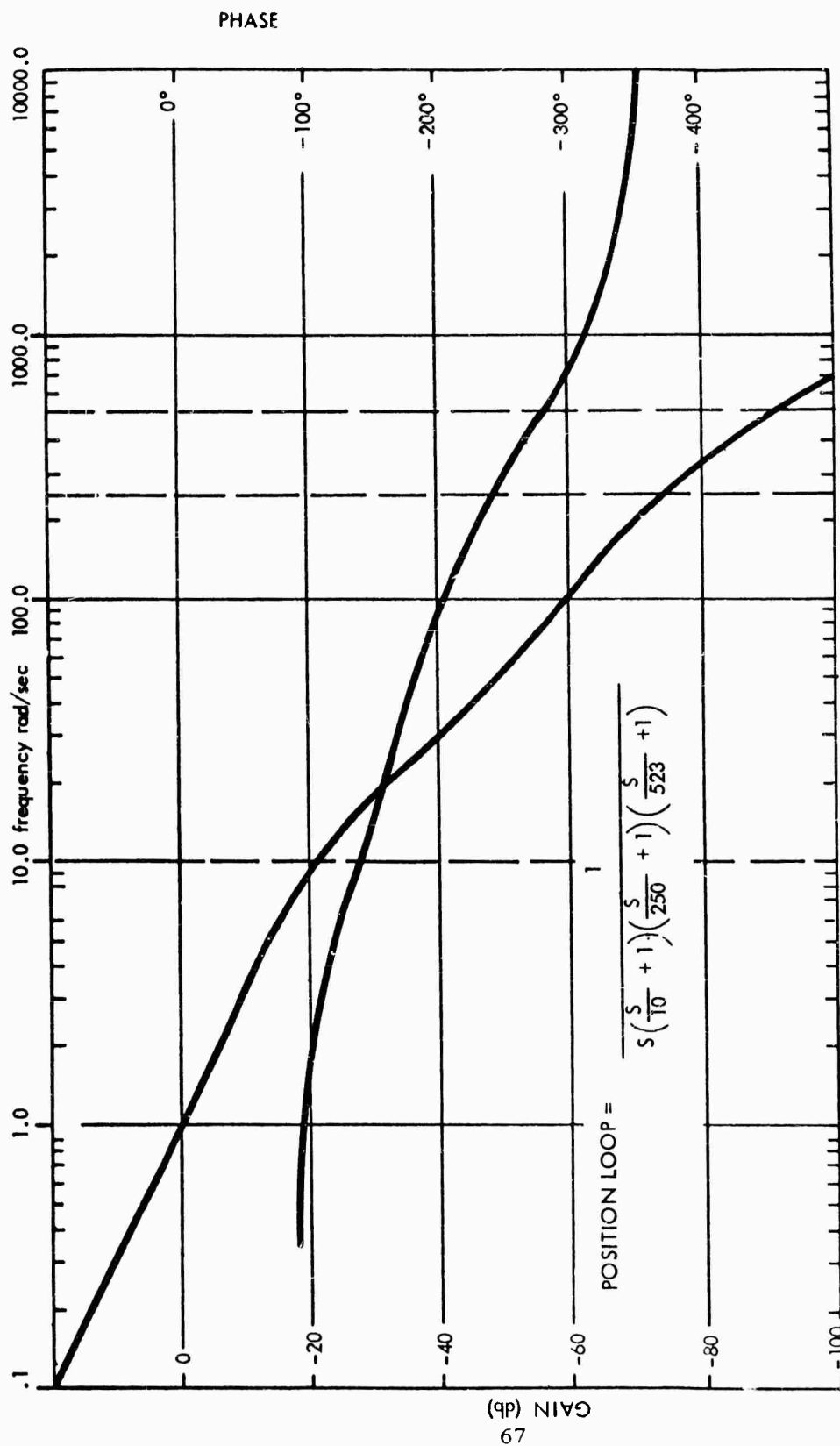


FIGURE C-5 - ELEVATION (INDEX) LOOP (40DB TACH F.B.)

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$$\text{Therefore, } R_2 = \frac{57.5}{50} \times R_t = \frac{57.5}{50} \times 40k = 46k$$

50 db

If instead we used 40 db of tach feedback,

$$\frac{R_f}{R_t} = \frac{100}{5.8} = 17.3$$

If once again  $R_t = 40 k$

$$R_f = 690 k$$

40 db

Now make  $K_v$  of the position loop 18 db (Figure C-5)

$$\omega_c = 6.28 \text{ rad/sec}$$

$$\frac{\theta}{\epsilon} = K_s A_s S = 8$$

$$S = \frac{8}{57.5} \frac{R_t}{R_2} \times \frac{1}{K_g} = 0.14 \frac{\text{rad/sec}}{\text{volt}} = 1.33 \frac{\text{rev/min}}{\text{volt}}$$

$$\text{Therefore, } \frac{R_t}{R_2} = \frac{8}{57.5} \times 5 = \frac{40}{57.5}$$

$$R_2 = \frac{57.5}{40} R_t = \frac{57.5}{40} \times 40k = 57.5k$$

40 db

Calculation of  $R_{a1}$ ,  $R_{a2}$ ,  $R_{a3}$ , and  $R_{a4}$

Select 25 volts maximum into power amplifier

$$R_{a1} = 100k, R_{a3} = 10k$$

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$$\frac{R_f}{R_2} = \frac{690k}{57k} = 12$$

$$i_{in \max} = \frac{25}{12} = 2.1 \text{ volts}$$

$$\text{Therefore, } A_2 = \frac{2.1}{35} = \frac{1}{16.7}$$

$$\frac{R_{a4}}{R_{a4} + 12000} = \frac{1}{16.7}$$

$$R_{a4} = 775 \text{ ohms}$$

$$A_1 = \frac{R_{a2} / 10k}{R_{a2} / 10k + 100k} = \frac{1}{2500/16.7} = \frac{1}{150}$$

$$R_{a2} = 750 \ \Omega \text{ (sufficiently close to above)}$$

Saturating Condition

The saturating condition is shown in Figure C-6.

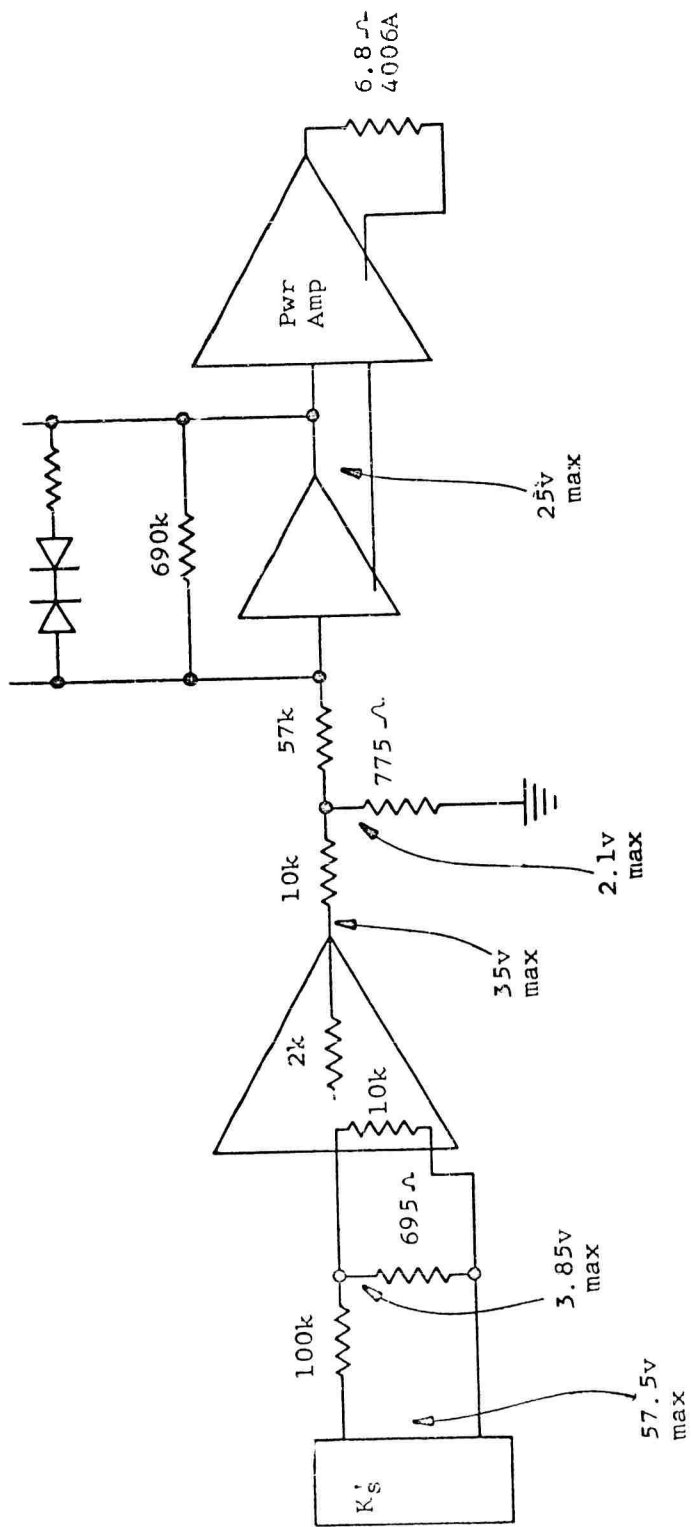
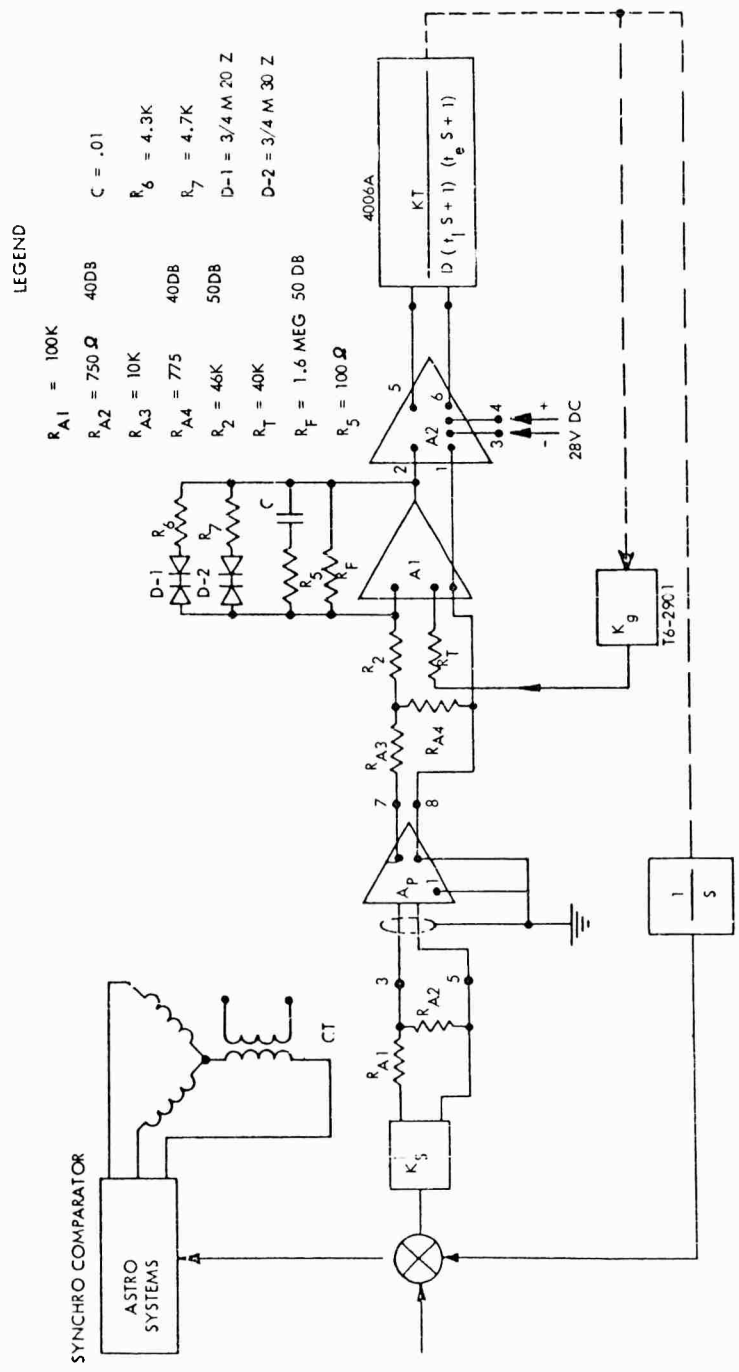


FIGURE C-6 - SATURATING CONDITION FOR THE INDEXING AXIS SERVO LOOP



LEGEND

- $R_{A1} = 100K$
- $R_{A2} = 750 \Omega$  40DB
- $R_{A3} = 10K$
- $R_{A4} = 775$  40DB
- $R_2 = 46K$  50DB
- $R_T = 40K$
- $R_F = 1.6 MEG$  50 DB
- $R_5 = 100 \Omega$
- $C = .01$
- $R_6 = 4.3K$
- $R_7 = 4.7K$
- $D-1 = 3/4 M 20 Z$
- $D-2 = 3/4 M 30 Z$

FINALIZED POSITION AND VELOCITY LOOPS OF THE INDEX AXIS

Figure C-7

APPENDIX D  
OPTICAL ROTARY TILT TABLE DATA

KEARFOTT DIVISION  
GP GENERAL PRECISION INC.  
LITTLE FALLS, NEW JERSEY

Certificate No.  
630312-1

# Certificate of Inspection

METROLOGY LABORATORY

OPTICAL ROTARY TILT TABLE

Submitted by 3-3940  
Date of Inspection 3-12-63  
Identification Marking ~~600~~ QMT (~~1000~~)

Errors indicated are with respect to 0° 00' 00" and does not include a constant error due to backlash.

0° 0"	90° 5"	180° 3"	270° 2"
5-1	95+5	185-3	275-2
10+1	100+5	190-4	280-1
15+2	105+4	195-3	285-2
20+2	110+3	200-4	290-1
25+2	115+3	205-2	295-1
30+2	120+3	210-4	300-2
35+2	125+2	215-4	305-2
40+2	130 0	220-4	310-1
45+2	135+1	225-3	315-1
50+2	140 0	230-2	320-2
55+2	145 0	235-2	325 0
60+3	150 0	240-2	330+1
65+4	155-2	245-3	335+1
70+6	160-1	250-1	340 0
75+5	165-3	255-0	345 0
80+5	170-3	260-1	350-1
85+3	175-4	265-2	355 0

Stabilization Time 48 hrs.  
Environmental Temperature at  
Time of Inspection 68 °F.

INSPECTION STAMP	SUPERVISOR'S APPROVAL
<i>T. K. ...</i>	<i>[Signature]</i>

QUALITY CONTROL DIVISION

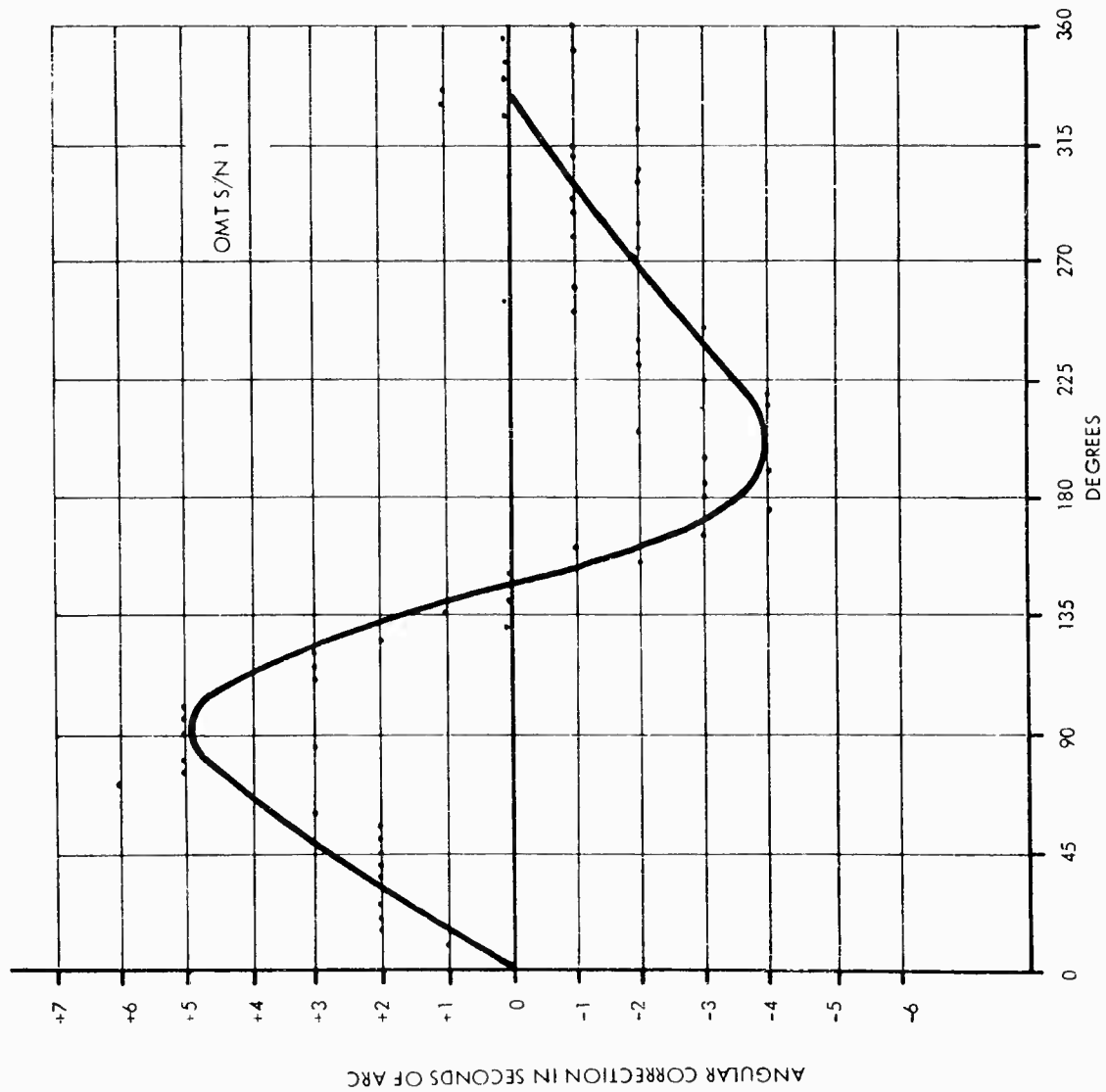


FIGURE D-1 - OPTICAL ROTARY TILT TABLE DATA

APPENDIX E  
STAR COUNTER

APPENDIX E

STAR COUNTER

Theory of Operation

Counter and Counter Controls (Refer to Schematic G-4, Appendix G)

AS-1, AS-2, AS-3, AS-4, AS-5, AS-6 - These are squaring circuits which convert input signals from the shaft encoders to T-Series levels. T-Series levels are  $-3\text{vdc} = "1"$ ,  $-11\text{vdc} = "0"$ .

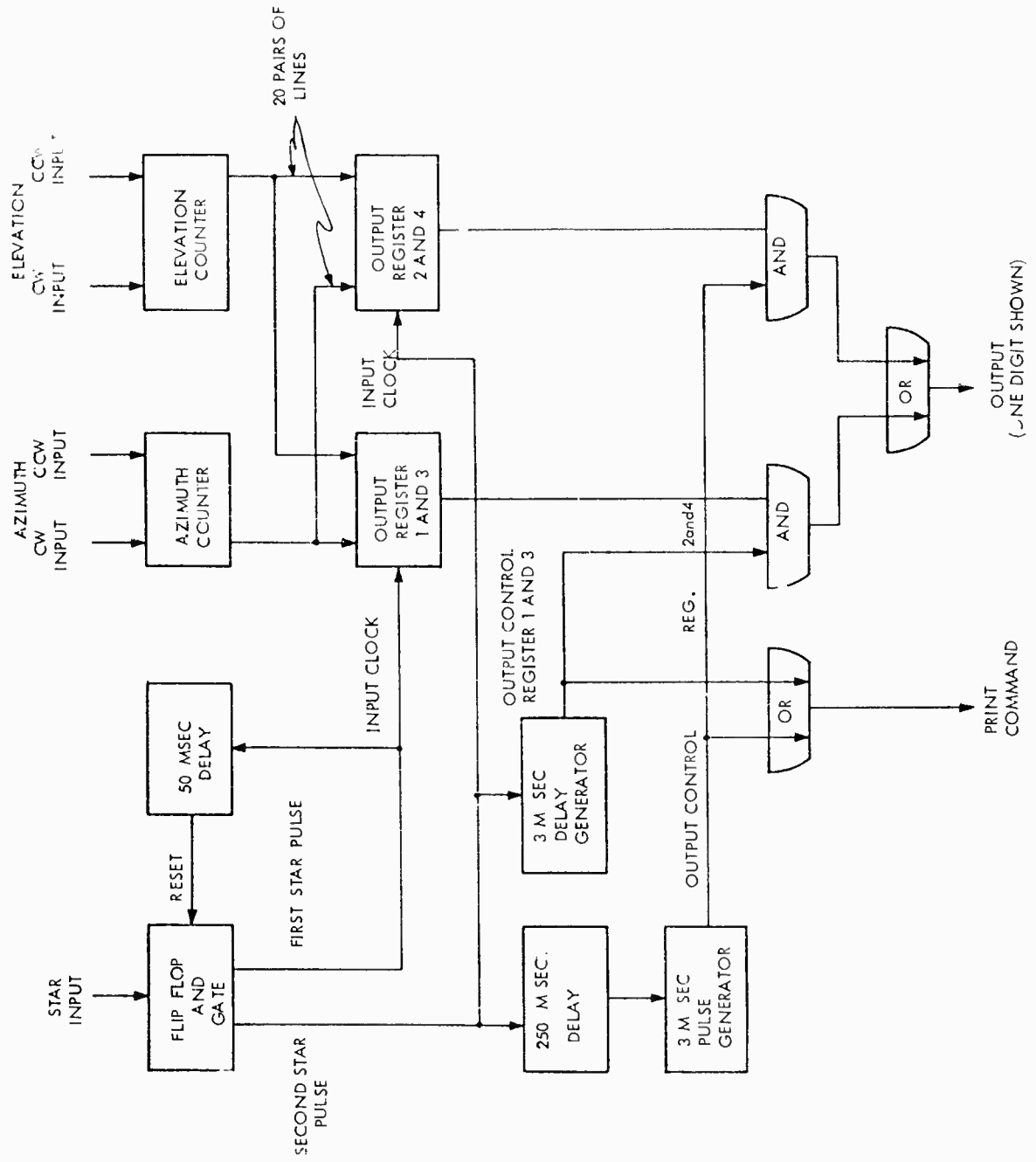
OR-2, OR-4 - "OR" gates which pass either the input from the shaft encoder or the simulated encoder signal. The frequency of the simulated signal is controlled by a 10-turn potentiometer mounted on the front panel.

FF-3, FF-4 - Provide the forward-reverse control signals for the counters. A CW count input produces a forward control signal and a CCW count input produces a reverse control signal.

OR-3, OR-5 - "OR" gates which pass either CW input pulses, CCW input pulses, or the simulated encoder signal.

OS-6, OS-9 - One-shot multivibrators accept pulses from OR-3 and OR-5, respectively, and delay them for five  $\mu$  sec, before they are passed on to the forward-reverse counter. This five  $\mu$  sec. delay is required to allow complete enabling of the counter by either the forward control or the reverse control before input pulses are received.

EF-3, EF-4, EF-5, EF-6 - Emitter followers which drive the forward-reverse input controls of the counters.



STAR COUNTER BLOCK DIAGRAM  
Figure E-1

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OS-7, OS-8, OS-10, OS-11 - One-shot multivibrators are used to stretch out the two- $\mu$  sec. wide zero-reference signal from the shaft encoder. At the maximum incoming frequency of 70 kc, pulses arrive at the counter every 14  $\mu$  sec. Since the entire counter requires approximately 80  $\mu$  sec. for reliable resetting, the reset operation is performed in two steps: OS-8 and OS-11 produce a 10- $\mu$  sec. reset pulse to reset only the first decade of the counters: OS-7 and OS-10 produce an 80- $\mu$  sec. pulse to reset the last four decades. In this way, 14  $\mu$  sec. after the beginning of the reset pulse, the first decade is able to accept pulses.

OR-10, OR-11, OR-12, OR-13 - "OR" gates which pass reset signals from either OS-7, OS-8, OS-10, OS-11, respectively or the master reset signal.

RD-3, RD-4, RD-5, RD-6 - Delay drivers which convert the -3 volt and -11 volt signals from OR-10, OR-11, OR-12 OR-13, respectively, to approximately -5 volts and zero volts to reset the counters. The -5 volt output occurs when there is a -11 volt input. The counters are reset with the -5 volt level.

Forward-Reverse Counters I through X - Decade counters with 1-2-4-8 code, which count pulses from shaft encoders or a simulated encoder signal. Decades I through V comprise a five-digit counter to accumulate azimuth pulses. Decades VI through X comprise a five-digit counter to accumulate elevation pulses.

Print Control

AS-7 - Squaring amplifier which converts incoming star pulses to T-Series levels.

OR-6 - Is a pulse "OR" gate which provides a pulse into OS-1 for each signal from the star pulse or the manual print command from OR-7.

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OS-1 - Delays the incoming print signals for five- $\mu$  sec. This delay compensates for the five- $\mu$  sec. delay on the input to the forward-reverse counter so that the transfer command is synchronous with the counter signals.

FF-5 - Pin L is normally "off" (-11 volt level). At the first input pulse FF-5 goes "on" thereby passing a pulse through OR-8 and enabling AND-1. The pulse through OR-8 is coupled through capacity drive CD-1 to transfer the count that is in the azimuth and elevation counters into storage registers 1 and 3, respectively. This pulse also triggers OS-3 which, after a 50 MS delay, resets FF-5. When the second signal comes through pin K off FF-5, it is also passed through the pulse input of AND-1. In order to be passed through AND-1, the second pulse must be received within 50 MS of the first pulse, because OS-3 provides an automatic reset of FF-5 50 MS after the first pulse. This reset of FF-5 disables AND-1.

AND-1 - Is enabled by the first print signal received from FF-5. If the second print signal is received within 50 MS (before FF-5 is reset), it is coupled through AND-1, OR-14, and OR-9 to trigger OS-2 and OS-4, respectively.

OS-2 - Provides a positive pulse three MS wide, which is coupled through EF-1 and is subsequently used to gate the information stored in storage registers 1 and 3 to the printer.

EF-1 - Emitter follower provides isolation between OS-2 and output "AND" gates.

OR-9 - Is used to pass either the Manual Print Register 2 and 4 signal from S-4 or the second print signal from AND-1 to OS-4.

OS-4 - At the time of the second print signal, OS-4 (S) provides a pulse which is coupled through CD-2 and is used to transfer the count stored in the azimuth and elevation counters into storage registers 2 and 4 respectively. OS-4 (R) provides a pulse which triggers OS-5, 250 MS after the second print command.

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OS-5 - Provides a positive pulse three NS wide, which is coupled through EF-2 and is subsequently used to gate the information stored in storage registers 2 and 4 to the printer.

EF-2 - Emitter follower used to provide isolation between OS-5 and output "AND" gates.

OR-8 - Is used to pass either the Manual Print Register 1 and 3 signal from OS-13 or the output of FF-5 to OS-3.

OS-3 - Provides a 50 MS positive pulse. The trailing edge of this pulse (positive-going) is used to reset FF-5.

CD-1, CD-2 - These are used to amplify the signals required to transfer the count from the counters into the registers. Each of these circuits drives 40 shift registers.

OR-1 - Passes three MS positive pulses from either OS-2 (through EF-1) or OS-5 (through EF-2). These pulses go directly to the printer as the print command. This command enables the printer to accept for printing whatever information is at its signal inputs.

S-3 - Is a pushbutton switch to initiate a manual print command to print data in the azimuth and elevation counters through registers 1 and 3.

OS-13 - Is used to provide a manual print command to print whatever information is in the azimuth and elevation counters by passing this information through registers 1 and 3, respectively. The input to OS-13 is generated by S-3.

S-4 - Is a pushbutton switch to initiate a manual print command to print data in the azimuth and elevation counter through registers 2 and 4.

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S-2 - Is a pushbutton switch to initiate the manual print cycle. The signal from this switch triggers OS-12.

OS-12 - When the manual print switch (S-2) is operated, OS-12 generates a pulse which is 20 MS ( $\pm 1$  MS) long.

OR-7 - Is a pulse "OR" gate which passes the signals from each output of OS-12, thereby producing two pulses 20 MS apart. These two pulses simulate star pulses.

Manual Reset

RD-7 - The resistor-capacitor network (R13, C17) connected to the input of RD-7 provides a momentary -12 volts into RD-7 at power turn-on. This provides a zero-volt output from RD-7 to reset FF-5 and operate Master Reset Signal Generator AS-8.

AS-8 - Is a squaring circuit to convert the output from RD-7 to T-Series levels. The output of AS-8 is the master reset signal.

S-5 - Is the Manual Reset pushbutton switch, and duplicates the operation of the reset at power turn-on.

Simulated Shaft Angle Encoder

MV-1 - Free-running Multivibrator which provides a square-wave output signal to simulate a CW input to the azimuth and elevation counters. The frequency is adjustable from approximately 30 kc to 70 kc by means of the 10-turn potentiometer (R-17) mounted on the front panel.

S-6 - Is a toggle switch which controls the output of MV-1 to the counters.

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FF-2 - Is used to limit the maximum count in the counters to 80,000. The "8" output of decade 1 (10,000's) sets FF-2 which inhibits the simulated encoder signal at gates AND-2 and AND-3, stopping the counter at 80,000. This limit is applied only to the simulated encoder signal.

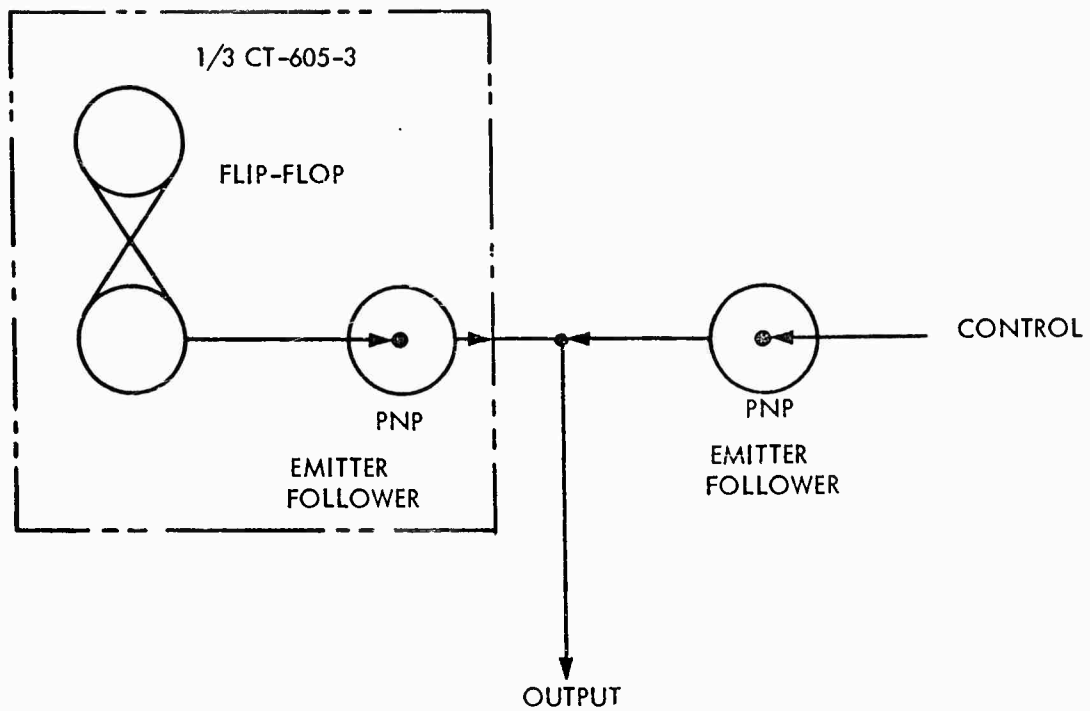
AND-2, AND-3 - Are pulse "AND" gates controlling the input signals to both counters. These gates are always open during normal operation.

Output Registers

Each storage register consists of 20 Shift Register Flip-Flops. The 20 outputs from the binary-coded-decimal forward-reverse counters are connected to the parallel inputs of the register. When the transfer pulse from the print control circuits is received from CD-1 or CD-2, the count is transferred from the counters into the registers. The information in the counter is not disturbed and the counter continues to count. Each shift register flip-flop has a PNP emitter follower output. The output of the flip-flop is controlled by connecting the output of another PNP emitter follower to the flip-flop output. This forms a DCTL "AND" gate. See Fig E-2. The input to the control emitter follower is the three-MS pulse generated by OS-2 and OS-5. The outputs of the two registers, through the "AND" gates, are OR'd together in the output "OR" gates. (The two registers' outputs are fed to the printer one at a time).

Slew and Reference

FF-1 - Is the Slew and Reference flip-flop and is used to operate a Slew indicator or a Reference indicator located on the front panel. When the Slew pushbutton is pushed, the Slew indicator illuminates. When the Reference pushbutton is pushed, the Slew indicator extinguishes, the Reference indicator illuminates, and the Reference relay is activated. Inputs are provided for remote control of the Slew and Reference flip-flop.



THE TWO PNP EMITTER FOLLOWERS FORM A DCTL "AND" GATE

STAR COUNTER  
Figure E-2

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RD-1 - Relay driver which produces output signal to drive remote relay.

RD-2 - Relay driver which actuates relay K1.

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APPENDIX F

SYSTEM TEST PROCEDURE

APPENDIX F

SYSTEM TEST PROCEDURE

All power is controlled by the power panel located at the base of the console. The panel contains three switches, (1) 28vdc, (2) 115v 400 cycle, and (3) 115v 60 cycle.

Before any one of these switches is operated, all switches on the front of the cabinet should be off. Also, before any of the latter switches is operated, the three switches at the rear of the cabinet should be on, i.e., switch on T2, T3 and T4. These switches may be left in the on position at all times.

Turn on the power supply with 28vdc, 115v 400-cycle, and 115v 60-cycle switches located on the power panel.

Warm-Up Phase

- (a) Turn on power supply to logic
- (b) Turn on printer power
- (c) Turn on oc switch on 300 vdc supply

Caution, do not turn on dc switch

- (d) Turn on oc switch on 150vdc supply

Caution, do not turn on dc switch

- (e) Turn on power switch on kilovolt supply

Caution, do not turn on high-voltage switch

- (f) Wait five minutes

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Power Turn-On

- (a) Turn on 150vdc
- (b) Turn switch on preamplifier to check battery supply
- (c) Turn on switch on preamplifier
- (d) Set voltage knobs on kilovolt supply to 1,560 volts
- (e) Turn off all room lighting
- (f) Turn on high-voltage switch on kilovolt supply
- (g) Turn on 300vdc; both axes should drive to their respective nulls
- (h) Printer on

Comparator is now set to scan the sky. To scan, push slew button on logic. Comparator will automatically scan the sky and after completing its scan will return to the originally set position. Another scanning cycle can be generated by simply pushing the slew button.

Stand-by Phase

Turn off all switches which were turned on for power turn-on phase only.

Shut-down

- (a) Place system in stand-by phase
- (b) Turn off all switches turned on in warm-up phase
- (c) Turn off power panel switches

Cable Interconnections and Continuity Checks

Nomenclature

300 series	-	On comparator
200 series	-	External to comparator
J series	-	Socket
P series	-	Plug

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Procedure

Connect plugs to sockets indicated.

<u>Plug</u>	<u>Socket</u>
P301	J301
P302	J302
P303	J303
P210	J210
P222	J222
P209	J209
P221	J221
P201	J201
P202	J202
P203	J203
P204	J204
P205	J205
P206	J206
P207	J207
P208	J208
P211	J211
P212	J212
P213	J213
P214	J214
P215	J215
P216	J216
P217	J217
P218	J218
P219	J219
P220	J220

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<u>Plug</u>	<u>Socket</u>
TB2	T2
TB3	T3
TB4	T4

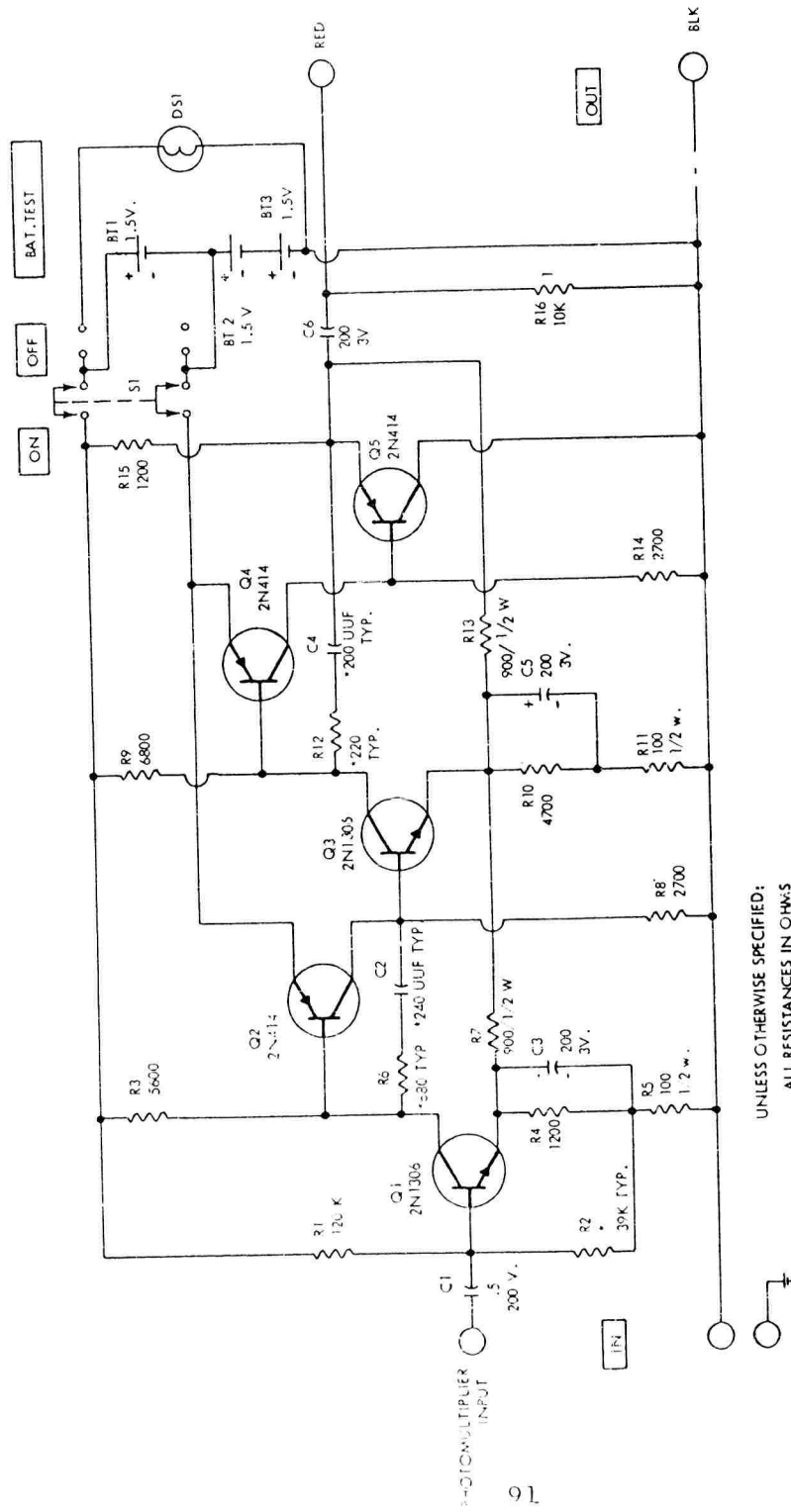
Power Required

28vdc

115v 400 cycle

115v 60 cycle

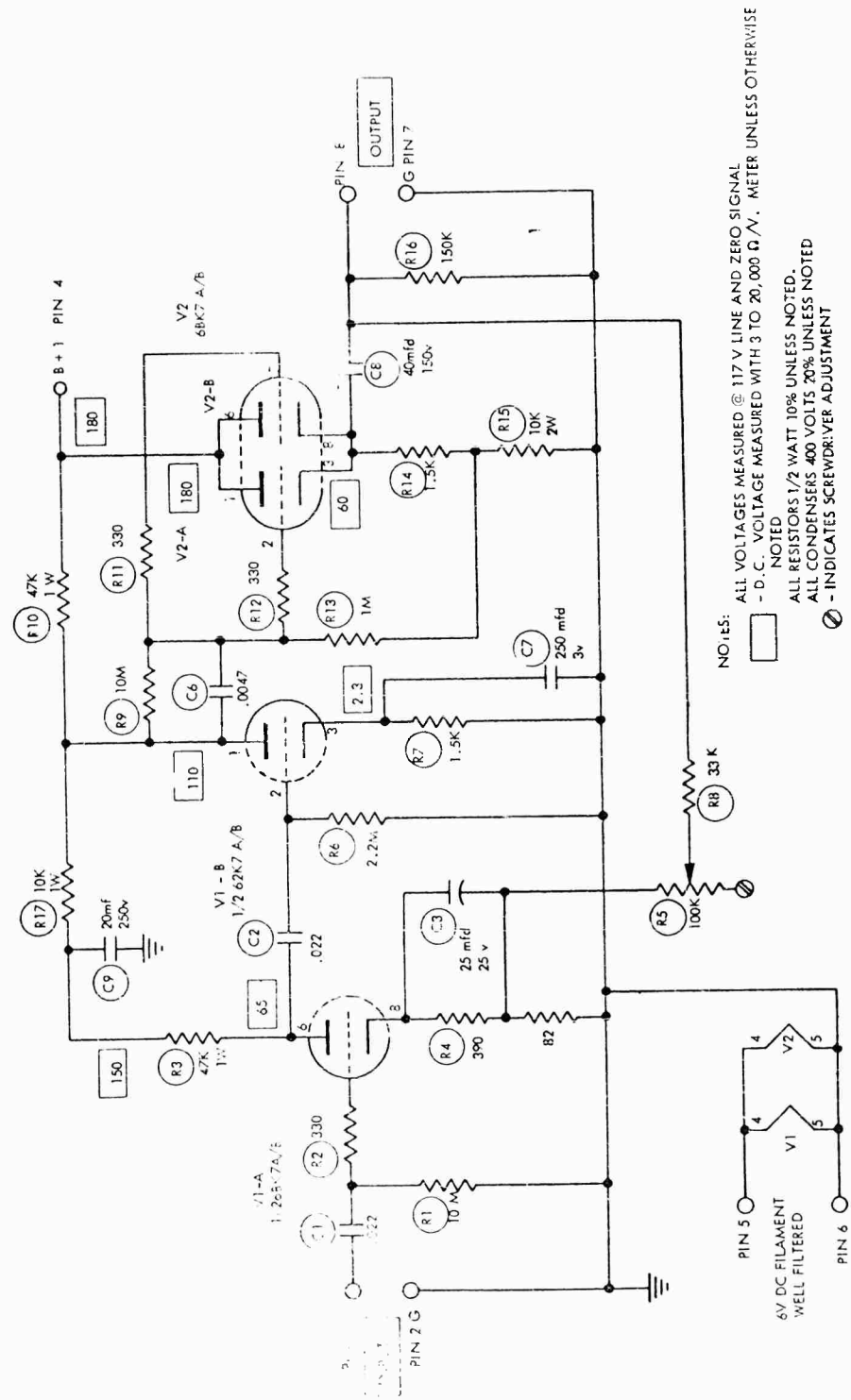
APPENDIX G  
SCHEMATICS



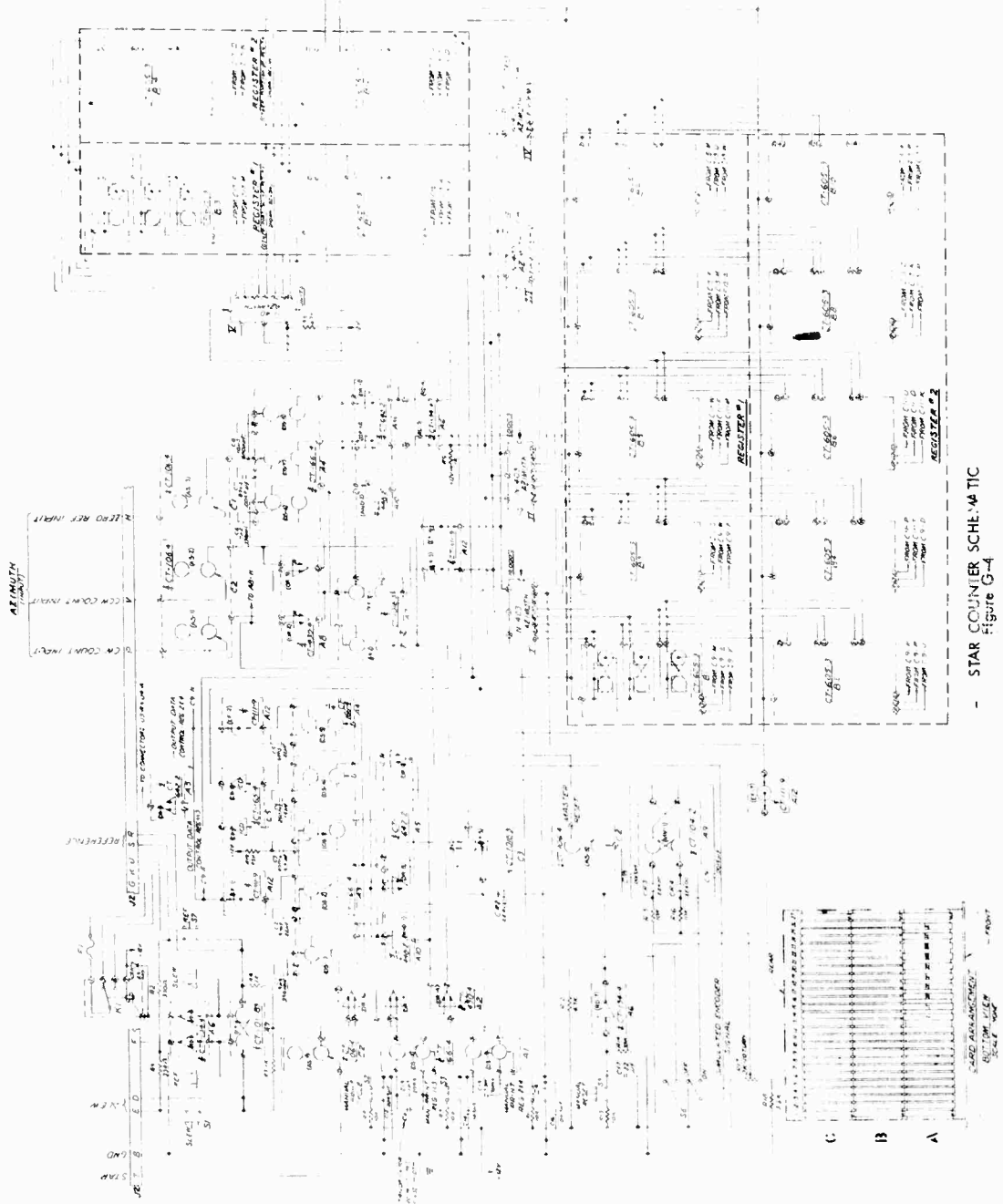
PHOTOMULTIPLIER PRE-AMPLIFIER

Figure G-1

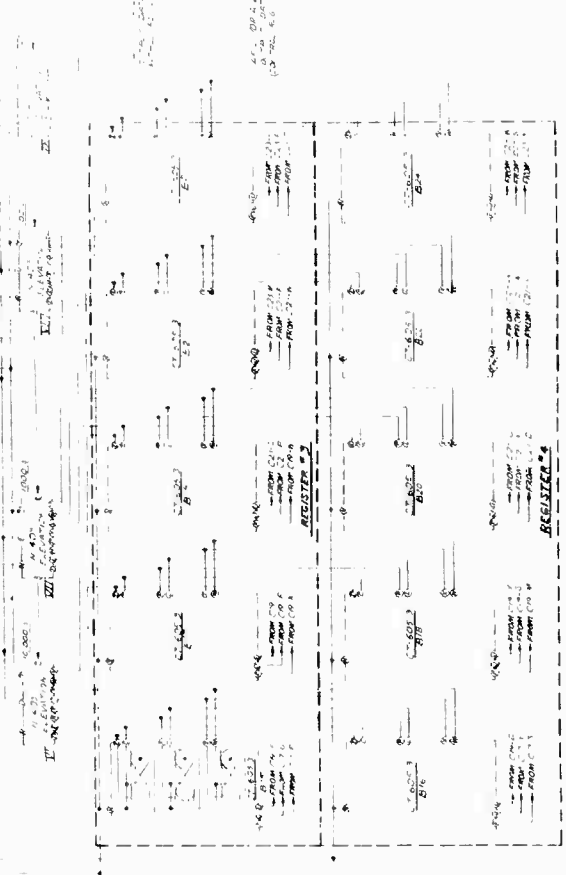
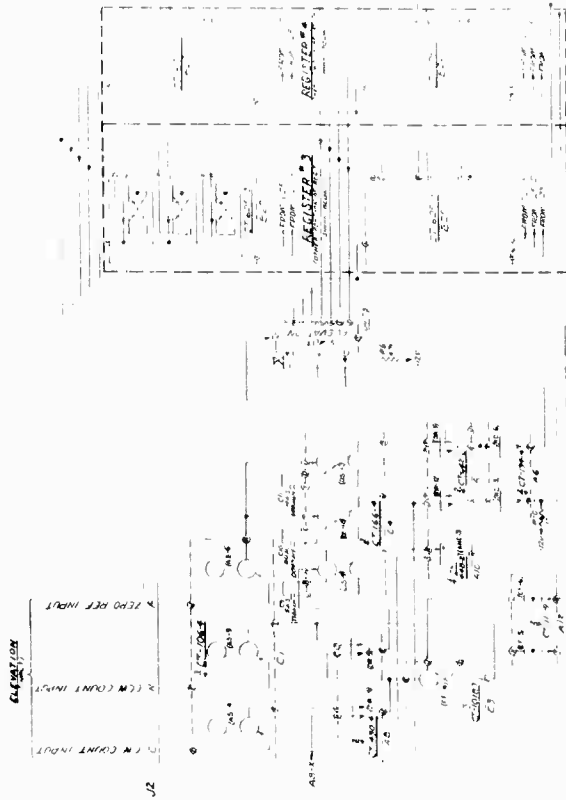




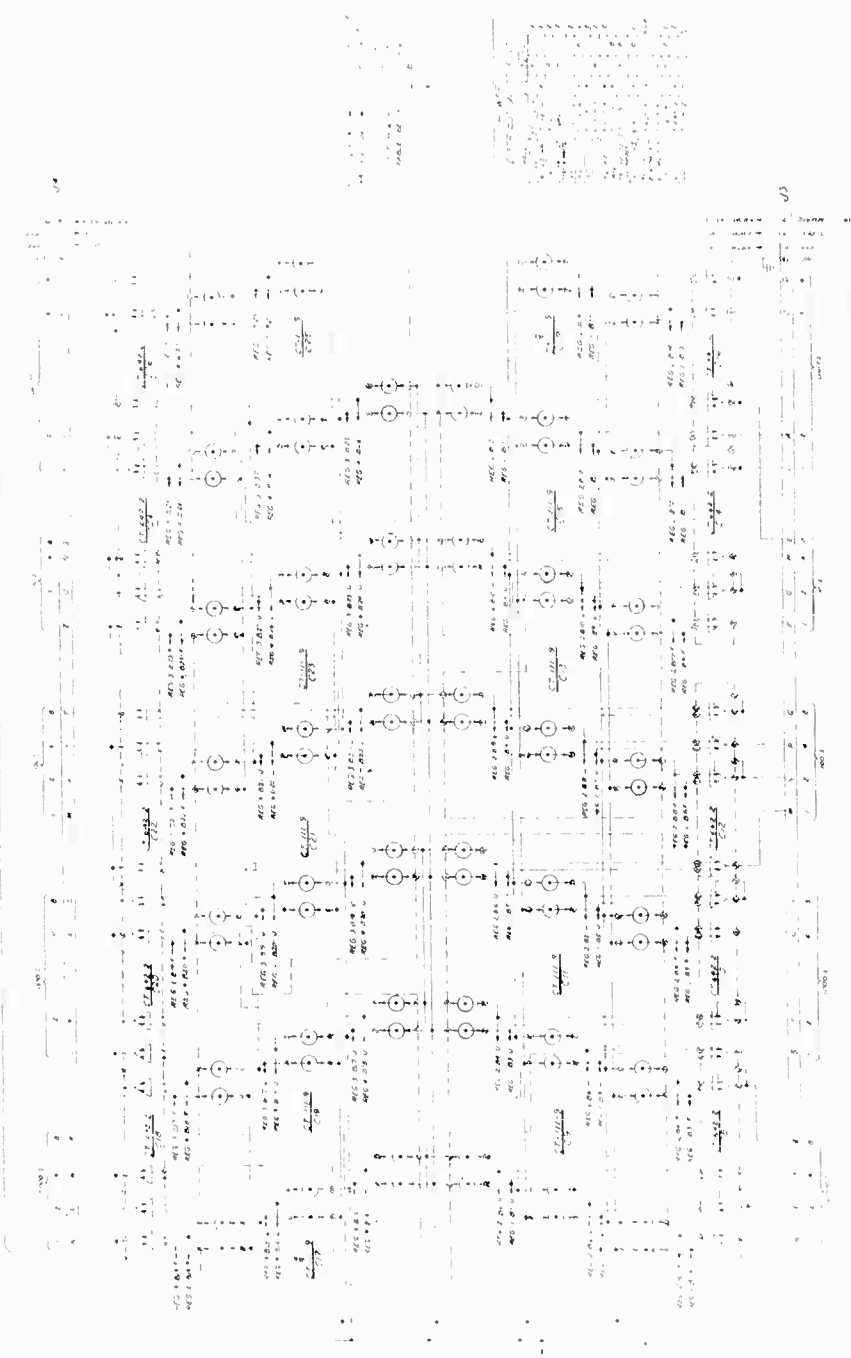
SECOND POST AMPLIFIER  
 Figure G-3



STAR COUNTER SCHEMATIC  
 Figure G-4  
 (Sheet 1 of 3)



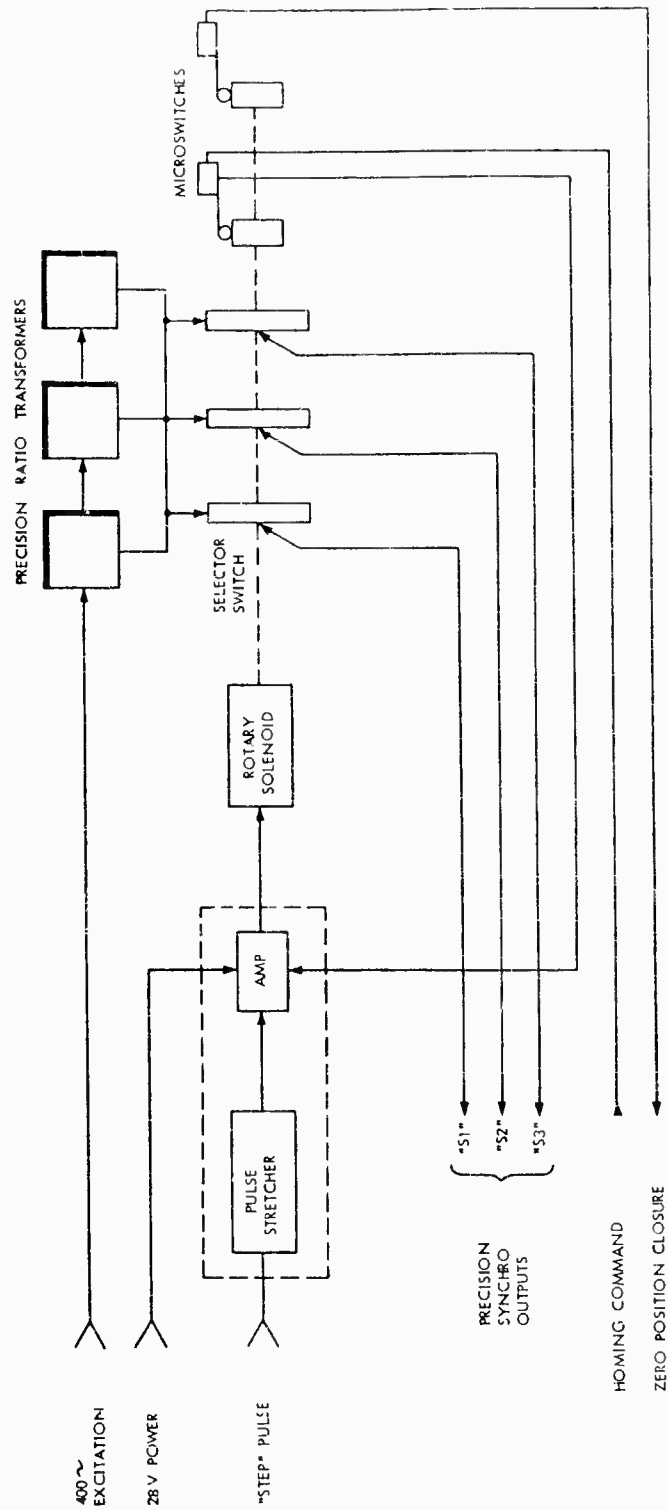
ELEVATION DRAWING



SECTION DRAWING

(Sheet 3 of 3)





BLOCK DIAGRAM, SYNCHRO STANDARD, PULSE OPERATED  
Figure G-6

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<p>Aeronautical Systems Division, AF Avionics Laboratory, Wright-Patterson AFB, Ohio Rpt No. ASD-TDR-63-586 DESIGN, FABRICATION, AND TEST OF A FEASIBILITY-MODEL RELATIVE STAR-ANGLE COMPARATOR, Final Rpt, May 63, 80 p., incl., illus., tables</p> <p>Unclassified Report</p> <p>A new and unique aerospace vehicle attitude system, designed around the Star-pair Angle Comparator, is described. The system basically measures the direction to any three of the fifty (50) brightest stars, computes the angles between them and processes the information to provide a two-star identification and a highly accurate spatial attitude determination.</p> <p>System operation and performance are discussed along with a detail description of the feasibility model subsystem and their components. It is shown that the optical-electrical subsystems provide an equivalent star tracker accuracy within ten arc seconds. The over-all system accuracy, including scanner, gimbaling and electronics, exceeds contractual requirements by a factor of two and is 20 arc seconds.</p>	<p>Aeronautical Systems Division, AF Avionics Laboratory, Wright-Patterson AFB, Ohio Rpt No. ASD-TDR-63-586 DESIGN, FABRICATION, AND TEST OF A FEASIBILITY-MODEL RELATIVE STAR-ANGLE COMPARATOR, Final Rpt, May 63, 80 p., incl., illus., tables</p> <p>Unclassified Report</p> <p>A new and unique aerospace vehicle attitude system, designed around the Star-pair Angle Comparator, is described. The system basically measures the direction to any three of the fifty (50) brightest stars, computes the angles between them and processes the information to provide a two-star identification and a highly accurate spatial attitude determination.</p> <p>System operation and performance are discussed along with a detail description of the feasibility model subsystem and their components. It is shown that the optical-electrical subsystems provide an equivalent star tracker accuracy within ten arc seconds. The over-all system accuracy, including scanner, gimbaling and electronics, exceeds contractual requirements by a factor of two, and is 20 arc seconds.</p>	<p>Navigation</p> <ol style="list-style-type: none"> <li>1. Optical instruments</li> <li>2. Celestial navigation</li> <li>3. Space navigation</li> <li>4. Attitude systems</li> <li>5. AFSC Project 4200, Task 420005</li> </ol> <ol style="list-style-type: none"> <li>II. Contract AF33 (657)-7997</li> <li>III. Kearfoot Division General Precision, Inc Little Falls, N.J.</li> <li>IV. P. Gevas, J. Abate</li> <li>V. G. Gulbenkian</li> </ol> <p>In DDC collection</p>	<p>Navigation</p> <ol style="list-style-type: none"> <li>1. Optical instruments</li> <li>2. Celestial navigation</li> <li>3. Space navigation</li> <li>4. Attitude systems</li> <li>5. AFSC Project 4200, Task 420005</li> </ol> <ol style="list-style-type: none"> <li>II. Contract AF33 (657)-7997</li> <li>III. Kearfoot Div. General Precision, Inc., Little Falls, N.J.</li> <li>IV. P. Gevas, J. Abate</li> <li>V. G. Gulbenkian</li> </ol> <p>In DDC collection</p>
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